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Carbon Dioxide Reduction Targets of Hot Water Showers for People in Hong Kong

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Received: 19 June 2017; Accepted: 31 July 2017; Published: 2 August 2017

Abstract: Improving water and energy efficiency in buildings is one of the best ways to reduce greenhouse gas emissions. This study examines various energy-related carbon dioxide (CO_2) reduction measures, including the use of water efficient showerheads and shower drain water heat recovery, in order to distinguish the significance of user influence on the water usage of a shower. The probability of taking a hot shower and the number of showers taken by an occupant per day, which can be evaluated from open literature data, are used as the parameters of user responses to water conservation measures in this study. A Monte Carlo model of water consumption and CO_2 reduction for showering is adopted to determine the contributions of user responses. The results demonstrate that the influence of users on CO_2 reduction is significant and compatible to the influence of water efficient showerheads. This study can be used as a reference to enhance water and energy incentives and to facilitate continuous improvement in building water systems.

Keywords: climate change; water efficiency; showering; carbon dioxide emission; behavioural response

1. Introduction

Scientific understanding of global warming is increasing [1]. Climate model projections indicated that, during the 21st century, the global surface temperature is likely to rise further by 0.3 to 1.7 °C in the best case scenario and 2.6 to 4.8 °C in the worst case scenario [1]. The Paris Agreement adopted under the United Nations Framework Convention on Climate Change (UNFCCC) established a global framework for reducing carbon dioxide (CO_2) emissions and noted that global warming should be limited to 1.5 °C [2]. Studies have quantified the carbon reduction potential due to a reduction of potable water usage [3]. In the U.S., the CO_2 embedded in the nation's water represents 5% of all U.S. carbon emissions [4]. In Japan, residential water supply systems account for 5% of total CO_2 emissions and about 60% of those emissions are from hot water bathing [5]. In Australia, a study showed that the average energy consumption from hot showers ranged between 2.9 and 4.5 GJ ps^{-1} yr^{-1}, corresponding to CO_2 emissions ranging between 160 and 245 kg CO_2 ps^{-1} yr^{-1} [6]. In Hong Kong, over 40% of domestic water consumption is used for showers for bathing [7], while about 19% of residential energy consumption in 2013 was used to provide hot water for showers and baths [8].

The urban water cycle can reduce its carbon footprint in various ways; three key initiatives are: (1) better water delivery system designs, (2) water efficiency improvements, and (3) water conservation programmes [9].

Better water delivery system designs, such as employing energy efficient pumps and adopting effective maintenance and replacement schedules, are proven to reduce energy use and thus CO_2 emissions [10,11]. A study reported that energy consumed by many existing high-rise water supply systems could be reduced by up to 50% via water storage tank relocations [12].

Some water appliances (e.g., low flow showerheads) consume lower amounts of water and hence require less energy for water pumping and end-use heating [3,5,13,14]. Reportedly, the total CO_2 emissions in Japan could be reduced by 1% due to the use of water saving equipment [15]. In Vietnam, the reduction potential was estimated to be 8% of total CO_2 emissions. The reduction potential is more significant in developing areas, as a water supply system is a major energy consumer. In Hong Kong, it was reported that the full implementation of Water Efficiency Labelling Scheme (WELS) rated showerheads could reduce 26% of CO_2 emissions from showers and baths [16]. Moreover, as waste heat from hot water bathing can be recovered from the drainage pipes, efficient drain water heat recovery can achieve energy savings of up to 15% for apartment washrooms [17,18].

Shower usage patterns play a significant role in water and energy conservation [19]. A monitoring project performed in a hot climate found that hot water consumption increased by 15–20% from summer to winter due to human uses [20]. This study identifies the significance of user influence on the water usage of a shower in order that water and energy incentives can be enhanced and public education on water conservation can be facilitated.

2. Methodology

2.1. Quantification for User Influence

The probability of taking a hot shower P_{sh} and the number of showers taken by an occupant per day $N_{s,j}$ are the parameters of user responses to water conservation measures in this study. It is noted that the reduction of P_{sh} resulted in a decrease in energy for water heating, while the reduction of $N_{s,j}$ resulted in a decrease in energy for both water heating and water supply and treatment.

A survey reported that all winter showers and over 90% of summer showers were hot showers [18]. Figure 1a shows the survey ratios P_{sh} of having hot showers against the ambient temperature $T_a \leq 21.5$ °C. A linear relationship for fractional $P_{sh,Ta}$ at hypothetical T_a = 35 °C with constants c_0 and c_1(Table 1) was assumed.

$$P_{sh} = c_{0i} + c_{1i}T_a;\ P_{sh} \in [0,\ 1];\ i = 0 \tag{1}$$

The energy conserved by an occupant taking fewer hot showers without changing the frequency of showers can be mathematically expressed by P_{sh} (=0.5–0.9) as shown in Figure 1a. All survey data was not less than P_{sh} = 0.9.

According to the survey, all occupants would take at least one shower per day [17]. A total of 597 occupants were interviewed; 269, 289, 37, and 2 of them would take one, two, three, and four showers in the summer while 537, 57, 3, and none of them would take one, two, three, and four showers in the winter respectively. Figure 1b–d illustrate the ratios of an occupant having one to three showers per day (i.e., P_{s1} to P_{s3}) against the mean ambient air temperature T_a (°C). The case averages are also shown (i.e., T_{sf} = 0 °C). As the correlations of the case averages were insignificant ($p > 0.05$, t-test), a probabilistic approach was adopted. It was found that more showers were taken in summer than in winter ($p < 0.01$, t-test). On average, an occupant would take $N_{s,j}$ = 1.6 (standard deviation (SD) = 0.6) showers on a summer day (June–August) and 1.1 (SD = 0.3) showers on a winter day (December–February), giving an overall average of 1.4 (SD = 0.6) showers per day.

A behavioural response to water conservation is to have fewer daily hot showers. In this study, it is expressed by a temperature shift T_{sf} (i.e., at an ambient air temperature $T_a + T_{sf}$) as shown in Figure 1b–d and determined by Equation (2), where T_a (°C) is the ambient air temperature, i is the number of showers per capita per day, U is a utility function, and c_0 and c_1 are the constants as presented in Table 1.

$$P_{si} = \frac{U_{si}}{\sum_i U_{si}};\ U_{Si} = c_{0i} + c_{1i}T_a;\ U_{si} \in [0,\ 1];\ i = 1,\ 2,\ 3, \tag{2}$$

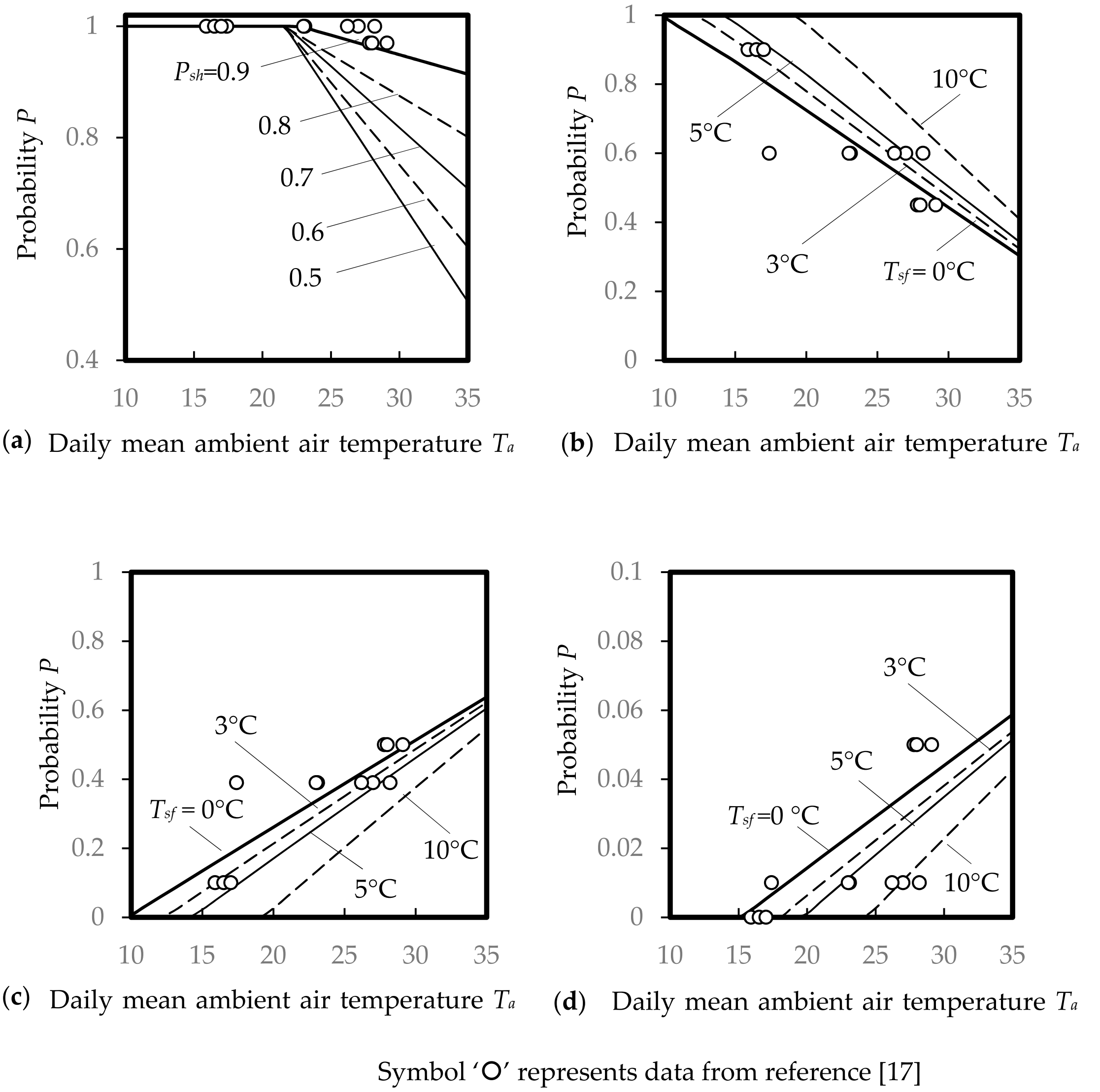


Figure 1. Probability of daily per capita shower usage: (**a**) Hot water used P_{sh}; (**b**) Once per day P_{s1}; (**c**) Twice per day P_{s2}; (**d**) Thrice per day P_{s3}.

Table 1. Constants for per capita showering characteristics.

Parameter *i*	c_{0i}	c_{1i}
0	1.15	−0.007
1	1.29	−0.028
2	−0.25	0.026
3	−0.05	0.003

Figure 2 graphs the expected number of showers per occupant per day determined by Equation (3). Averages (i.e., T_{sf} = 0 °C) from a previous study are also shown for comparison. The figure shows that there is approximately a 1% reduction in the number of showers per day for each 1 °C increment in T_{sf}.

$$N_s = \sum_{i=1}^{3} iP_{si}, \tag{3}$$

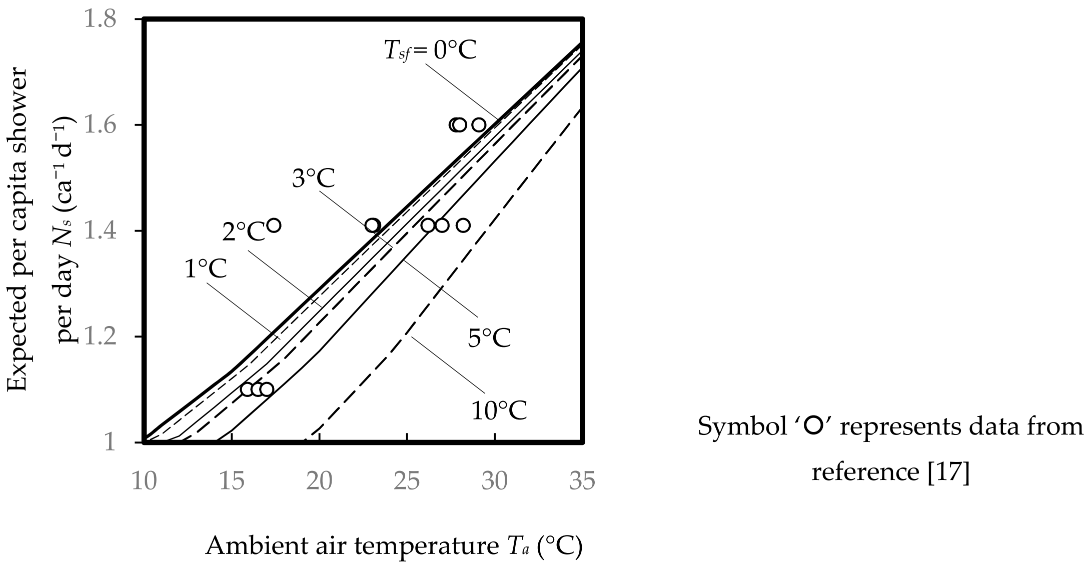


Figure 2. Expected number of showers per occupant per day N_s.

2.2. Simulations

In this study, simulations were performed to obtain the confidence intervals for water and energy consumption and to determine the CO_2 emissions associated with the consumption. Moreover, a Monte Carlo model of water consumption and CO_2 reduction for showering was adopted to investigate the influence of a century-scale rise in the average temperature of the Earth's climate system and its related effects on water consumption and CO_2 emissions from showers for bathing [16,19].

Higher ambient air temperatures as a result of climate change have a great impact on shower usage patterns, and thus a significant influence on subsequent energy used and CO_2 produced. The ambient air temperatures of Hong Kong in the years 1986–2005 and the projected temperature changes up to year 2100 were used in this study to simulate the scenarios of average ambient air temperature change from +1 to +4 °C [21]. As compared with the average air temperature of 1986–2005, the temperature projection suggested that the ambient air temperature increase by 2100 would be 1.4 to 3.2 °C and 3.1 to 5.5 °C for the Representative Concentration Pathways (RCP) 4.5 and 8.5, respectively.

In the simulations, a uniformly distributed random number $x \in [0,1]$ was taken from a random number set generated by the prime modulus multiplicative linear congruential generator, and the input parameters described below (i.e., $\zeta_i = \{t_s, T_o, T_a, k, P_s, P_L, L_e\}$) were sampled from the defined distribution functions. The input value $\zeta_{i,x}$ of a parameter ζ_i was then determined from the descriptive distribution function $\widetilde{\zeta}_i$ at percentile x.

$$\zeta_i = \zeta_{i,x}; \int_0^{\zeta_{i,x}} \widetilde{\zeta}_i d\zeta_i = x; \zeta_i \in \widetilde{\zeta}_i \tag{4}$$

Per capita annual CO_2 emissions M_p (kg-CO_2 ps^{-1} yr^{-1}) from hot showers are linked with water consumption V_p (m^3 ps^{-1} yr^{-1}) and energy consumption E_p (GJ ps^{-1} yr^{-1}),

$$M_p = \alpha V_p + \beta E_p; V_p = \frac{1}{60}\sum_j v_j N_{s,j}\, t_s; E_p = \rho c_p \sum_j P_{sh,j} V_{p,j}\left(T_o - T_j\right) \tag{5}$$

where j is a day of a year, ρ (=1000 kg m^{-3}) is the density of water, c_p (=4.2 × 10^{-6} GJ kg^{-1} K) is the specific heat capacity of water, α (=0.94 kg-CO_2 m^{-3}) and β (200 kg-CO_2 GJ^{-1}) are emission factors per unit water consumed and per unit energy consumed respectively, T_o (°C) is the expected shower water temperature, t_s is the expected showerhead operating time, and N_s is the expected number of showers per occupant per day.

The showerhead flow rate v (L min^{-1}), which is subject to user adjustments and limited by the maximum water supply flow rate, is described by:

$$v = \begin{cases} v_p & ; \quad v_p \leq v^* \\ v^* & ; \quad v_p > v^* \end{cases} . \tag{6}$$

The user preferred showerhead flow rate v^* (L min^{-1}) is given by a cumulative distribution function $\int_0^{v^*} f(v^*)\,dv$, and is expressed by a probabilistic user acceptance φ as given in Equation (7), where a probabilistic occupant acceptance range of 0.03–0.97 is within a showerhead flow rate range of 3–18 L min^{-1} [16]:

$$\varphi = \frac{\exp\left(-4.88 + 0.47v^*\right)}{1 + \exp\left(-4.88 + 0.47v^*\right)}. \tag{7}$$

The maximum showerhead flow rate v_p (L min^{-1}) available from the water supply system is determined by the showerhead water pressure P (kPa) and the showerhead resistance factor k (kPa min^2 L^{-2}):

$$v_p = \sqrt{\frac{P}{k}}. \tag{8}$$

The showerhead water pressure P (kPa) is given by the difference between the static pressure at the showerhead P_s (kPa) (in the design range of 150–350 kPa for typical high-rise water supply systems) and the pressure drop along the water supply pipe P_L (kPa),

$$P = P_s - P_L. \tag{9}$$

It is noted that for WELS rated showerheads with a standard deviation SD = 1.74 kPa min^2 L^{-2} in a resistance factor range of 0.81–9.04 kPa min^2 L^{-2}, the average resistance factor k is 3.8 kPa min^2 L^{-2} [16].

In a typical high-rise water supply system, a pipe pressure drop from $P_{L,0}$ to $P_{L,1}$ corresponding to a flow rate from v_0 to v_1 due to the number of showerheads connected can be approximated by Equation (10), where P_L/L_e = 0.1–0.5 kPa m^{-1} with an equivalent pipe length range L_e = 100–300 m [22,23].

$$\frac{P_{L,1}}{P_{L,0}} \sim \left(\frac{v_1}{v_0}\right)^2. \tag{10}$$

The expected showerhead operating time t_s (s) is given by Equation (11), with the assumption of 99% confidence intervals $CI_{99\%}$ = 185–1093 s for a lognormal distribution [24],

$$t_s = 496 - 13k. \tag{11}$$

The cold water temperature T_j (°C) is given by the following expression, where T_a (°C) is the ambient air temperature:

$$T_j = 10.4T_a^{0.29}. \tag{12}$$

A higher shower temperature for maintaining user comfort was reported for showerheads with lower flow rates [25]. In a temperature range of 33.4–42.7 °C with SD = 2.6 °C, the expected shower water temperature T_o (°C) is expressed by [23]:

$$T_o = 36.2 + 1.1k. \tag{13}$$

3. Results and Discussion

Based on the 1986–2005 ambient temperature data and the existing shower usage patterns, the simulation results for water consumption, energy consumption, and CO_2 emissions are 35.6 m^3 ps^{-1} yr^{-1}, 2.16 GJ ps^{-1} yr^{-1}, and 465 kg-CO_2 ps^{-1} yr^{-1}, respectively.

Figure 3, which illustrates the plotted results of V calculated from Equation (14) with a temperature shift T_{sf}, shows the linear trend of the percentage change in water consumption $\%V$ against the change in ambient air temperature ΔT_a for an average increment of 2.3% °C^{-1}. The outcome shows a linear upward trend of -1.6% °C^{-1} in warmer environments.

$$V = 0.0232\,\Delta T_a - 0.0156\,T_{sf} \quad (14)$$

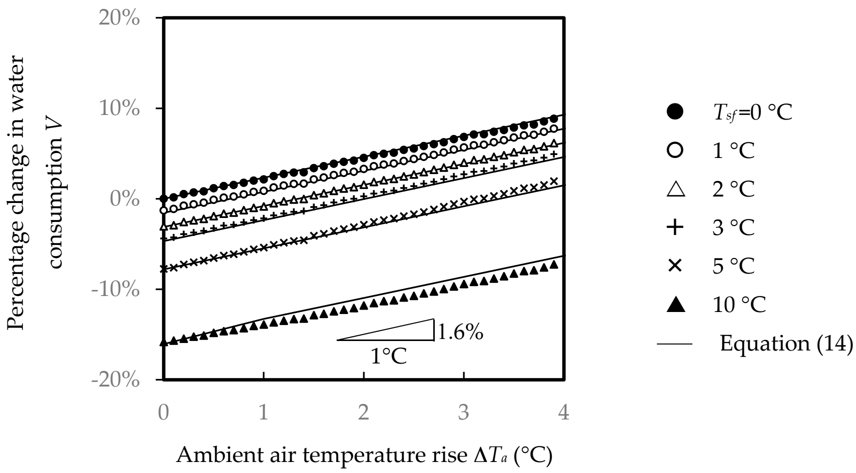
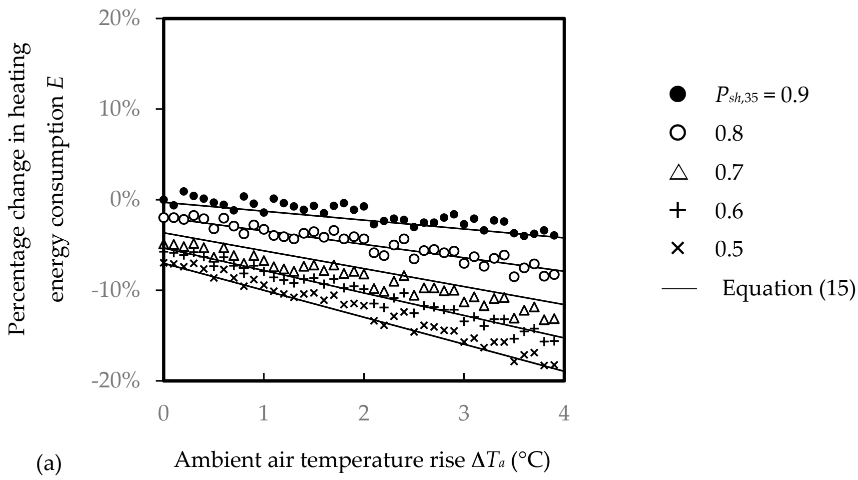


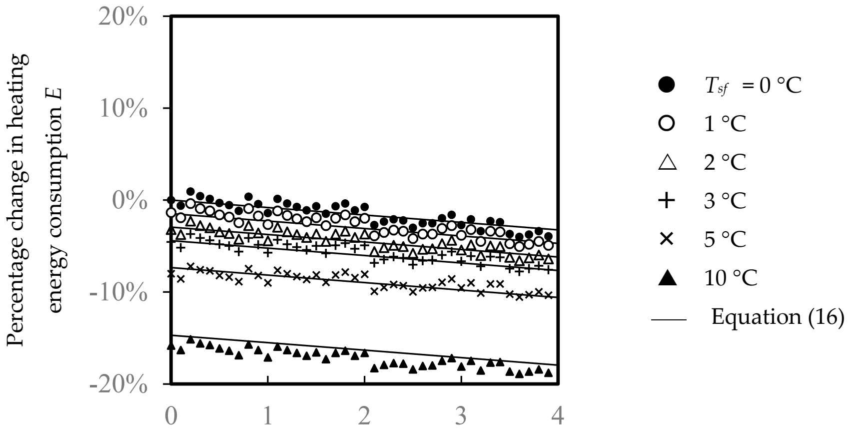
Figure 3. Percentage change in shower water consumption against ambient air temperature rise.

Figure 4 exhibits the percentage change in heating energy consumption E against the change in ambient air temperature ΔT_a. The results reveal that the heating energy required for additional water consumption is less dominating than the heating energy reduced in a warmer environment. Although there are variations of E in the simulations, a general downward trend against warmer environments is observed. As shown in Figure 4a,b, energy credits can be achieved, respectively, by taking fewer hot showers and by taking one more shower in a warmer period while adopting a positive temperature shift.



(a)

Figure 4. *Cont.*



(b)

Figure 4. Percentage change in heating energy consumption against ambient air temperature rise: (**a**) Behavioural responses related to taking fewer hot showers; (**b**) Behavioural responses to a positive temperature shift.

The results also show that using 10% less hot shower water can save 1.7% energy, with additional savings of 0.5% $°C^{-1}$ in warmer environments. An expression given by Equation (15) is shown in Figure 4a to illustrate the change in energy used E.

$$E = (0.05\, P_{sh,35} - 0.0548)\, \Delta T_a + (0.168\, P_{sh,35} - 0.154) \quad (15)$$

By measuring the temperature shift, the gradients in Figure 4a indicate user behavioural changes. With a lessened energy burden, an average energy credit of 1.5% $°C^{-1}$ is expected. Reportedly, there is a linear downward trend of 0.8% $°C^{-1}$ in warmer environments. An expression given by Equation (16) is shown in Figure 4b to illustrate the change in energy used E.

$$E = -0.0081\, \Delta T_a - 0.0147\, T_{sf} \quad (16)$$

Figure 5 presents the percentage changes in CO_2 emissions for showering in warmer environments. It can be observed that the energy consumed for water heating is more significant than that for water supply and treatment. Despite variations in the simulation results, there is an overall downward trend. However, less energy savings can be seen in the figure as compared with Figure 4, because energy is required for more showers in warmer environments.

For every 10% reduction in the number of hot showers, it is expected to save 1.5% energy, with additional savings of 0.46% $°C^{-1}$ in warmer environments. As shown in Figure 5a, the maximum CO_2 emissions reductions are 14% and 20% at ΔT_a = 3 °C and 4 °C, respectively.

Regarding the temperature shift, a carbon credit of 1.5% $°C^{-1}$ is expected. A linear downward trend of 0.8% $°C^{-1}$ for hot showers is observed in warmer environments. As shown in Figure 5b, the maximum CO_2 changes are 9.5% and 10% at ΔT_a = 3 °C and 4 °C, respectively.

The changes in CO_2 emissions C as expressed by Equations (17) and (18) are shown in Figure 5a,b, respectively, for illustration.

$$C = (0.046\, P_{sh,35} - 0.048)\, \Delta T_a + (0.154\, P_{sh,35} - 0.141) \quad (17)$$

$$C = -0.0054\, \Delta T_a - 0.0157\, T_{sf} \quad (18)$$

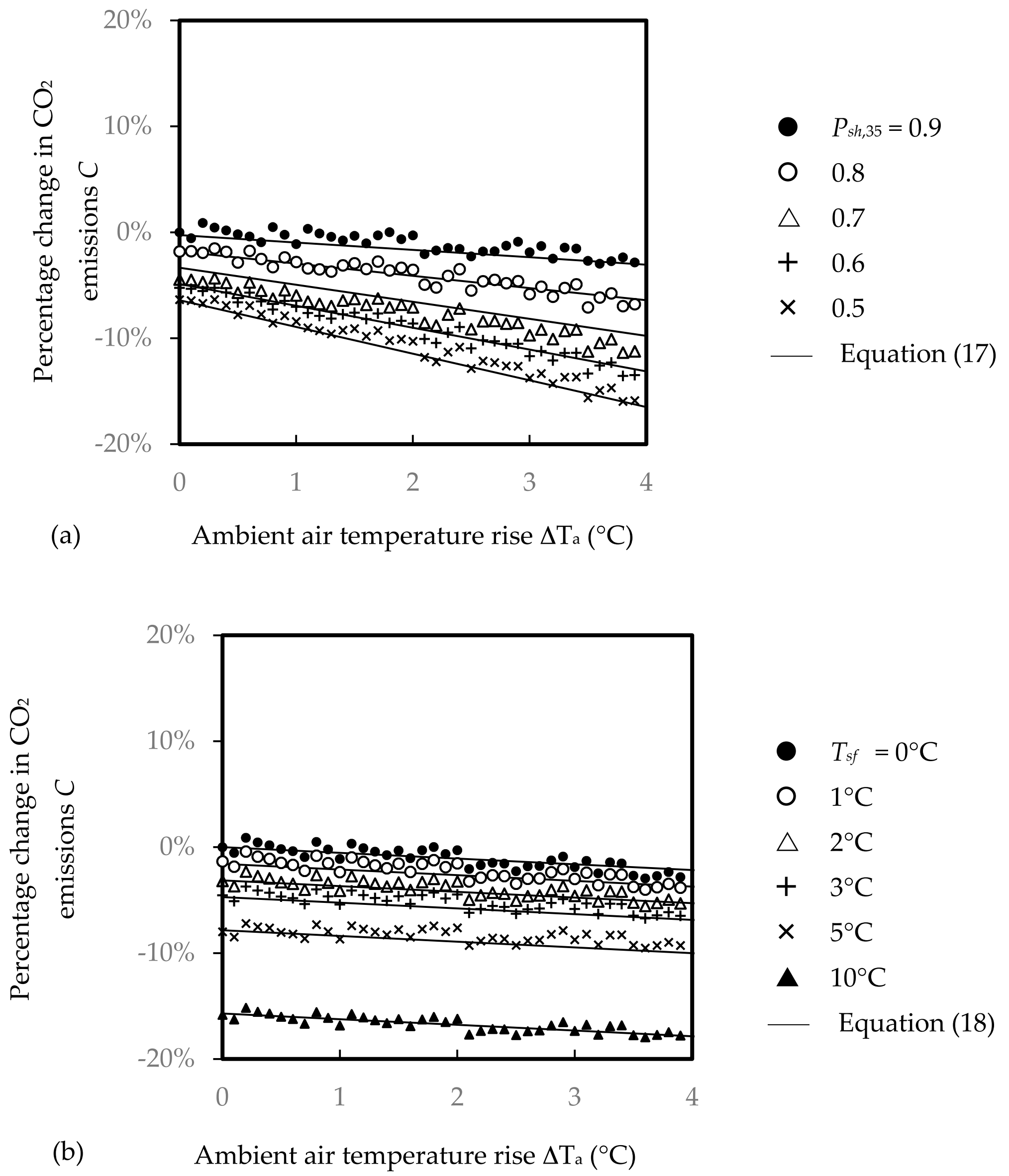


Figure 5. Percentage change in CO_2 emissions against ambient air temperature rise: (**a**) Behavioural responses related to taking fewer hot showers; (**b**) Behavioural responses to a positive temperature shift.

The CO_2 emissions from the water supply system and water heater according to user influences can be determined by Equation (19), where C_α and C_β are the changes in CO_2 emissions due to the water supply system and water heater, respectively, while k_α (=0.06) and k_β (=0.94) are the constants for CO_2 emission fractions for water supply and treatment and water heating (approximately 1:15), respectively [16]. Figure 6 exhibits various target CO_2 reductions based on user behavioural changes for $P_{sh,35} \geq 0.5$ and $T_{sf} \leq 5$ °C. The maximum CO_2 reduction shown in the figure is 22% for $\Delta T_a \leq 3$ °C, where C_α and C_β are −9.5% and −24.3%, respectively.

$$C = k_\alpha \prod_i (1 + C_{\alpha,i}) + (1 - k_\beta) \prod_i (1 + C_{\beta,i}) - 1 \tag{19}$$

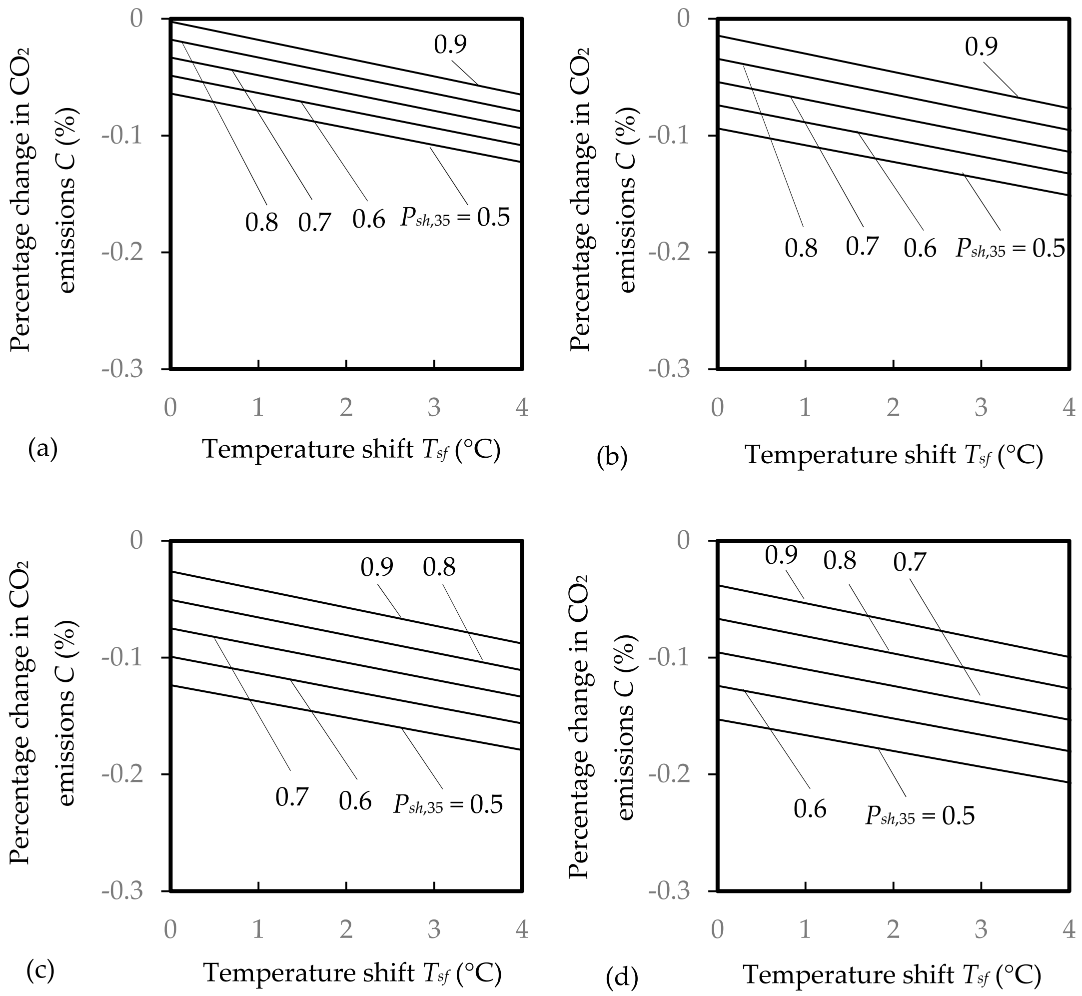


Figure 6. User influence on the percentage change in CO_2 emissions: (**a**) ΔT_a = 0 °C; (**b**) ΔT_a = 1 °C; (**c**) ΔT_a = 2 °C; (**d**) ΔT_a = 3 °C.

Table 2 summarizes the maximum CO_2 reduction estimates from various measures, including water conservation programmes that target $P_{sh,35} \geq 0.5$ and $T_{sf} \leq 5$ °C, water efficient products, shower drain water heat recovery, and energy efficiency improvements for water supply systems [11,12,16,17]. The influence of users on CO_2 reduction is found to be significant and compatible to that of water efficient showerheads. The contributions from heat recovery systems can also be significant. The maximum CO_2 reduction calculated from all of the measures listed in Table 2 using Equation (19) is estimated to be 52%.

Table 2. Maximum CO_2 reductions (C_{max}) estimated for showering in Hong Kong.

Description	C_{max}	References
Water conservation programmes	22%	This study
Water efficient showerheads	26%	[16]
Shower drain heat recovery	14%	[17]
Water supply efficiency improvement in buildings	2%	[11,12]
Expected overall maximum CO_2 reduction	52%	

4. Conclusions

Improving water and energy efficiency in buildings is one of the best ways to reduce greenhouse gas emissions. It is necessary to identify the most significant measures to achieve the target. This study examined various energy-related CO_2 reduction measures, including the use of water efficient showerheads and shower drain water heat recovery, in order to distinguish the significance of user influence on the water usage of a shower. The results demonstrated that the influence of users on CO_2 reduction is significant (up to 22%) and compatible to the influence of water efficient showerheads (up to 26%). In contrast, the CO_2 reduction is less significant for heat recovery from hot showers in cities of hot climates (such as Hong Kong) (up to 14%) and water supply efficiency improvement in buildings (up to 2%). This study can be used as a reference to enhance water and energy incentives, and to facilitate continuous improvement in building water systems.

Acknowledgments: The work described in this paper was partially supported by a grant from the Research Grants Council of the Hong Kong Special Administrative Region (HKSAR), China (PolyU 5272/13E), and by three other grants from The Hong Kong Polytechnic University (GYBA6, GYM64, GYBFN).

Author Contributions: Ling-tim Wong and Kwok-wai Mui planned for the study; Ling-tim Wong and Yang Zhou executed the simulations. All authors contributed to data analysis and preparing the manuscript.

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

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