buildings

Article

Establishing the Relationship between Occupants' Thermal Behavior and Energy Consumption during Showering

Dadi Zhang, Kwok-Wai Mui and Ling-Tim Wong *

Department of Building Environment and Energy Engineering, The Hong Kong Polytechnic University, Hong Kong, China
* Correspondence: beltw@polyu.edu.hk

Abstract: Despite an increased awareness about energy conservation in the past decade, the energy consumed for water heating has increased by 7% from 2008 (17%) to 2018 (24%) in Hong Kong. A literature review on existing energy-saving technologies during showering showed that occupants' behavior significantly impacted energy consumption. However, the exact relationship between them was not yet fully understood. Therefore, this study developed a mathematical energy consumption model to investigate the relationship between occupants' behavior and energy consumption during showering. This relationship identified an effective energy-saving strategy in the shower without scarifying occupants' thermal comfort. The main variables that influence energy consumption and thermal comfort in bathrooms namely air temperature, water temperature, ventilation rate, and water flow rate, were considered. It was found that among them, water flow rate and ventilation rate are the most and least influential variables, respectively, in energy saving. Therefore, the ventilation rate was suggested to be at least 0.03 kg·s^{-1}, and the water flow rate was meant to be lower than 0.15 kg·s^{-1} (based on related requirements). These findings could help residential occupants and facility managers determine the optimal showering settings for thermal comfort, energy consumption, and environmental effects.

Keywords: energy consumption; thermal comfort; showering; human behavior; water temperature; air temperature; ventilation rate; water flow rate

check for updates

Citation: Zhang, D.; Mui, K.-W.; Wong, L.-T. Establishing the Relationship between Occupants' Thermal Behavior and Energy Consumption during Showering. *Buildings* **2023**, *13*, 1300. https://doi.org/10.3390/buildings13051300

Academic Editors: Elisa Belloni and Gabriele Maria Lozito

Received: 31 March 2023
Revised: 12 May 2023
Accepted: 13 May 2023
Published: 16 May 2023

1. Introduction

Since the international environmental treaty was established to combat climate change, almost all fields, including agriculture, industry, transportation, and building, have been looking for effective ways to save energy and reduce emissions [1,2]. Water utilities are no exception since water and energy always work together. Studies showed that the proportion of energy used for domestic water heating among the total energy consumption was 18% in the United States [3], 15% in Poland [4], 13–18% in Australia [5], and 20% in Hong Kong [6]. Moreover, these proportions have continuously increased in recent years because of decreased energy consumption in other fields, such as space heating and lighting [7].

According to the investigation of energy consumed in the United States, approximately 4.8 × 10^{16} kJ of energy was consumed for water-related purposes. Most of them were lost at the point of transmission, distribution, and end-use [8]. Furthermore, Spang et al. [9] estimated that 1830 GWh of electricity could be saved by water conservation in California in one year. One of the daily actions that are responsible for both energy and water consumption is showering. In Hong Kong, hot water showers consume around 40% and 19% of the total domestic water and energy consumption, respectively [10]. According to a field survey conducted in 1300 households in Hong Kong [11], the shower frequency was around 1.4 times (SD = 0.6) per day, which is more than three times as many as in other cities in England (0.4 times) [12]. Moreover, as indicated in an energy consumption survey conducted by Wan and Yik [13] in Hong Kong, the annual electricity consumption for water heaters accounted for almost half of the total electricity consumption per household and was more tensive in winter. This demonstrates considerable energy-saving potential during shower time in Hong Kong, especially in winter.

Although significant energy saving could be achieved through the optimal operation of the hot water system during showering, it might decrease occupants' comfort [14]. Energy-saving and maintaining comfort appear to conflict with each other. As stated by Pomianowski et al. [7], people tend to increase the number and duration of showers to obtain comfort, and the water must be delivered at the required temperature. Thus, efforts still need to be made to reach the balance between energy efficiency and comfort indicators during showering.

Therefore, this study was conducted to identify an effective energy-saving strategy in hot water showers without scarifying occupants' thermal comfort by varying the showering air and water temperature. To achieve this goal, a literature review was conducted to understand the current situation and knowledge gaps on technologies developed for energy saving in the shower and identify the most promising strategy for further research. Then, on top of that, this study conducts a series of theoretical calculations and develops an energy consumption model to examine the contributions of each influencing factor and further proposes practical suggestions for energy conservation in the shower.

2. Literature Review

In the past decades, we have witnessed the development of energy-saving technologies and equipment for hot water showering systems. To better understand the current situation regarding energy consumption for showering, a literature study was conducted by searching the articles on the Web of Science using three keywords "hot water showering", "building", and "energy". Sixty-one articles were identified, and a bibliometric analysis was conducted using VOSviewer [15]. Figure 1 illustrates the high-frequency items that occurred in the abstracts of these articles. As can be seen, alternative energy sources, especially solar energy (the green parts in Figure 1) and waste heat recovery (the red parts in Figure 1), are the two main topics for showering-related studies. By carefully checking these references, the specific commonly used energy-saving technologies can be classified into four categories: heat recovery systems, solar collectors, heat pump water heaters combined with water supply efficiency improvements, and water-efficient showerheads.

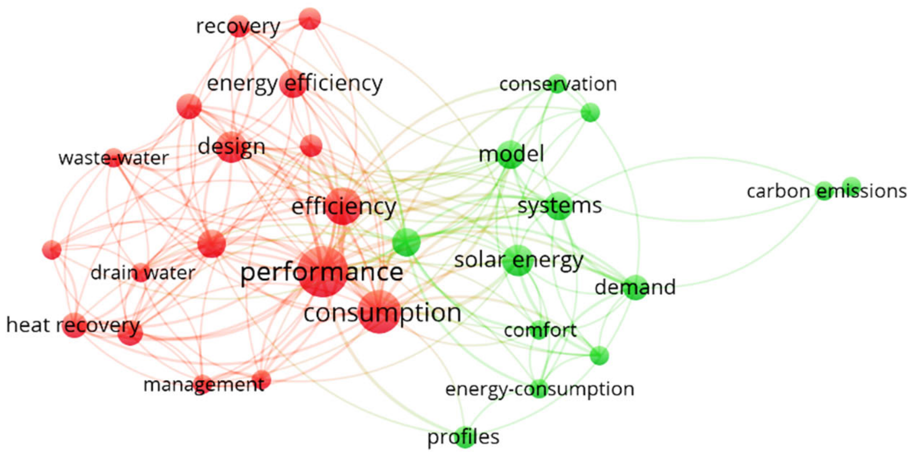

Figure 1. High-frequency items occurred in the studies on energy consumption in the shower.

2.1. Heat Recovery Systems

Considering the huge amount of energy in shower wastewater, utilizing the energy recovered from the wastewater to heat shower water is significant in energy saving [16]. A previous study revealed that only 5% or less of the energy used for shower-water heating was spent on actual showering events. Over 85% of the energy used for shower-water heating was wasted on the drain [5]. Consequently, many heat recovery techniques were proposed and tested [6,17]. For example, Wong et al. [6] investigated the performance of a compact single-pass counter-flow heat exchanger for apartments that could save 4–15% of heat from shower wastewater annually. McNabola and Shields [18] presented a horizontal heat exchanger with a certain number of loops and claimed that this new structure could increase energy efficiency by up to 50%. Tomlinson [19] designed a vertical, counterflow heat exchanger named gravity-film heat exchanger and concluded that a 50% saving of energy used to heat shower water is achievable with this system.

2.2. Solar Collectors

To avoid the climate disruption caused by fossil fuels, renewable energy sources, such as solar energy, are encouraged to be used by governments worldwide. However, the energy-saving potential of solar collectors largely depends on the climate condition and cities' building density. Previous studies indicated that solar collectors could save 60–74% of energy in cities with high sunlight hours and low-density buildings, such as those near the Mediterranean region [20,21]. By contrast, although the solar condition is not bad in Hong Kong, most territories are hilly, and the limited developed lands are full of high-rise buildings, making installing solar collector panels difficult [22]. One proposed solution to this problem is the building-integrated photovoltaic/water-heating system that can be installed on vertical walls. According to a simulation study, the annual thermal efficiency of this system could be 38% under the conditions in Hong Kong [23].

2.3. Combination of Heat Pump Water Heater and Instantaneous Shower

Heat pump water heater (HPWH) is another standard water heating method with high energy efficient heat treatment. However, since HPWHs are usually centrally located in a building, a certain amount of water and associated energy are inevitably lost during the conveyance to the end users due to leakage or evaporation [24]. Moreover, some cold water in the pipe is wasted before the hot water is transmitted to the end users. Therefore, to avoid conveyance loss, tankless (also known as "instantaneous") water heating was recommended [25]. Yet this technology might increase the energy input during the peak time since it heats water on demand. To tackle this problem, Henze et al. [26] developed a modal predictive control (MPC) for tankless water heating. To further improve the energy efficiency of this system, Wanjiru et al. [24,27] suggested involving renewable energy in this system as well. They stated that by combining HPWH, instantaneous shower, optimal control, and renewable energy, 23.4% energy and 19 L water could be saved daily [27].

2.4. Water-Efficient Showerheads

Policies have promoted low-flow appliances (water-efficient showerheads) in the past decades. A water-efficient showerhead could reduce the water flow rate from 25 $L \cdot min^{-1}$ to 7 $L \cdot min^{-1}$. Its water-saving potential is straightforward and can be directly perceived through the senses. According to a simulation study that compared five energy-saving technologies, low-flow appliances performed best, with around 30% energy conservation for domestic water use [28]. Yet, no significant changes in residents' water usage were identified [29]. The low satisfaction rate of these water-efficient showerheads might cause this. Wong et al. [30] surveyed satisfaction with water-efficient showerheads and found that most customers were unsatisfied with the showerhead's pressure and water flow rate.

Furthermore, studies found that the water-saving amount is closely related to users' satisfaction with water-efficient devices. If the devices reduce users' satisfaction, they might resort to other ways, such as longer showers, to compensate [31,32]. Therefore, the design of low-flow devices should focus on users' comfort and satisfaction and understanding their showering behavior might be crucial to adopting energy-saving devices.

2.5. Knowledge Gaps

To date, the impact of occupants' showering behavior on energy consumed by the showering water systems has not been fully understood, unlike the importance of occupants' behavior on energy consumption of buildings on the Heating, Ventilation, and Airconditioning (HVAC) or lighting systems [33,34]. Wong et al. [10] evaluated the influence of users' behaviors on CO_2 reduction through simulations and compared it with other energy-related CO_2 reduction measures. Results indicated that users' behavior played a vital role in energy saving during showering, and its effect on CO_2 reduction (22%) is more significant than heat recovery from shower wastewater (14%) as well as being compatible with water-efficient showerheads (26%) [10]. Park & Chung [35] also identified the significance of occupants' behavior in domestic hot water and energy use in buildings with a mandatory zero-energy policy. However, the underlying causes of CO_2 reduction and the specific relationships between occupants' behavior and energy consumption in bathrooms remains to be studied.

Zeiler et al. [33] found that comfort levels usually drove human behavior and most actions were taken to deal with uncomfortable conditions. For example, people turn on fans or air conditioning when they feel warm [36] and turn on lights when they are in the dark [37]. Additionally, many studies showed that these comfort-seeking behaviors are closely related to energy consumption [36,37]. To date, studies on the relationships between occupants' comfort, behaviors, and energy consumption mainly focused on thermal comfort [38,39] since the HVAC system accounts for one of the most significant proportions of energy consumption in modern buildings [40]. Furthermore, most of them were about the environment in offices [37,39], living rooms, and bedrooms [41]. However, occupants' behavior, comfort, and energy consumption in bathrooms were rarely studied. Thus, much uncertainty still exists about the relationships between occupants' showering behavior, thermal comfort, indoor thermal environment, and energy consumption. Understanding these relationships might be the key to further saving energy in the shower.

3. Mathematical Model

The radiator and the water heater mainly cause energy consumption during showering to maintain a comfortable showering environment. This study proposes a simple model for describing the energy consumption during showering by calculating the energy consumed by the radiator and water heater separately and considering occupants' thermal comfort.

3.1. Initial Conditions and Assumptions

Previous surveys on showering behaviors in different seasons indicated that people prefer to shower longer and increase the water temperature in winter [42]. Radiators or other types of heaters were usually used in the bathroom in winter to keep a comfortable thermal showering environment. Thus, more energy was consumed in the shower in winter, and more energy-saving potential was also expected. Therefore, this study regards winter as the research target and 17 °C, the average outdoor temperature from December 2022 to February 2023 [43], was selected as the typical outdoor ambient temperature in winter in Hong Kong. Additionally, other initial conditions were assumed as follows:

1. The ventilation rate in the bathroom was assumed to be 0.01–0.03 $kg\cdot s^{-1}$. The minimum level (0.01 $kg\cdot s^{-1}$) was decided based on equation (1) to keep the CO_2 concentration in the bathroom below 1000 ppm [44]. The maximum level (0.03 $kg\cdot s^{-1}$) was decided based on the ASHRAE requirement for bathroom ventilation, which considers contamination elimination:

$$m_a = \frac{100 \times n \times G_p \times \rho_a}{6 \times (C_s - C_{out})} = \frac{100 \times 0.46 \times 1.29}{6 \times (1000 - 400)} = 0.01 \quad (1)$$

where G_p is the average CO_2 generation rate per person ($l\cdot min^{-1}$) for a standing male adult aged from 16–40, $G_p = 0.46\ l\cdot min^{-1}$ [45]; ρ_a is the density of the air ($kg\cdot m^{-3}$); for air at constant pressure, ρ_a = 1.29 $kg\cdot m^{-3}$; C_s is the steady-state indoor CO_2 concentration (ppm); C_{out} is the outdoor CO_2 concentration (ppm).

2. The range of water flow rate for showering was assumed to be 0.08–0.27 $kg \cdot s^{-1}$. These values were decided based on the recommendation of the Institute of Plumbing [46] and WELS (water efficiency labeling scheme) [47].
3. The water temperature was assumed to be 32–40 °C, and the air temperature was assumed to be 20–40 °C. These were according to the comfortable temperature range of showering water identified by Wong et al. [42]. Using these values, the occupant's thermal sensation vote (TSV) during showering can be calculated based on the following equation [42]:

$$TSV = c_a(T_a - T_{a,o}) + c_w(T_w - T_{w,o}) \quad (2)$$

where T_a is the air temperature in the bathroom (°C); T_w is water temperature (°C); $T_{a,o}$ is the air temperature (°C) when the occupants feel thermal neutral (TSV = 0) during showering, determined by a previous study as 25.8 °C. $T_{w,o}$ is the water temperature (°C) when the occupants feel thermal neutral during showering, which is determined by a previous study as 38.8 °C; c_a is the change in TSV caused by a unit change in air temperature. It is 0.17 when $T_a > T_{a,o}$, 0.008 when $T_a < T_{a,o}$; c_w is the change in TSV caused by a unit change in water temperature. It is 0.73 when $T_w > T_{w,o}$, 0.033 when $T_w < T_{w,o}$.

Additionally, the following assumptions were made in this study to establish the model:

1. The occupant was in a thermal balanced state; no energy was emitted or absorbed by the human body.
2. Only two energy sources i.e., hot water and a radiator, were assumed to be in the bathroom. The energy emission by the lighting system is insignificant.
3. The energy efficiencies of the water heater and radiator were assumed to be 100%.

3.2. Energy Released in the Bathroom

The total energy release rate in the bathroom ($\dot{Q}$, kW) can be calculated using Equation (3) developed by Foote et al. [48], who identified the correlations between the rise in air temperature and the heat release rate in a forced-ventilated compartment (like a bathroom):

$$\frac{\Delta T_g}{T_\infty} = 0.63\left(\frac{\dot{Q}}{m_a c_p T_\infty}\right)^{0.72}\left(\frac{h_k A_T}{m_a c_p}\right)^{-0.36} \quad (3)$$

where ΔT_g is when the air temperature rises above the ambient temperature (K); T_∞ is the ambient air temperature (K) before the heat is released, which is 290 K in the current study; m_a is the compartment mass ventilation rate ($kg \cdot s^{-1}$); c_p is the specific heat of gas ($kJ \cdot kg^{-1} \cdot K^{-1}$), which is 1.005 $kJ \cdot kg^{-1} \cdot K^{-1}$ for air at constant pressure; A_T is the total area of the bathroom surface (m^2), for a normal size (1.5 (w) × 2.1(l) × 2.5 (h)) bathroom, $A_T = (1.5 \times 2.1 + 1.5 \times 2.5 + 2.1 \times 2.5) \times 2 = 24.3\ m^2$; h_k is the effective heat transfer coefficient ($kW \cdot m^{-1} \cdot K^{-1}$), since $t < t_p$ (thermal penetration time), h_k is calculated based on the following equation [48]:

$$h_k = \left(\frac{k\rho c}{t}\right)^{1/2} \quad (4)$$

where k is the thermal conductivity of the compartment surface ($kW \cdot m^{-1} \cdot K^{-1}$), which is 1.6×10^{-3} $kW\ m^{-1} \cdot K^{-1}$ for ceramic tiles [49,50]; ρ is the density of the compartment surface ($kg \cdot m^{-3}$), which is 2400 $kg \cdot m^{-3}$ for ceramic tiles [49]; c is the specific heat of the compartment surface material ($kJ \cdot kg^{-1} \cdot K^{-1}$), which is 1 $kJ \cdot kg^{-1} \cdot K^{-1}$ for ceramic [50]; t is the shower time (s), which is assumed to be 600 s in the current study. So, h_k is 0.08 kW/m·K ($h_k = \left(\frac{k\rho c}{t}\right)^{1/2} = \left(\frac{1.6\times10^{-3}\times2400\times1}{600}\right)^{1/2} = 0.08$).

Based on Equations (3) and (4), the total energy release rate in the bathroom can be calculated as follows:

$$\begin{aligned}\dot{Q} &= Q_w + Q_r = m_a c_p T_\infty \left(\frac{T_a + 273 - T_\infty}{0.63 T_\infty}\right)^{1.389} \left(\frac{h_k A_T}{m_a c_p}\right)^{0.5} \\ &= m_a \times 1.005 \times 290 \times \left(\frac{T_a - 17}{0.63 \times 290}\right)^{1.39} \left(\frac{0.08 \times 24.3}{m_a \times 1.005}\right)^{0.5}\end{aligned} \quad (5)$$

3.3. Energy Consumption during Showering

Two sources contribute to the total energy released in the bathroom during showering: hot water (Q_w) and a radiator (Q_r). The energy release rate of the hot water and radiator can be calculated based on Equations (6) and (8), respectively. Correspondingly, the total energy consumed while showering also consists of the energy consumed by the water heater (Q_{wh}) and the radiator (Q_r). For the water part, since the water in the drain still contains lots of energy, the energy consumed by the water heater is much larger than the energy released by hot water in the bathroom. The energy efficiency was assumed to be 100% for the radiator and all the energy it consumed was released to the ambient air in the bathroom:

$$Q_w = m_w \times c_w \times \Delta T_w \quad (6)$$

where m_w is the water flow rate for showering ($kg \cdot s^{-1}$); c_w is the specific heat capacity of water ($kJ \cdot kg^{-1} \cdot K^{-1}$), which is 4.18 $kJ \cdot kg^{-1} \cdot K^{-1}$; ΔT_w is the temperature difference between the shower head and the drain (°C), which can be calculated based on the following equation established by Wong [6]:

$$\Delta T_w = 3.6 \times 10^{-10} \times {T_w}^{6.673} \times {T_a}^{-0.530} \quad (7)$$

Then, the energy release rate of the radiator, which is also the energy consumed by the radiator, can be calculated as follows:

$$\begin{aligned}Q_r = \dot{Q} - Q_w &= m_a \times 1.005 \times 290 \times \left(\frac{T_a - 17}{0.63 \times 290}\right)^{1.39} \left(\frac{0.08 \times 24.3}{m_a \times 1.005}\right)^{0.5} \\ &\quad - m_w \times 4.18 \times 3.6 \times 10^{-10} \times {T_w}^{6.673} \times {T_a}^{-0.530}\end{aligned} \quad (8)$$

The energy consumed by the water heater to heat the water from the supply temperature, which can be deduced based on the ambient temperature [6], to the comfort temperature can be calculated as:

$$Q_{wh} = m_w \times c_w \times \left(T_w - 10.4 \times {T_\infty}^{0.29}\right) = m_w \times 4.18 \times \left(T_w - 10.4 \times 17^{0.29}\right) \quad (9)$$

The total energy consumption rate during showering can be calculated using Equation (10). As shown, the determining factors of the energy consumption rate during showering are air temperature, water temperature, water flow rate, and ventilation rate:

$$\begin{aligned}Q_{total} = Q_r + Q_{wh} &= m_a \times 1.005 \times 290 \times \left(\frac{T_a - 17}{0.63 \times 290}\right)^{1.39} \left(\frac{0.08 \times 24.3}{m_a \times 1.005}\right)^{0.5} \\ &\quad - m_w \times 4.18 \times 3.6 \times 10^{-10} \times {T_w}^{6.673} \times {T_a}^{-0.530} + m_w \times 4.18 \times \left(T_w - 10.4 \times 17^{0.29}\right)\end{aligned} \quad (10)$$

The data collected during showers by a previous study [42] was applied to verify the above equations. According to the control cases in the study conducted by Wong et al. [42] in a bathroom of the same size as this study, the average ambient temperature was 17.4 °C, the average air temperature in the bathrooms was 25.7 °C, the water temperature was 38.8 °C, and the water flow rate was fixed as 6 L/min (i.e., 0.1 kg/s). Moreover, an exhaust fan with a ventilation rate of 0.1 m^3/s (i.e., 0.13 kg/s) and a heater with a power of 1 kW was used to maintain health and comfort conditions. In these cases, the energy release rate of the hot water was about 1.078 kW, according to Equation (9). Thus, the total energy release rate released during the shower was about 2.078 kW. Then, based on Equation (3), ΔT_g should be 8.9 °C, which was quite close to the real situation (25.7–17.4 = 8.3). Therefore, the calculation procedure was considered to be valid.

3.4. Data Analysis

Figure 2 illustrates the present study's data preparation, organization, and analysis process. The data preparation and organization were accomplished in the following steps: (i) assigned ten values between 0.01–0.03 to the ventilation rate; (ii) for each given ventilation rate, ten values between 0.08–0.27 were assigned to the water flow rate; (iii) for each offered water flow rate, ten values between 32–40 were given to the water temperature; (iv) for each given water temperature, ten values between 20–40 were assigned to the air temperature; (v) based on these assigned values, the energy consumed by the radiator was calculated using Equation (8); (vi) the cases, based on the radiator energy, were screened; For typical bathroom radiators, the size range is from 0.3 m^2 to 1.1 m^2 [51]. The output range is from 835 $W \cdot m^{-2}$ (single steel) to 2354 $W \cdot m^{-2}$ (double convector) [52], so the radiator energy output rate is about 0.3–2.6 kW. Accordingly, the cases with Q_r outside of this range were filtered out from the database. (vii) the total energy consumption and occupant's TSV for each possible physical showering condition were calculated using Equations (2) and (10), respectively.

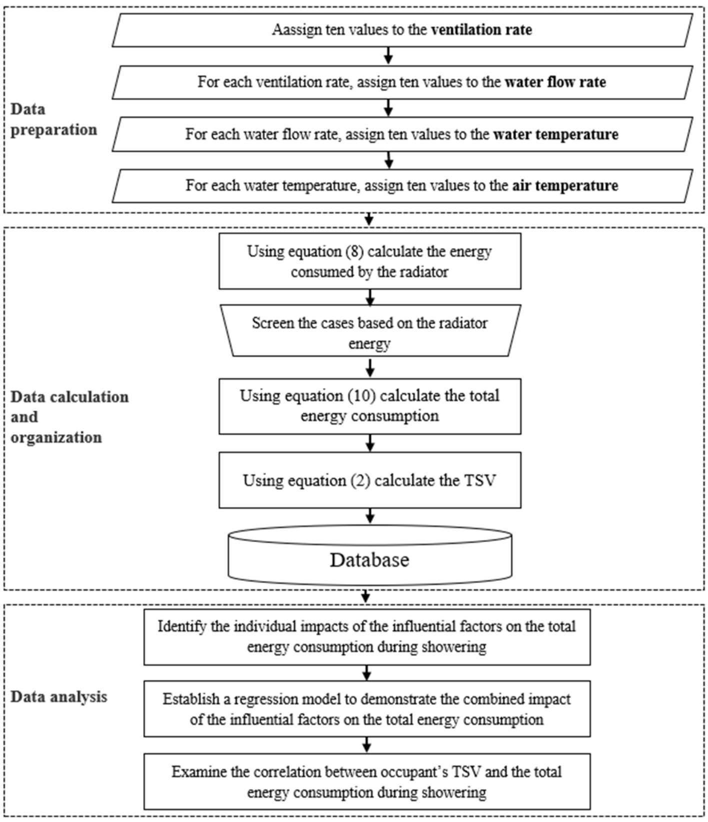

Figure 2. The flowchart of the creation of the databases.

The database was then imported into IBM SPSS Statistics 27.0 (SPSS Inc. Chicago, IL, USA) for the data analysis. Different regression models between the total energy consumption and water temperature/air temperature/ventilation rate/water flow rate were established to investigate the personal impact of these variables on energy consumption during showering. For each variable, different types of regression models, such as linear, multinomial, and exponential were established, and the one with the highest R^2 (the coefficient of determination) was selected. After that, a multivariate regression model was established between the energy consumption and ventilation rate, water flow rate, air temperature, and water temperature to examine the combined impact of these variables on the total energy consumption. Furthermore, each independent variable's Variance Inflation Factor (VIF) was checked to avoid the multi-collinearity issue. Additionally, a standardized regression model was also established to find out the most influential variable in terms of energy consumption during showering. At last, the Pearson correlation analysis was conducted to evaluate the relationship between the total energy consumption and the occupant's TSV.

4. Results and Discussions

To better understand the impacts of air temperature, water temperature, water flow rate, and ventilation rate on the energy consumption and an occupant's thermal sensation during showering, the Pearson correlation and different regression models were established among these influencing variables and the total energy consumption/TSV. Table 1 lists all the Pearson correlation coefficients. This data shows that all the variables were closely related to the total energy consumption and an occupant's thermal sensation. For the regression models, the quadratic polynomial models were the best-fitted ones (with the highest R^2) among all the possible regression models. The R^2 of all the quadratic polynomial models was >0.99, which means that the models could explain the relationships between these variables and the total energy consumption very well. Moreover, a multivariate regression model was established to explain better these variables' integrated impact on the total energy consumption during showering. The details of these models were introduced in the following subsections. It is worth noting that the data analysis only focused on the minimum energy consumption since the current study aims at energy conservation.

Table 1. Pearson correlation coefficients between the influencing variables and energy consumption/TSV during showering.

	Air Temperature	Water Temperature	Ventilation Rate	Water Flow Rate
Total energy consumption	0.558 (<0.001)	0.389 (<0.001)	0.162 (<0.001)	0.833 (<0.001)
TSV	0.764 (<0.001)	0.867 (<0.001)	−0.054 (<0.001)	0.055 (<0.001)

Note: the values in the parentheses are *p*-values.

4.1. Impact of Air Temperature and Water Temperature on Energy Consumption

A previous study found that air and water temperatures are the main variables influencing the occupants' thermal comfort during showering [42] consistent with the results shown in Table 1. The Pearson coefficients for air temperature (r = 0.76) and water temperature (r = 0.87) were >0.5, demonstrating their strong and positive effects on occupants' TSV.

Figure 3 shows the average values of energy consumption and TSVs under the same air temperatures and the trends in energy consumption and TSV with the changes in air temperature during showering. It demonstrates that when the air temperature was between 24–40 °C, it positively correlated with the total energy consumption and an occupant's thermal sensation. According to Table 1, both correlations were strong (r > 0.5). It should be noted that although the air temperature setting was 20–40 °C, no cases with air temperature lower than 24 °C existed since the radiator and hot water continuously heated the bathroom air during showering. As shown in Figure 3, the thermal neutral air temperature (TSV = 0) during showering was 32.8 °C and the thermal neutral zone (−0.5 < TSV < 0.5) was 30.8–34.9 °C (the shadow area in Figure 3). The corresponding energy consumption range was 7.9–9.8 kW to maintain a comfortable air temperature.

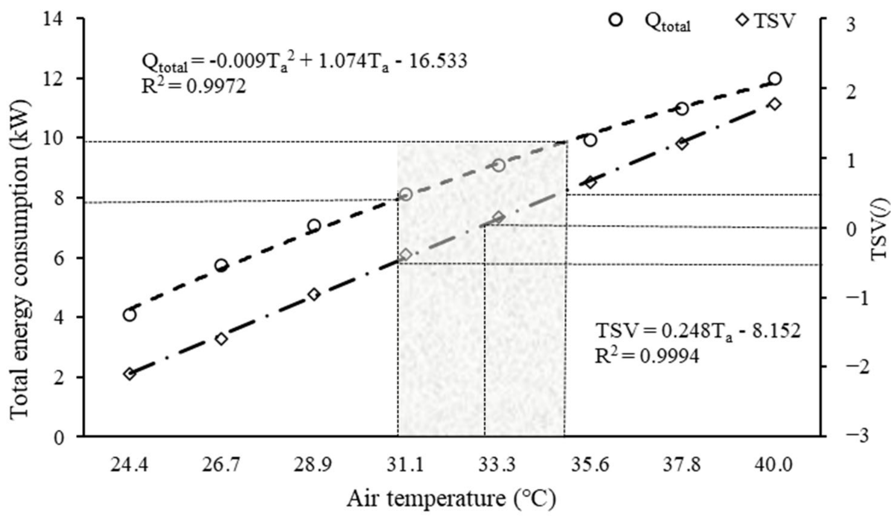

Figure 3. Impact of air temperature on the total energy consumption and occupant's thermal sensation. **Note**: ventilation rate was 0.01–0.03 kg·s^{-1}; water flow rate was 0.08–0.27 kg·s^{-1}; water temperature was 32–40 °C.

As mentioned above, the water temperature significantly and positively impacted occupants' TSV. Figure 4 shows the trends in energy consumption and TSV with the changes in air temperature during showering. During showering, the thermal neutral water temperature was 34.6 °C and the comfort zone was 33.5 to 35.7 °C. Correspondingly, the total energy consumption was 8.6–9.9 kW. Regarding the impact on the total energy consumption, as shown in Table 1, water temperature only had a moderate effect (r = 0.39), which was less significant than the air temperature. Similarly, the relatively flat trendline of energy consumption in Figure 4 demonstrates the water temperature's less significant impact.

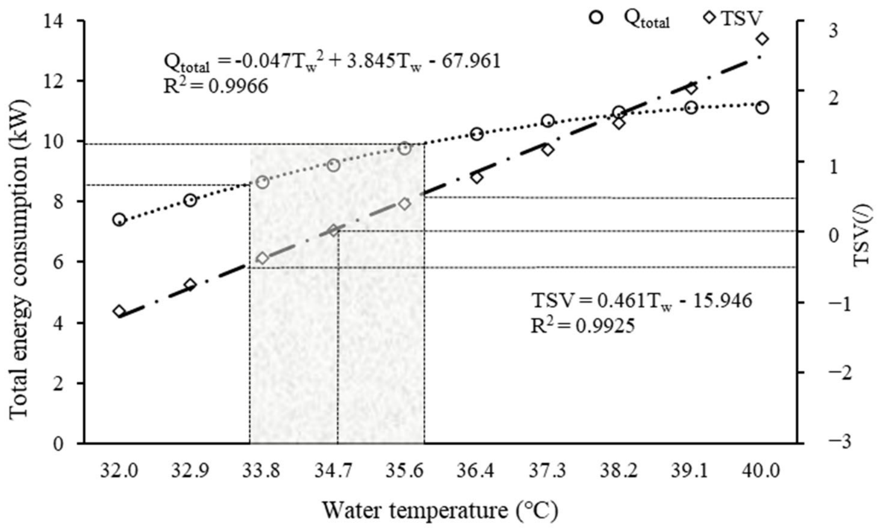

Figure 4. Impact of water temperature on the total energy consumption and occupant's thermal sensation. **Note**: ventilation rate was 0.01–0.03 kg·s^{-1}; water flow rate was 0.08–0.27 kg·s^{-1}; air temperature was 20–40°C.

4.2. Impact of Ventilation Rate and Water Flow Rate on Energy Consumption

Unlike the impacts of air and water temperatures, the effects of ventilation and water flow rate on occupants' TSV were relatively weak, with the Pearson correlation coefficients much less than 0.3 (see Table 1). Furthermore, as shown in Figures 5 and 6, no matter which values the ventilation rates or water flow rates were, the average TSV of these cases was always slightly warm (from 0 to 1) and hardly any changes were identified. Therefore, the current study considers ventilation and water flow rates in the practical ranges insignificant to an occupants' thermal sensations.

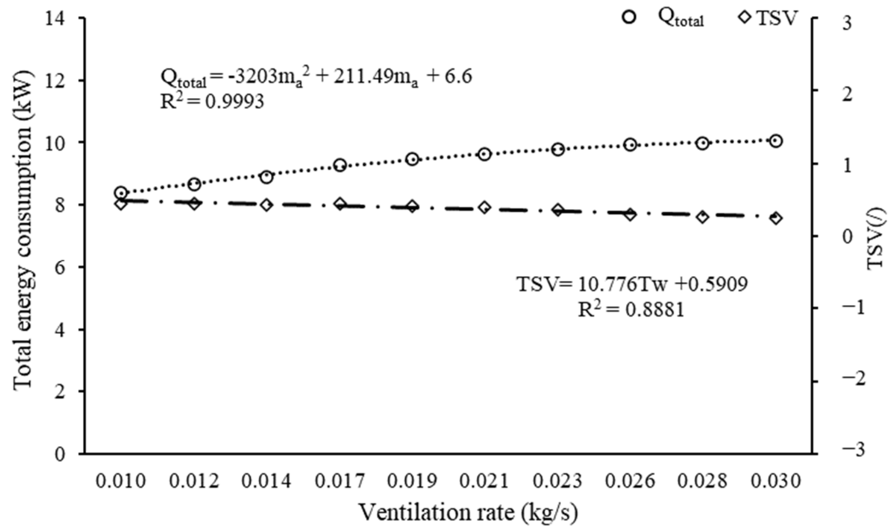

Figure 5. Impact of ventilation rate on the total energy consumption and occupants' thermal sensation. **Note**: water flow rate was 0.08–0.27 kg·s^{-1}; water temperature was 32–40 °C; air temperature was 20–40°C.

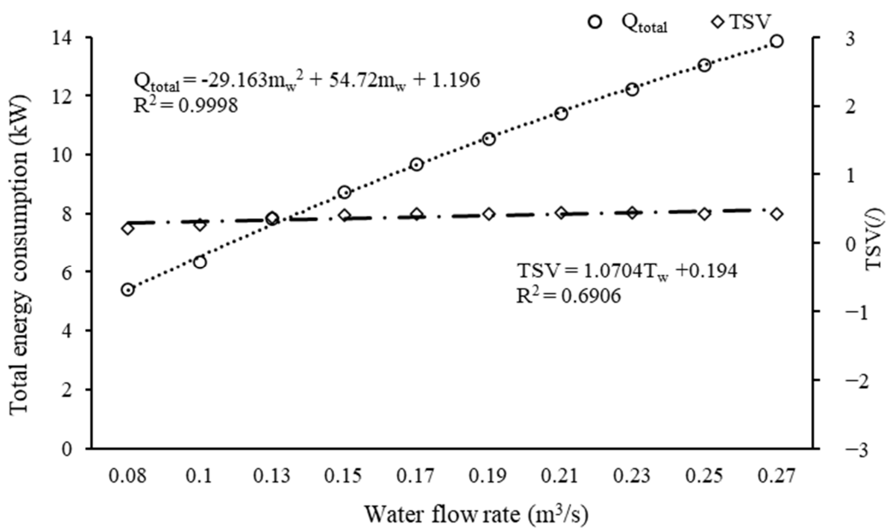

Figure 6. Impact of water flow rate on the total energy consumption and occupants' thermal sensation. **Note:** ventilation rate was 0.01–0.03 kg·s^{-1}; water temperature was 32–40 °C; air temperature was 20–40 °C.

In terms of the impact of the ventilation rate on the total energy consumption, it was also weak (r = 0.162). As shown in Figure 5, even though the ventilation rate increased twice (from 0.01 to 0.03 kg·s^{-1}), the energy consumption only increased within 2 kW (from 8.4 to 10.1 kW). In contrast, the impact of the water flow rate on the total energy consumption was quite strong, and the Pearson correlation coefficient between them was the highest (r = 0.833) among the coefficients between other influencing variables and the total energy consumption (see Table 1).

4.3. Integrated Impact of Air Temperature, Water Temperature, Water Flow Rate, and Ventilation Rate on Energy Consumption

Considering the interaction between the air temperature, water temperature, water flow rate, and ventilation rate, a multiple regression model was established between these variables and the total energy consumption to understand their integrated impact better. Detailed information about this model is shown in Table 2. All the variables significantly impacted the energy consumption and no multicollinearity was identified between them (VIF < 4). In addition, the R^2 of this model is 0.987, which means this regression model can explain 99% of the variability observed in the total energy consumption:

$$Q_{total} = 0.19 \times T_a + 0.51 \times T_w + 62.08 \times m_a + 43.37 \times m_w - 23.85 \left(R^2 = 0.987\right) \quad (11)$$

Table 2. Multivariate regression model of energy consumption.

Variables	β Coefficient	Standardized Coefficients Beta	95.0% Confidence Interval for β	*p* Value [a]	VIF [b]
Air temperature (°C)	0.193	0.237	0.188–0.197	<0.001	1.441
Water temperature (°C)	0.512	0.388	0.505–0.519	<0.001	1.279
Ventilation rate ($kg \cdot s^{-1}$)	62.081	0.122	59.569–64.593	<0.001	1.147
Water flow rate ($kg \cdot s^{-1}$)	43.372	0.807	43.103–43.641	<0.001	1.183

Note: [a]. *p* value less than 0.05 means the observed impact is statistically significant; [b]. variance inflation factor (VIF) represents how well other independent variables explain the variable.

Since units and ranges differ a lot between the air temperature, water temperature, water flow rate, and ventilation rate, the β coefficients identified in the multivariate regression model cannot be used to compare the influence of these variables. To find out the most important/influential variable in energy consumption during showering, the focus was given to the standardized coefficients of these variables obtained by establishing another regression model on the standardized form of the variables. As shown in Table 2, among the four variables, the water flow rate has the highest standardized coefficient, followed by water temperature and air temperature, and the ventilation rate has the lowest standardized coefficient. This indicates that water temperature had the most significant impact on the total energy consumption. It was about twice as important as the air temperature, three times as important as the air temperature, and six times as important as the ventilation rate in predicting total energy consumption during showering.

4.4. Relationship between the Total Energy Consumption and Occupant's Thermal Sensation during Showering

According to the Pearson correlation coefficient between the total energy consumption and an occupant's TSV, they had a statistically significant relationship ($p < 0.001$). Figure 7 illustrates the correlation between the total energy consumption and the occupant's thermal sensation during showering. As can be seen, the total energy consumption increased with the increase in occupant's TSV. For the cases where the occupant felt neither hot (TSV > 0.5) nor cold (TSV < −0.5), the average total energy consumption rate was 5.13–5.32 kW, corresponding to an energy consumption of 0.86–0.89 kWh for a ten-minute thermally acceptable shower. Additionally, Figure 7 also shows the relationships between the TSV and the water/air temperature. It can be seen that the ranges of the water temperature and air temperature were 33.5–35.7 °C and 30.8–34.9 °C, respectively, for the thermal neutral zone, which was the same as the results reported in the above sections.

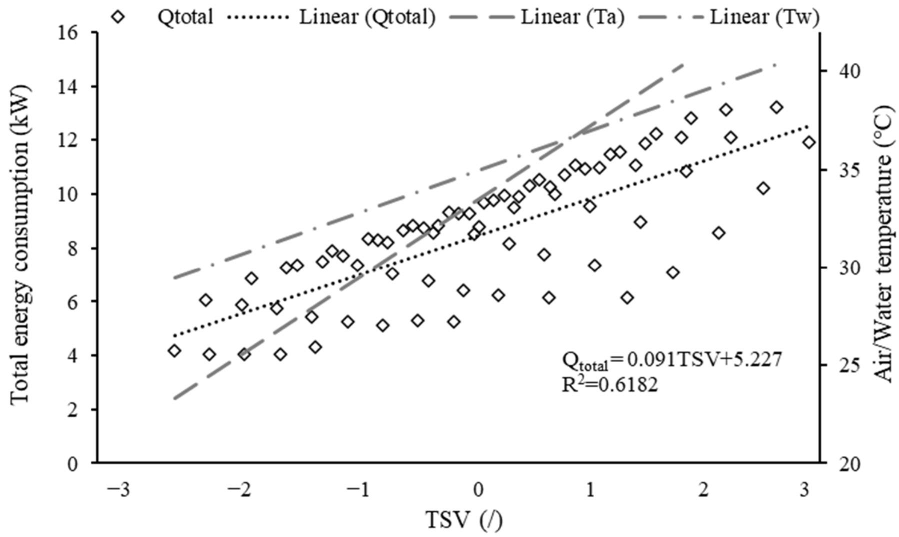

Figure 7. Relationship between the total energy consumption and occupant's thermal sensation during showering.

5. Discussions

5.1. Implications and Suggestions for Residentials and Facility Managers

According to the models listed in Table 2, although the absolute coefficient of the ventilation rate was the highest, the impact of the ventilation rate on the total energy consumption was the least since the value of the ventilation rate itself was very low (i.e., 0.01–0.03 kg·s^{-1}). As can be seen from Figure 5, even though the ventilation rate tripled from 0.01 to 0.03 kg·s^{-1}, the total energy consumption was not changed too much. Therefore, considering the importance of ventilation on condensation [53] and health risks [54], which were highlighted in the past two years because of the spread of COVID-19, the ventilation rate in the bathroom is suggested to be as high as possible, and not less than 0.03 kg·s^{-1} to remove particles efficiently [55]. Moreover, as shown in the standardized regression model, the water flow rate was the most crucial factor in determining the total energy consumption during showering. Hence the water flow rate is suggested to be 0.15 kg·s^{-1}, corresponding to the minimum level of WELS grade 1. According to Figure 6, reducing the water flow rate from 0.26 kg·s^{-1} (corresponds to the maximum level of WELS grade 3) to 0.15 kg·s^{-1} (corresponds to the minimum level of WELS grade 1) could save around 35% of energy during showering. Furthermore, considering the significant impacts of water and air temperature on an occupant's thermal sensation and their relatively small impacts of them on the total energy consumption, they are suggested to be kept within the thermal neutral zone, namely, 33.5–35.7 °C and 30.8–34.9 °C for water temperature and air temperature, respectively.

However, according to Kurz et al. [56], encouraging people to reduce the shower water rate might not be easy because showering, as a daily habit, has its actual functions and is related to occupants' satisfaction and comfort [56]. Additionally, Abrahamse et al. [57] and Gardner and Stern [58] found that although media education and campaigns could raise people's attention on energy consumption, they could not effectively change people's behavior. Compared with changing occupants' habits, taking one-off action (such as choosing low-flow rate shower appliances) might be easy to realize [59]. Under this circumstance, the low-flow rate water supply system designed by Zhou et al. [60], the low-flow rate multi-jet spray atomizer designed by Panão and Delgado [61], or any other similar water-saving appliances could be a wise choice. Therefore, the residential facility managers are encouraged to install the low-flow showerhead in the bathrooms and assess the plumbing structures regularly to ensure they are well sealed.

5.2. Limitations and Future Studies

Although the combinations of wide ranges of air and water temperatures and water and ventilation flow rates were considered in this study, there is still uncertainty about the results because of the assumptions about the input data.

First, the total energy consumption would be underestimated by neglecting energy emission/absorption of the occupant and lighting. The primary energy consumers, both the hot water and radiator were substantially considered in the current study and could give a reasonable estimate of the total energy consumption. However, the energy consumption of these parts is negligibly small for a ten-minute hot water shower.

Second, the settings of variable ranges might only cover some of the conditions. However, these conditions were sufficient to demonstrate the impacts of an occupant's behavior on energy consumption during showering and significant correlations between the influential variables and the total energy consumption have been established. Lastly, more accurate data is needed to validate the model developed by this study, which could undermine its credibility. Thus, field studies should be carried out in the future to validate and improve the accuracy of this model.

6. Conclusions

This study develops an energy consumption model for an optimal showering environment by considering the occupant's thermal comfort and energy consumption in bathrooms. Four variables (including air temperature, water temperature, ventilation rate, and water flow rate) that influence thermal quality and energy consumption were considered. Their impacts on energy consumption were analyzed, both individually and integrally. The results indicated that all these variables were significantly related to the energy consumption. The water flow rate was the most critical variable in predicting the total energy consumption during showering and reducing the 0.11 (i.e., from 0.26 to 0.15) $kg \cdot s^{-1}$ water flow rate could save 35% energy. Therefore, reducing the shower flow rate should be the first task and low-flow rate shower appliances were suggested to be adopted.

Additionally, the ventilation rate was found to have a negligible impact on energy consumption in the bathroom. Considering its importance on air quality and the occupant's health, a high ventilation rate was suggested. The minimum value should be 0.03 $kg \cdot s^{-1}$, the same value ASHRAE requires to eliminate bathroom pollutants. Regarding water and air temperatures, their impacts on the total energy consumption were relatively small, while their effects on an occupant's TSV were significant. Therefore, water and air temperatures were suggested to be kept within 33.5–35.7 °C and 30.8–34.9 °C, respectively, to maintain a thermally neutral ($-0.5 < TSV < 0.5$) showering environment.

The energy consumption model developed by this study could help residents and facility managers to establish an optimal showering environment for an occupants' comfort, health, and energy consumption. In particular, these findings could help residents decide which variables should be given more attention and which values should be set for these variables, allowing facility managers to select the most energy-efficient device for showering. Further work is still needed to validate and improve the accuracy of the energy consumption models.

Author Contributions: Conceptualization, L.-T.W. and K.-W.M.; methodology, L.-T.W., K.-W.M. and D.Z.; software, D.Z.; validation, D.Z.; formal analysis, L.-T.W. and D.Z.; investigation, L.-T.W. and D.Z.; resources, L.-T.W. and K.-W.M.; data curation, L.-T.W. and D.Z.; writing—original draft preparation, D.Z.; writing—review and editing, L.-T.W. and K.-W.M.; visualization, D.Z.; supervision, L.-T.W. and K.-W.M.; project administration, K.-W.M.; funding acquisition, L.-T.W. and K.-W.M. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by the General Research Fund, Research Grants Council of the Hong Kong Special Administrative Region, China (Project no. 15217221, PoyU P0037773/Q86B) and partially supported by the PolyU internal funds (P0040864 and P0043831).

Data Availability Statement: The data presented in this study are available on request from the corresponding author.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. United Nations Environment Programme. *Emissions Gap Report 2020*; United Nations: Nairobi, Kenya, 2020.
2. The United Nations Environment Programme. The Six-Sector Solution to the Climate Crisis. *The United Nations.* 2020. Available online: https://www.unep.org/interactive/six-sector-solution-climate-change/ (accessed on 17 April 2023).
3. Liu, X.; Lau, S.-K.; Li, H. Optimization and analysis of a multi-functional heat pump system with air source and gray water source in heating mode. *Energy Build.* **2014**, *69*, 1–13. [CrossRef]
4. Kordana, S.; Słyś, D.; Dziopak, J. Rationalization of water and energy consumption in shower systems of single-family dwelling houses. *J. Clean. Prod.* **2014**, *82*, 58–69. [CrossRef]
5. Kenway, S.J.; Scheidegger, R.; Bader, H.-P. Dynamic simulation of showers to understand water-related energy in households. *Energy Build.* **2019**, *192*, 45–62. [CrossRef]
6. Wong, L.; Mui, K.; Guan, Y. Shower water heat recovery in high-rise residential buildings of Hong Kong. *Appl. Energy* **2010**, *87*, 703–709. [CrossRef]
7. Pomianowski, M.; Johra, H.; Marszal-Pomianowska, A.; Zhang, C. Sustainable and energy-efficient domestic hot water systems: A review. *Renew. Sustain. Energy Rev.* **2020**, *128*, 109900. [CrossRef]
8. Sanders, K.T.; Webber, M.E. Evaluating the energy consumed for water use in the United States. *Environ. Res. Lett.* **2012**, *7*, 034034. [CrossRef]
9. Sprang, E.E.; Holguin, A.A.; Loge, F.J. The estimated impact of California's urban water conservation mandate on electricity consumption and greenhouse gas emissions. *Environ. Res. Lett.* **2018**, *13*, 014016. [CrossRef]
10. Wong, L.-T.; Mui, K.-W.; Zhou, Y. Carbon Dioxide Reduction Targets of Hot Water Showers for People in Hong Kong. *Water* **2017**, *9*, 576. [CrossRef]
11. Wong, L.T.; Mui, K.W. Drainage demands of domestic washrooms in Hong Kong. *Build. Serv. Eng. Res. Technol.* **2009**, *30*, 121–133. [CrossRef]
12. Hall, M.J.; Hooper, B.D.; Postle, S.M. Domestic per Capita Water Consumption in South West England. *Water Environ. J.* **1988**, *2*, 626–631. [CrossRef]
13. Wan, K.; Yik, F. Building design and energy end-use characteristics of high-rise residential buildings in Hong Kong. *Appl. Energy* **2004**, *78*, 19–36. [CrossRef]
14. Zhu, M.; Pan, Y.; Wu, Z.; Xie, J.; Huang, Z.; Kosonen, R. An occupant-centric air-conditioning system for occupant thermal preference recognition control in personal micro-environment. *Build. Environ.* **2021**, *196*, 107749. [CrossRef]
15. Van Eck, N.J.; Waltman, L. Software survey: VOSviewer, a computer program for bibliometric mapping. *Scientometrics* **2010**, *84*, 523–538. [CrossRef]
16. Piotrowska, B.; Słyś, D. Comprehensive Analysis of the State of Technology in the Field of Waste Heat Recovery from Grey Water. *Energies* **2023**, *16*, 137. [CrossRef]
17. Juan, Y.-K.; Chen, Y.; Lin, J.-M. Greywater Reuse System Design and Economic Analysis for Residential Buildings in Taiwan. *Water* **2016**, *8*, 546. [CrossRef]
18. McNabola, A.; Shields, K. Efficient drain water heat recovery in horizontal domestic shower drains. *Energy Build.* **2013**, *59*, 44–49. [CrossRef]
19. Tomlinson, J.J. *Heat Recovery from Wastewater Using a Gravity-Film Heat Exchanger*; Federal Energy Management Program; Oak Ridge National Laboratory: Oak Ridge, TN, USA, 2005.
20. Sayigh, A. (Ed.) *Mediterranean Green Buildings & Renewable Energy: Selected Papers from the World Renewable Energy Network's Med Green Forum*; Springer International Publishing: Manhattan, NY, USA, 2017.
21. Balaras, C.A.; Droutsa, K.; Argiriou, A.A.; Asimakopoulos, D.N. Asimakopoulos Potential for energy conservation in apartment buildings. *Energy Build* **2000**, *31*, 143–154. [CrossRef]
22. Hui, S.C. Solar Energy Development in Hong Kong and Its Implications to Energy Market Reform. In Proceedings of the International Conference on Energy Market Reform: Issues and Problems (Second Asian Energy Conference), Hong Kong, China, 25–26 August 2003; pp. 25–26.
23. Chow, T.; Chan, A.; Fong, K.; Lin, Z.; He, W.; Ji, J. Annual performance of building-integrated photovoltaic/water-heating system for warm climate application. *Appl. Energy* **2009**, *86*, 689–696. [CrossRef]
24. Wanjiru, E.M.; Sichilalu, S.M.; Xia, X. Model predictive control of heat pump water heater-instantaneous shower powered with integrated renewable-grid energy systems. *Appl. Energy* **2017**, *204*, 1333–1346. [CrossRef]
25. Prijyanonda, J.; Milward, R. *Electric Tankless Water Heating: Competitive Assessment*; Global Energy Partners, LLC: Lafayette, CA, USA, 2005.
26. Henze, G.P.; Yuill, D.P.; Coward, A.H. Development of a Model Predictive Controller for Tankless Water Heaters. *HVAC&R Res.* **2009**, *15*, 3–23. [CrossRef]

27. Wanjiru, E.M.; Sichilalu, S.M.; Xia, X. Optimal control of heat pump water heater-instantaneous shower using integrated renewable-grid energy systems. *Appl. Energy* **2017**, *201*, 332–342. [CrossRef]
28. Hadengue, B.; Morgenroth, E.; Larsen, T.A. Screening innovative technologies for energy-efficient domestic hot water systems. *J. Environ. Manag.* **2022**, *320*, 115713. [CrossRef] [PubMed]
29. Adeyeye, K.; She, K.; Meireles, I. Beyond the flow rate: The importance of thermal range, flow intensity, and distribution for water-efficient showers. *Environ. Sci. Pollut. Res.* **2020**, *27*, 4640–4660. [CrossRef]
30. Wong, L.-T.; Mui, K.-W.; Zhou, Y. Impact Evaluation of Low Flow Showerheads for Hong Kong Residents. *Water* **2016**, *8*, 305. [CrossRef]
31. Lee, M.; Tansel, B. Water conservation quantities vs customer opinion and satisfaction with water efficient appliances in Miami, Florida. *J. Environ. Manag.* **2013**, *128*, 683–689. [CrossRef]
32. Koomey, J.G.; Dunham, C.; Lutz, J.D. The effect of efficiency standards on water use and water-heating energy use in the U.S.: A detailed end-use treatment. *Energy* **1995**, *20*, 627–635. [CrossRef]
33. Zeiler, W.W.; Vissers, D.; Maaijen, H.R.; Boxem, G.G. Occupants' behavioural impact on energy consumption: 'human-in-the-loop' comfort process control. *Arch. Eng. Des. Manag.* **2014**, *10*, 108–130. [CrossRef]
34. Lourenço, P.; Pinheiro, M.D.; Heitor, T. Light use patterns in Portuguese school buildings: User comfort perception, behaviour and impacts on energy consumption. *J. Clean. Prod.* **2019**, *228*, 990–1010. [CrossRef]
35. Park, B.R.; Chung, M.H. Analysis of the additional energy-saving potential of residential buildings after mandatory zero-energy buildings to achieve carbon neutrality in South Korea. *Build. Environ.* **2023**, *228*, 109908. [CrossRef]
36. He, Y.; Chen, W.; Wang, Z.; Zhang, H. Review of fan-use rates in field studies and their effects on thermal comfort, energy conservation, and human productivity. *Energy Build.* **2019**, *194*, 140–162. [CrossRef]
37. Yun, G.Y.; Kong, H.J.; Kim, H.; Kim, J.T. A field survey of visual comfort and lighting energy consumption in open plan offices. *Energy Build.* **2012**, *46*, 146–151. [CrossRef]
38. Nicol, J.F.; Humphreys, M.A. Humphreys. A Stochastic Approach to Thermal Comfort-Occupant Behavior and Energy Use in Buildings Discussion. *ASHRAE Trans.* **2004**, *110*, 554.
39. Klein, L.; Kwak, J.-Y.; Kavulya, G.; Jazizadeh, F.; Becerik-Gerber, B.; Varakantham, P.; Tambe, M. Coordinating occupant behavior for building energy and comfort management using multi-agent systems. *Autom. Constr.* **2012**, *22*, 525–536. [CrossRef]
40. Che, W.; Tso, C.Y.; Sun, L.; Ip, D.Y.; Lee, H.; Chao, Y.H.C.; Lau, A.K. Energy consumption, indoor thermal comfort and air quality in a commercial office with retrofitted heat, ventilation and air conditioning (HVAC) system. *Energy Build.* **2019**, *201*, 202–215. [CrossRef]
41. Stopps, H.; Touchie, M.F. Managing thermal comfort in contemporary high-rise residential buildings: Using smart thermostats and surveys to identify energy efficiency and comfort opportunities. *Build. Environ.* **2020**, *173*, 106748. [CrossRef]
42. Wong, L.-T.; Mui, K.-W.; Chan, Y.-W. Showering Thermal Sensation in Residential Bathrooms. *Water* **2022**, *14*, 2940. [CrossRef]
43. Hong Kong Observatory. Monthly Weather Summary. 2023. Available online: https://www.hko.gov.hk/en/wxinfo/pastwx/mws/mws.htm (accessed on 28 March 2023).
44. Batterman, S. Review and Extension of CO2-Based Methods to Determine Ventilation Rates with Application to School Classrooms. *Int. J. Environ. Res. Public Health* **2017**, *14*, 145. [CrossRef]
45. Persily, A.; de Jonge, L. Carbon dioxide generation rates for building occupants. *Indoor Air* **2017**, *27*, 868–879. [CrossRef] [PubMed]
46. The Institute of Plumbing. *Plumbing Engineering Services Design Guide*; The Institute of Plumbing: Dagenham, UK, 2002.
47. Hong Kong Water Supplies Department. Voluntary Water Efficiency Labelling Scheme on Showers for Bathing. Hong Kong Water Supplies Department. 2018. Available online: https://www.wsd.gov.hk/en/plumbing-engineering/water-efficiency-labelling-scheme/wels-on-showers-for-bathing/voluntary-water-efficiency-labelling-scheme-on-sho/index.html (accessed on 12 October 2022).
48. Foote, K.; Pagni, P.; Alvares, N. Temperature Correlations For Forced-ventilated Compartment Fires. *Fire Saf. Sci.* **1986**, *1*, 139–148. [CrossRef]
49. García, E.; de Pablos, A.; Bengoechea, M.; Guaita, L.; Osendi, M.; Miranzo, P. Thermal conductivity studies on ceramic floor tiles. *Ceram. Int.* **2011**, *37*, 369–375. [CrossRef]
50. Effting, C.; Güths, S.; Alarcon, O.E. Evaluation of the thermal comfort of ceramic floor tiles. *Mater. Res.* **2007**, *10*, 301–306. [CrossRef]
51. Mark Draper. 6 Steps to Choosing the Right Bathroom Radiator. *Justdoproperty. 1 March 2023.* Available online: https://justdoproperty.co.uk/6-steps-to-choosing-the-right-bathroom-radiator/ (accessed on 22 March 2023).
52. Castrads. Panel Radiator Outputs. 2023. Available online: https://www.castrads.com/us/resources/calculators/panel-radiator-outputs/ (accessed on 22 March 2023).
53. Liu, J.; Aizawa, H.; Yoshino, H. CFD prediction of surface condensation on walls and its experimental validation. *Build. Environ.* **2004**, *39*, 905–911. [CrossRef]
54. Ding, E.; Zhang, D.; Bluyssen, P.M. Ventilation regimes of school classrooms against airborne transmission of infectious respiratory droplets: A review. *Build. Environ.* **2021**, *207*, 108484. [CrossRef]
55. *ASHRAE Standard 62.2-2022*; Ventilation and Acceptable Indoor Air Quality in Low-Rise Residential Buildings. ASHRAE: Peachtree Corners, GA, USA, 2022. Available online: www.ashrae.org (accessed on 22 March 2023).

56. Kurz, T.; Gardner, B.; Verplanken, B.; Abraham, C. Habitual behaviors or patterns of practice? Explaining and changing repetitive climate-relevant actions. *WIREs Clim. Chang.* **2015**, *6*, 113–128. [CrossRef]
57. Abrahamse, W.; Steg, L.; Vlek, C.; Rothengatter, T. A review of intervention studies aimed at household energy conservation. *J. Environ. Psychol.* **2005**, *25*, 273–291. [CrossRef]
58. Gardner, G.T.; Stern, P.C. The Short List: The Most Effective Actions U.S. Households Can Take to Curb Climate Change. *Environ. Sci. Policy Sustain. Dev.* **2008**, *50*, 12–25. [CrossRef]
59. Shahmohammadi, S.; Steinmann, Z.; King, H.; Hendrickx, H.; Huijbregts, M. The influence of consumer behavior on energy, greenhouse gas, and water footprints of showering. *J. Ind. Ecol.* **2019**, *23*, 1186–1195. [CrossRef]
60. Zhou, Y.; Mui, K.-W.; Wong, L.-T. Evaluation of Design Flow Rate of Water Supply Systems with Low Flow Showering Appliances. *Water* **2019**, *11*, 100. [CrossRef]
61. Panão, M.; Delgado, J. Toward the design of low flow-rate multijet impingement spray atomizers. *Exp. Therm. Fluid Sci.* **2014**, *58*, 170–179. [CrossRef]