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Heat loss from non-circulating domestic hot water pipes increases water consumption and energy demand

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ABSTRACT

Hot water use in showers is a major contributor to residential water and energy consumption, and associated costs and carbon emissions. This study aims to quantify how heat loss from non-circulating pipes contributes to water and energy consumption in residential showers. Heat loss from pipes was modelled for detached dwellings in Melbourne, Australia, using Monte Carlo analysis to quantify variability. Sensitivity analysis was conducted to identify key factors contributing to heat loss. This is the first study to quantify the variability of the impact of heat loss from pipes into increased water (and hence energy) consumption in showers. Under Melbourne conditions, we predicted that heat loss from pipes contributes approximately 2 to 10 % in average shower hot water consumption. Longer pipes, smaller diameter, longer showers and longer intervals between showers were the primary factors driving additional hot water consumption.

1. Introduction

There is an urgent need to globally address climate change, water security and the cost-of-living crisis. As climate change worsens, the risk of severe weather events such as droughts and floods will increase, resulting in limited and unpredictable water supply. Simultaneously, the cost-of-living is continuing to increase, largely due to rising water and energy costs.

Conservation of water and energy will play a critical role in addressing these challenges. Energy conservation will be essential to support the transition to renewable power sources (Riahi et al., 2021) and water conservation will be necessary to manage the impacts of limited water supply (Beal et al., 2012). Both water and energy constitute a major cost for families, thus conservation will also result in reduced cost-of-living (de Oliveira et al., 2022).

Domestic hot water consumption is a major contributor to residential water consumption and energy demand. In modern residential properties, hot water consumption contributes 30–50 % of energy consumption, compared to 20–35 % in older homes (Pomianowski et al., 2020). The proportion of domestic energy consumption attributed to hot water is increasing because other services such as space heating are using less energy. Meanwhile, there has been limited intervention to improve energy efficiency of hot water systems (Hadengue et al., 2022a).

Therefore, reductions in domestic hot water consumption can play a role in lowering carbon emissions and improving water security (Chen, 2020). For example, Hadengue et al. (2022b) found that the installation of water-efficient shower-heads could reduce energy for hot water by 31 %. Showers are typically the greatest component of hot water consumption, comprising between 27 % (Kenway et al., 2013) and 48 % (Jiang et al., 2016). Hot water requirements for showers can also be reduced using drain water heat recovery, which has been shown to result in energy savings of 20 % to 50 % (Manouchehri and Collins, 2022).

Heat loss from hot water pipes is one of the major components of energy consumption for domestic hot water, comprising 2 % (Kenway et al., 2013) to 55 % (Genuardi et al., 2023). Moss and Critoph (2022) also demonstrated that heat loss from pipes resulted in water waste of 2.9 to 5.0 L/shower event. To reduce the water consumption due to heat loss, circulating hot water systems are an effective solution (Moss and Critoph, 2022), but they require more energy (Guo and Goumba, 2018). In circulating hot water systems, heat loss is responsible for between 20 % (Hamburg et al., 2021) and 70 % (Cholewa et al., 2019) of the energy for hot water, whereas heat loss in non-circulating hot water systems is between 2 % (Kenway et al., 2019) and 20 % (Hadengue et al., 2020).

According to Pomianowski et al. (2020), detached dwellings typically have non-circulating hot water systems. In Australia, approximately 70 % of residential dwellings are detached houses (Australian Bureau of Statistics, 2022), and in the USA, approximately 70 % of

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Nomenclature

Variable name description units

Cp	heat capacity of water (J/(kg K))
E_{SL}	energy required to heat the additional hot water due to standing losses (J)
E_{FL}	energy required to heat the additional hot water due to flowing losses (J)
E_T	total energy required to heat hot water for shower (J)
h	convective heat transfer coefficient for hot water pipe outer surface (W/(m^2 K))
k	thermal conductivity of hot water pipe insulation (W/(mK))
L	length of hot water pipe between mixing valves (m)
L_c	time constant: an arbitrarily defined value which enables partial nondimensionalization of Eq. (25). Consequently when $L = L_c$, $T_f = T_\infty + (T_0 - T_\infty)e^{-1} \approx T_\infty + (T_0 - T_\infty)2/3$, which means the hot water has lost approximately 2/3 of its energy when it has travelled a length equivalent to L_c. Therefore, the value of L_c provides key information about the significance of flowing heat loss from the hot water pipe. For example, if $L \ll L_c$, the temperature drop along the hot water pipe is small and we can deduce that the flowing heat loss is insignificant (m)
ρ	density of water (kg/m^3)
Q	flow rate in hot water pipe (m^3/s)
Q_F	flow rate in hot water pipe during flushing period (m^3/s)
Q_{FL}	additional flow rate out of hot water tank due to flowing heat loss from the hot water pipe (m^3/s)
Q_{HW}	realistic flow rate out of hot water tank during a shower (with flowing heat loss from the hot water pipe taken into account) (m^3/s)
Q_{HWF}	flowrate out of hot water tank during the flushing period (m^3/s)
Q_{HWI}	ideal flow rate out of hot water tank during a shower (without flowing heat loss from the hot water pipe taken into account) (m^3/s)
Q_{Sh}	shower flow rate (m^3/s)
Q_{SL}	additional flow rate out of hot water tank due to standing heat loss from the hot water pipe (m^3/s)
r_1	radius of hot water pipe (m)
r_2	outer radius of hot water pipe including insulation (m)
Δr	thickness of insulation (m)
T_{CW}	temperature of cold water supplied to household (°C)
T_{HW}	temperature of hot water at the outlet of the hot water system (°C)
T_{Sh}	shower temperature (°C)
$T_{f,cool}$	temperature of hot water at inlet to second mixing valve, at the end of the shower interval (°C)
T_f	temperature of hot water at inlet to second mixing valve, during the shower (°C)
$T_{0,cool}$	temperature of hot water at outlet of first mixing valve, at the end of the shower interval (°C)
T_0	temperature of hot water at outlet of first mixing valve, during the shower (°C)
T_∞	ambient temperature surrounding hot water pipe (°C)
t_F	duration of flushing period (s)
t_I	shower interval: time between the end of the previous shower and the start of the current shower (s)
t_{Sh}	duration of shower (s)
τ_c	time constant: an arbitrarily defined value which enables partial nondimensionalization of Eq. (29). Consequently when $t_I = \tau_c$, $T_{f,cool} = T_\infty + (T_f - T_\infty)e^{-1} \approx T_\infty + (T_f - T_\infty)2/3$, which means the hot water has lost approximately 2/3 of its energy when it has cooled for an amount of time equivalent to τ_c. Therefore, the value of τ_c provides key information about the significance of standing heat loss from the hot water pipe. For example, if $t_I \ll \tau_c$, the temperature drop in the period of time is small and we can deduce that the standing heat loss is insignificant (s)
V_{FL}	additional hot water consumption due to flowing heat loss from pipes (m^3)
V_{SL}	additional hot water consumption due to standing heat loss from pipes (m^3)
V_T	total volume of hot water consumed for the shower (m^3)

residential dwellings are single family houses (United States Census Bureau, 2021). In Germany (IWU - Institute for Housing and Environment, 2014) and Great Britain (Ltd, 2014), approximately 45 % and 95 % respectively of residential dwellings are single family houses. Considering the prevalence of detached dwellings, this study has focussed on non-circulating hot water systems.

Heat loss from non-circulating hot water pipes in detached dwellings has received limited attention because it is more complex to model compared to other components. In detached, non-circulating systems, transient analysis is necessary to fully understand the mechanisms governing heat loss. Kenway et al. (2019) and Hadengue et al. (2020) both recognized the need for transient calculations, but both studies focussed only on a single case study. Similarly, Marini et al. (2021) only considered two case study households. Hamburg et al. (2021) and Braas et al. (2020) consider heat loss in 21 and 11 buildings respectively, however they both model circulating hot water systems.

Furthermore, previous studies on heat loss from non-circulating hot water pipes have purely focussed on the energy associated with heat loss, rather than quantifying the effect of that heat loss on water and energy consumption. Moss and Critoph (2022) discussed this concept at length and provided empirical evidence, however their model did not account for this as it was focussed on circulating hot water systems as a solution to the water waste problem. Araújo and Pereira (2017), Hofer et al. (2023) and Marini et al. (2021) all modelled the heat loss pipes directly without considering their impact on hot water consumption.

This paper uses mathematical modelling to estimate heat loss from pipes in detached dwellings under typical conditions found in Melbourne, Australia, and to quantify the effect of pipe heat loss on water and energy consumption associated with showers. The novelty of this study is that it seeks to quantify the impact of heat loss on increased on hot water consumption, rather than assessing the heat loss in isolation. The model has been used to assess the impact of variable piping and heat transfer conditions and to identify the key factors driving heat loss and associated water and energy consumption. This fills a major gap in the literature, as previous studies have focused only on selected case studies.

2. Methods

We have developed a thermodynamic model to calculate heat loss from hot water pipes and the associated increase in water and energy consumption (Python code available on request). The model is called Domestic Hot Water Heat Loss from Pipes (DHW-HLP). The main output is the additional hot water consumption due to heat loss from hot water pipes. The model is intended to capture the transient nature of heat loss whilst maintaining efficient computation, in contrast to the existing models (Kenway et al., 2019; Hadengue et al., 2020), which capture the detail of the dynamic processes at the expense of simulation run-time.

The modelled hot water system (Fig. 1) represents a theoretical

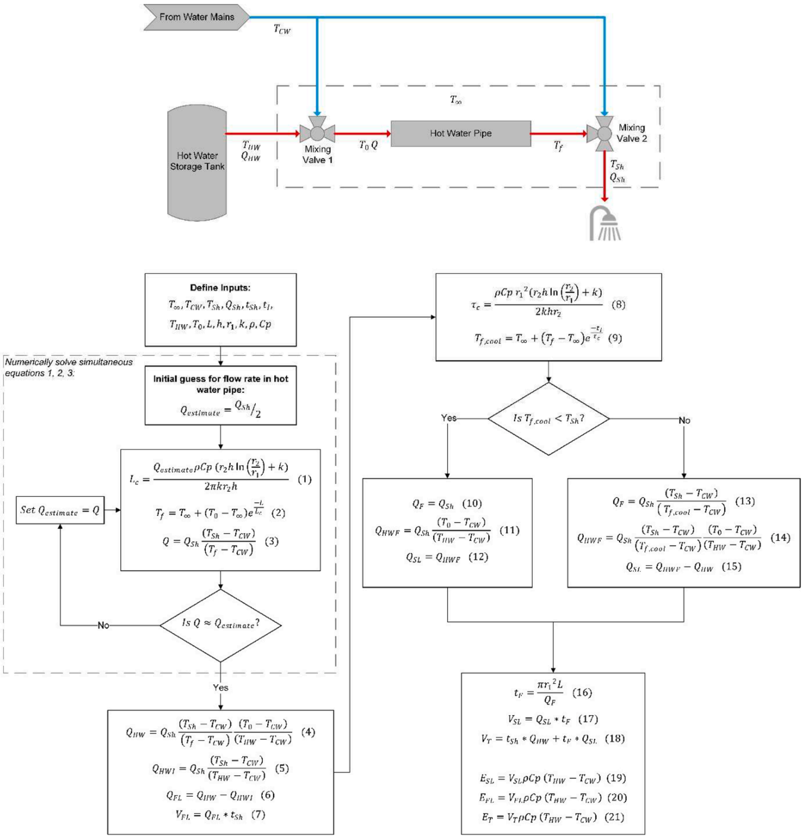

Fig. 1. System flow diagram and calculation process used for Domestic Hot Water Heat Loss from Pipes (DHW-HLP) model.

household with a hot water storage tank servicing a single end-use. Hot water flows out of the tank at its highest temperature (T_{HW}). The hot water in the tank must be kept at this temperature to prevent growth of bacteria (Marszal-Pomianowska et al., 2021). Immediately after exiting the storage tank, the hot water (T_{HW}) is mixed with cold water (T_{CW}) so that the hot water provided to the household is at a safe temperature to prevent scalding (T_0). The hot water then flows through the main section of the hot water pipe towards the shower mixing valve. Over the length of this hot water pipe, the hot water cools to T_f. At the second mixing valve, cold water is added again to reduce to the target shower temperature (T_{Sh}).

Heat loss from the hot water pipes was considered in two subsets (standing and flowing), which both result in additional hot water consumption. Standing loss was defined as the heat loss while water cools in the pipe between showers. When water cools in the pipes, the cooled water must be flushed before fresh hot water arrives at the shower. During flushing, water draws from the hot water system, so the flushed water volume was defined as additional hot water consumption due to standing heat loss (V_{SL}). Flowing loss was defined as the heat loss while hot water flows through the pipes during a shower. Due to heat loss, the hot water at the inlet to the second mixing valve (T_f) is cooler than an ideal case without loss, so more hot water is required to reach the target temperature. Therefore, this additional volume was defined as the additional hot water consumption due to flowing heat loss (V_{FL}).

The mathematical model has been carefully developed and tested under a wide range of conditions in order to assess the validity of the assumptions. The Supplementary Information outlines the model development process in full detail, with all assumptions and simplifications documented and tested. The most significant assumptions were that cold water is equal to ambient temperature, there is no correlation between ambient temperature and shower temperature, and there is no axial mixing. We conducted Monte Carlo simulations with and without these assumptions, and demonstrated that there was limited differences in the results.

The model results for the volume of hot water attributable to standing losses (V_{SL}) were validated against data presented by Moss and Critoph (2022). Moss and Critoph (2022) presented data for four shower events, including details of the piping characteristics and hot water flowrates/temperatures. We used these parameters to calculate the additional volume of water consumed as a result of standing losses (V_{SL}) using DHW-HLP. The results of DHW-HLP were compared to the measured values reported by Moss and Critoph (2022). The comparison found a root mean squared error of 0.7 L/shower event, with the total waste for each event ranging from 2.9 L/shower to 5.0 L/shower. There was no systematic error observed (i.e. the model did not overpredict or underpredict results). For further details of this process, please refer to the supplementary information.

To assess variability in the hot water consumption due to heat loss from pipes, Monte Carlo analysis was conducted (100 000 iterations). All parameters were varied randomly according to the distributions indicated in Table 1. The Monte Carlo simulations were also supported by sensitivity analysis to understand the key factors driving the variability. The baseline scenario for the sensitivity analysis was generated using the mean values for each parameter. Each parameter was then varied individually between the minimum and maximum values.

2.1. Mathematical calculations

To calculate the hot water consumption due to flowing loss (V_{SL}), DHW-HLP calculates the difference between the realistic hot water flow rate (i.e. with flowing loss taken into account) (Q_{HW}) and the ideal hot water flow rate (i.e. without flowing loss taken into account) (Q_{HWI}). The additional hot water consumption due to standing loss (V_{SL}) depends on the temperature at the inlet to the second mixing valve, at the end of the shower interval ($T_{f,cool}$). At the start of the next shower event, if $T_{f,cool}$ is below the shower temperature (T_{Sh}), then it is not possible to reach T_{Sh}.

Table 1
Model input values and distributions. These values were developed based on the context of detached dwellings in Melbourne, Australia. For further details on the data and analysis supporting the selected parameter values, please refer to pages 8 and 9 of the Supplementary Information for this paper. The upper and lower cut-off values were implemented to avoid the occurrence of unreasonable values (e.g. negative flowrate), and discussion on how these were implemented is also included in the Supplementary Information.

	Unit	Average	Std Dev	Min (Lower cut-off for normal distributions)	Max (Upper cut-off for normal distributions)	Distribution	Source
Ambient temperature Melbourne (T_∞)	°C	13.6	4.5	2	28	Normal	(Australian Government - Bureau of Meteorology, 2023)
Shower temperature (T_{Sh})	°C	37	3	30	43	Normal	(Kenway et al., 2016)
Shower flow rate (Q_{Sh})	L/min	7.8	2.7	3	20	Normal	YVW End-Use data
Shower duration (t_{Sh})	min	6.9	4.0	1	30	Normal	YVW End-Use data
Hot water temperature (tank outlet) (T_{HW})	°C	N/A	N/A	55	65	Uniform	Estimated based on (Victorian Building Authority, n.d.)
Hot water temperature (mixing valve 1 outlet) (T_0)	°C	N/A	N/A	40	50	Uniform	Estimated based on (Victorian Building Authority, n.d.)
Hot water pipe length (L)	m	N/A	N/A	5	20	Uniform	Estimated based on (Kenway et al., 2016)
Heat transfer coefficient (h)	W/(m^2 K)	N/A	N/A	2	25	Uniform	Natural convection in air (Çengel and Ghajar, 2020)
Hot water pipe radius (r_1)	m	N/A	N/A	0.005	0.01	Uniform	Estimated based on (Kenway et al., 2016)
Insulation thickness (Δr)	m	N/A	N/A	0	0.05	Uniform	Estimated based on (Plastics Industry Pipe Association of Australia, 2010)
Thermal conductivity of insulation (k)	W/(mK)	N/A	N/A	0.04	N/A	Uniform	Expanded polystyrene (Çengel and Ghajar, 2020) (Kenway et al., 2019)
Density of water (ρ)	kg/m^3	N/A	N/A	1000	N/A		(Çengel and Ghajar, 2020)

Therefore, all water in the hot water pipe must be flushed before the shower duration commences. On the other hand, if the water has not cooled below T_{Sh}, then the shower duration can commence, but a greater flow rate of hot water is required until the cooled water is flushed, to account for the lower temperature.

Mass and energy balances were conducted over the hot water pipe to determine the temperature profile along the length of the pipe during flow, and over time as the water cools. Conduction through the insulation and convection from pipe to air were considered, assuming that the hot water pipe is fully surrounded by ambient air. The conduction through the copper pipe was neglected because the copper pipe is very thin and has high thermal conductivity (50–400 W/(mK) depending on purity) compared to the insulation (0.04 W/(mK)) (Çengel and Ghajar, 2020). Similarly, convection from water to pipe was neglected because typical convection coefficients for liquids are high (10–1000 w/(m^2 K)) compared to gases (2–25 W/(m^2 K)) (Çengel and Ghajar, 2020), so convection in air is the dominant heat transfer resistance.

Combining Eqs. (2) and (9) (Fig. 1) gave the following equation to describe the temperature at the inlet to the second mixing valve, at the end of the shower interval ($T_{f,cool}$).

$$T_{f,cool} = T_\infty + (T_0 - T_\infty)e^{-\left(\frac{t_{Sc}}{\tau_c}+\frac{L}{L_c}\right)} \tag{1}$$

The resulting Eq. (1) is very useful to understand the physical processes driving heat loss. When $t_{Sc} \ll \tau_c$, or $L \ll L_c$, the exponent approaches 0, so we can deduce that the temperature change over time or length respectively is insignificant.

For details of the full set of equations developed for DHW-HLP, their derivation and underlying assumptions, refer to the Supplementary Information.

2.2. Input data

A combination of normal distributions and uniform distributions were used as the inputs to the Monte Carlo simulations (Table 1). Where data was available for standard deviations, a normal distribution has been used. Details of the data analysis for these distributions is provided in the Supplementary Information. The data analysis includes comparisons of the raw data distributions to the manufactured data distributions based on the values presented in Table 1. For other parameters, a uniform distribution has been used based on estimated maximum and minimum values.

Research partners Yarra Valley Water (YVW) provided data from a high-resolution end-use study conducted from 2017 to 2019, which has informed input data for shower flowrates, durations, and intervals. Over this period, water consumption for 105 households was monitored at 1-minute intervals. This data was disaggregated to end-uses using Autoflow (Nguyen et al., 2015).

3. Results and discussion

Heat loss from pipes was estimated to contribute a median of 4.0 % to the total hot water consumption across a range of cases in the context of Melbourne, Australia (Fig. 2a). In absolute terms, the additional consumption of hot water due to heat loss was between 0.8 and 2.2 L/shower (interquartile range) (Fig. 2b). This equates to an approximate median energy consumption of 63 to 170 kWh/year (assuming 4 shower events per household per day) (Fig. 2c). This result is similar to other values reported in literature (Table 2) for detached dwellings.

The additional hot water consumption due to standing heat loss was shown to be more significant than the flowing loss (Fig. 2). The additional hot water consumption due to standing loss was between 1.4 % and 8.2 % (interquartile range) of the hot water consumption, and the flowing loss was between 0.3 % and 0.7 %. When the standing hot water cools below the shower temperature, all water in the pipe needs to be flushed before the shower duration can commence. The standing water needed to cool for up to 60 min before it reaches the shower (Fig. 4a). Therefore, for the 70 % of showers that are greater than 60 min apart, all the hot water in the pipe needed to be flushed with fresh hot water. Conversely, the hot water would need to flow through at least 200 m of pipe (Fig. 4b) before it cools to the shower temperature, which demonstrates why the flowing losses were relatively insignificant.

3.1. Sensitivity analysis

According to DHW-HLP, the most significant factors influencing the additional hot water consumption due to heat loss from pipes were the

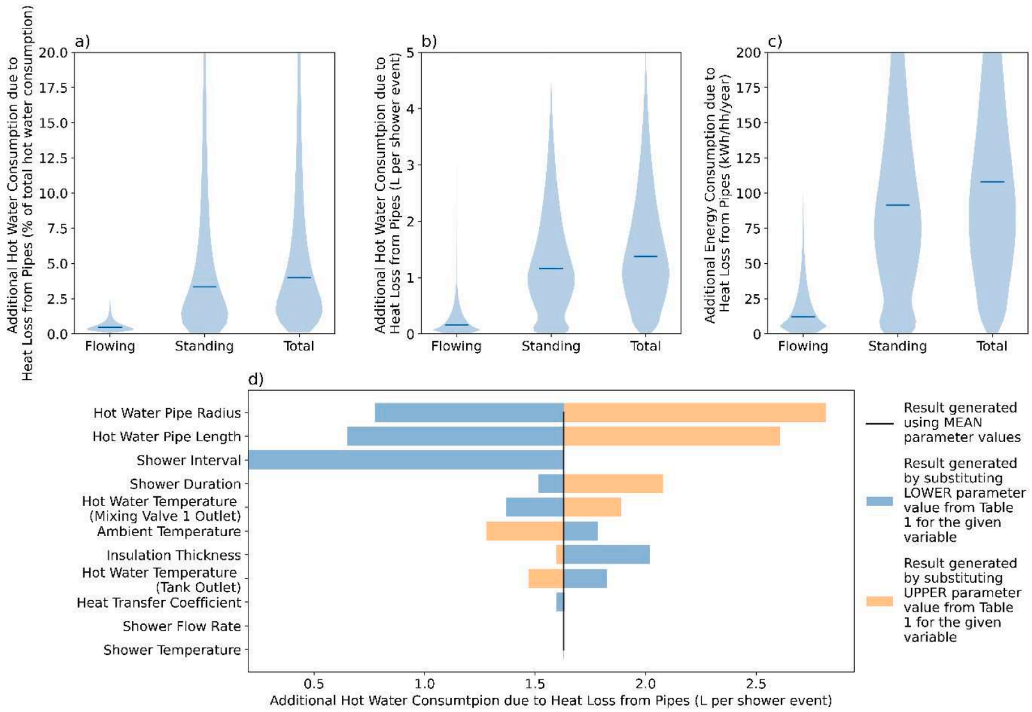

Fig. 2. Additional hot water consumption due to heat loss from pipes as a proportion of total hot water consumption (a), and as an absolute value (b); additional energy consumption due to heat loss from pipes (c); sensitivity analysis of key factors (d).

Table 2
Summary of pipe energy losses reported in literature.

Study	Percentage additional hot water consumption due to heat loss from pipes[a]	Pipe lengths	System scope	Dwelling type
Our study	2–10 % (interquartile range)	5 to 20 m	Showers	Detached
Kenway et al. (2013)	3 %	7 m	All hot water taps	Detached
Kenway et al. (2019)	8 %	14 m	Showers	Detached
Hadengue et al. (2020)	17 %	Not stated	All hot water taps	Detached
Binks et al. (2016)	2–8 %	5 m to 15 m	All hot water taps	Detached
Marini et al. (2021)	4–8 %	13 m to 20 m	All hot water taps	Detached
Zhou et al. (2022)	42 %	Not stated	Not stated	Apartments
Braas et al. (2020)	39–52 %	15 m to 78 m	All hot water taps	Apartments
Guo and Goumba (2018)	12 %	Not stated	Not stated	Apartments

[a] Most papers do not directly present this value, so it has been calculated from other reported outputs.

pipe radius, pipe length, shower interval and shower duration (Fig. 2d). In the sensitivity analysis (Fig. 2), the additional hot water consumption varied from 0.8 L/shower to 2.8 L/shower for the range of radii, and from 0.7 L/shower to 2.6 L/shower for the range of lengths. The additional hot water consumption varied from 0.2 L/shower to 1.6 L/shower for the shower interval, and from 1.5 L/shower to 2.1 L/shower for the shower duration.

The modelled additional hot water consumption due to heat loss from pipes increased with increasing hot water pipe length and increasing radius (Fig. 3a). In 70 % of cases, the standing loss resulted in the flushing of the entire volume of the hot water pipe. Since the volume of the pipe is a function of its radius and length, it follows clearly that these two factors have a strong influence on the additional consumption of hot water due to pipe loss. The effect of hot water pipe length on the heat loss from pipes was much stronger when the shower interval was greater than 20 min. Beyond a shower interval of 25 min, the additional hot water consumption due to heat loss was 2.6 L/shower for a hot water pipe length of 20 m and 0.7 L/shower for a pipe length of 5 m.

The clear dependence on length helps to explain the variation present in the literature (Table 2). For example, Braas et al. (2020) reported additional hot water consumption due to heat loss from pipes of between 39 % and 52 %, significantly higher than any of the other studies considered here. Their results also exceeded the maximum values presented in our study. The most likely reason for this discrepancy is that they considered apartment buildings in which the hot water system was located far from the end-use point. The smallest hot water pipe length Braas et al. (2020) considered was 23 m, whereas our study of detached dwellings has considered a maximum pipe length of 20 m.

Similarly, the additional hot water consumption due to heat loss from pipes increased with increasing shower interval, until the shower interval reached 25 min (Fig. 3a). Beyond this point, the shower interval did not influence the additional hot water consumption due to heat loss. Between the shower intervals of 20 min and 25 min, there was a sharper increase in the additional hot water consumption. This corresponded to the shower interval at which the hot water pipe cooled to below the shower temperature (Fig. 3a). The link between target shower temperature and additional hot water consumption is highlighted by the black lines in Fig. 3a and c.

The impact of shower interval may explain the difference between results reported by Hadengue et al. (2020) and Kenway et al. (2019), which both modelled the same household. Hadengue et al. (2020) found that heat loss contributed 17 % of the hot water consumption in the household, whereas Kenway et al. (2019) found that heat loss

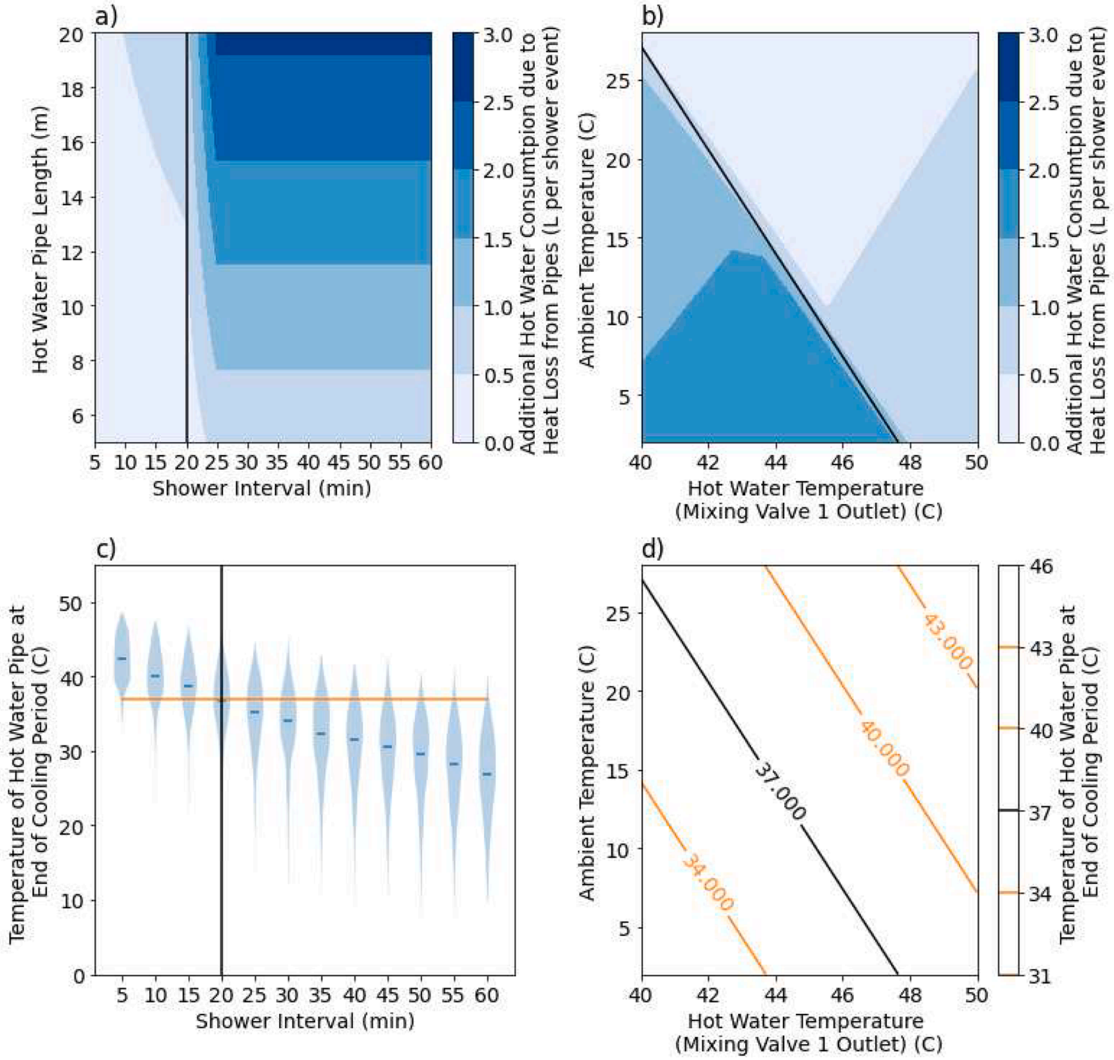

Fig. 3. Predicted additional hot water consumption due heat loss from pipes (standing + flowing), as a function of pipe length and time between showers (a), and ambient temperature and temperature at outlet of first mixing valve (b); temperature of hot water at the inlet to the second mixing valve, at the end of the shower interval, as a function of shower interval (c), and as function of ambient temperature and temperature at outlet of first mixing valve (d).

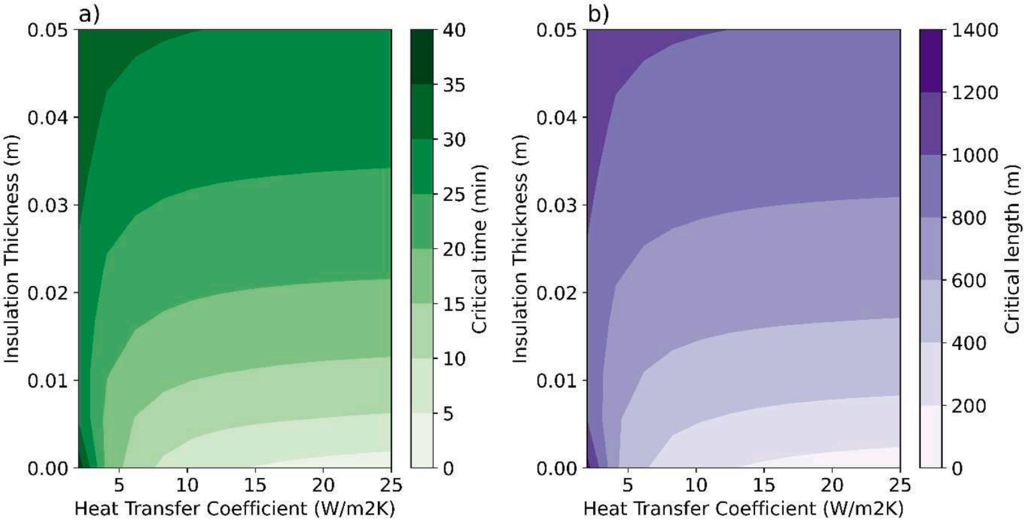

Fig. 4. Impact of heat transfer coefficient and insulation thickness on critical time (a) and critical length (b). Here the critical length and time are defined as the point at which the hot water in the pipe has cooled to the shower temperature (i.e. 37 °C.

contributed 8 %. A possible reason for this is that Hadengue et al. (2020) modelled the entire household dynamically, whereas Kenway et al. (2019) modelled the shower only. Therefore, Hadengue et al. (2020) included heat loss from pipes for other hot water uses, such as kitchen or bathroom sinks, which tend to use shorter and more frequent draw-offs than showers (Marini et al., 2021). These shorter and more frequent draw-offs are likely to result in a higher proportion of heat loss from pipes since there are more cooling intervals relative to the volume of hot water used.

The critical length and time increased with increasing insulation thickness and decreased with increasing heat transfer coefficient (Fig. 4). Here we defined critical length and time as the point at which the hot water cooled to the showering temperature (37 °C). The critical time varied between 5 min and 60 min for the range of parameters considered in Fig. 4a. The critical length varied between 200 m and 1200 m in Fig. 4b. These cooling lengths are much larger than typical pipe lengths in detached dwellings which are less than 20 m.

Insulation had a surprisingly small impact on the additional hot water consumption due to heat loss according to the model (Fig. 2d). Generally, it is assumed that thicker insulation equates to less heat loss, however, this does not account for the true influence of heat loss on hot water consumption. Specifically, it does not consider the fact that the shower interval is usually much larger than the time taken for the hot water pipes to cool to the shower temperature. Therefore, in most cases, insulation had no impact.

3.2. Implications for theory and practice

This paper presented a new model (DHW-HLP) to calculate heat loss from DHW pipes, which incorporated a high level of detail whilst enabling quick and easy parameter variation. Historically, models presented in the literature have achieved one of these objectives in isolation, but to the authors knowledge, this is the first study to achieve them simultaneously. The parameter which has typically been the barrier to achieving the objectives simultaneously is the shower interval. In other models, this has either been ignored, simplified excessively, or required a time series input. The time series input leads to a lack of flexibility in the model inputs, as well as longer run-times. DHW-HLP addressed this limitation by developing equations as a function of the shower interval, so shower interval was a single input.

Additionally, DHW-HLP presented a novel perspective, considering the heat loss from pipes in terms of its impact on the total hot water consumption, which is more representative than presenting the heat loss as an energy value. Consideration of the impact on hot water consumption accounts for the fact that all the water in the pipe needs to be flushed if the temperature of the hot water pipe falls below the target shower temperature.

The sensitivity analysis conducted in this study has enabled a better understanding of the variability of heat loss reported previously. Kenway et al. (2019) greatly improved on the calculation of heat loss from pipes by using a 1-minute resolution time-series analysis. This ensured that all shower intervals were adequately captured. However, due to the detailed nature of this model, and time required to process simulations, it did not have the power to assess a wide range of scenarios. DHW-HLP overcomes this limitation and offers flexibility to vary parameters and assess sensitivity, and still captures all shower intervals (refer to Supplementary Information for a comparison between DHW-HLP and DYNWAREHO).

A key implication of the results is that insulation of pipes may not have a significant impact on the additional hot water consumption due to heat loss. After 60 min, the water cooled below 37 °C in all but the most extreme cases (Fig. 3c). Therefore, even with the best insulation, all the water in the pipe needed to be flushed if the shower interval was greater than 60 min. So beyond 60 min, the insulation did not influence the additional hot water consumption due to heat loss from pipes.

Conversely, one of the more effective options to conserve DHW would be to reduce length and radius of hot water pipes. This is also effective to conserve water and is most relevant to new households. Locating the hot water system as close as possible to the end-use will reduce the standing heat loss from pipes, saving water and energy (Klein, 2013). It may be beneficial to review sizing guidelines for hot water piping, which are often oversized due to outdated requirements.

Another insight from these results is that energy and water can be saved by taking showers within a 20–25 min window of each other. Whilst this is not necessarily a feasible behaviour change in all households, it may be beneficial to advertise this fact to households, as some may wish to act on it. Another way to reduce the shower interval could be for individuals to make use of communal showering facilities, such as end-of-trip facilities for cyclists.

This study could be crucial to informing decisions for households, government and utilities to target energy and water consumption of hot water systems. For example, it may inform future updates to building codes with respect to length and insulation guidelines. It could also support household incentives to achieve energy efficient hot water systems. Additionally, it may inform household behaviours, with knowledge of the energy and water efficiency of back-to-back showering.

3.3. Limitations and future work

The validation of this model is limited (only four cases are assessed), however this is consistent with most studies in this field. To date, complete validation of heat loss models against household data has not been possible. For example, Tanha et al. (2015) conducted validation of the energy requirements for hot water in two households, however their study did not model hot water consumption. Conversely, Binks et al. (2016) modelled the hot water consumption as well as associated energy, and although they validated against total measured household energy consumption, they did not have data for the hot water system energy requirements.

Therefore, we strongly recommend that future work in this field prioritises data collection for validation. This would require extensive metering of households, including hot water flowrates, appliance flowrates and times of use, hot water tank energy input, and temperatures in the tank and along the hot water pipes (Heidari et al., 2022). Alternatively, it would require the establishment of customised laboratory testing facilities. The technical parameters of the hot water system would need to be recorded in parallel, for example the tank size, pipe lengths, insulation thickness etc. To build on the literature, this data would need to be collected simultaneously for at least one household. However, to validate the model with confidence, it would need to be collected for a much larger number of households.

Whilst this study has expanded on previous literature by considering heat loss from pipes in more than 10 individual household configurations, the results are specific to detached dwellings with non-circulating hot water systems in the location of Melbourne. However, this tool could be applied to new scenarios with relative ease. The most important scenarios to consider in future would be the application to circulating hot water systems, large apartment buildings and colder climates. Based on the trends presented in this study, circulating hot water systems would likely result in greater energy use than a detached dwelling, but similar levels of water waste due to sections of non-circulating pipes at the draw-offs. For colder climates, the hot water systems and piping are more likely to be located indoors, so the temperature around the pipe would likely be more consistent at about 18–20 °C. Thus the water waste as a result of heat loss would be smaller due to a reduced driving force for heat transfer. We recommend that these scenarios be tested with further modelling.

Additionally, this study has not quantified the implications for cost and carbon emissions. However, the analysis presented here could be used to inform design of solutions to reduce water and energy consumption and subsequent economic and life cycle analysis of those solutions. Based on our results, it is anticipated that the reduction in water and energy consumption would result in reductions to household costs and carbon emissions, but this would need to be verified with additional modelling and analysis.

4. Conclusions

Simulations based on Melbourne, Australia showed that the median additional hot water consumption due to heat loss from hot water pipes was 1.4 L/shower (4.0 %), with an interquartile range of 0.8 to 2.2 L/shower (1.9 to 8.9 %). This corresponded to an additional 108 kWh/household/year energy consumption on average, which has associated cost and carbon emissions. The result is directly applicable to the context of Melbourne detached dwellings, however the range of input parameters used has similarities with other cities and household types.

The impact of heat loss from pipes between hot water events (standing loss) was greater than the impact of heat loss during hot water events (flowing loss) in the majority of cases. The additional hot water consumption due to standing loss was 6.4 % on average, and due to flowing loss was 0.6 %. This was largely due to the need to flush the entire hot water pipe in cases where the shower interval is high, because water had cooled below the showering temperature.

The simulated key factors influencing the additional hot water consumption due to heat loss from pipes were the pipe length and radius, along with shower interval and duration. Insulation thickness was found to have little impact on the additional hot water consumption due to heat loss from pipes. Simulations suggested the hot water cools to below the shower temperature within 30 min of showering in most cases, even with the best insulation.

This study has presented a novel model (DHW-HLP) to determine the additional hot water consumption due to heat loss from hot water pipes, which simultaneously enabled detailed analysis, and flexibility to conduct parameter variation. This enabled new insights into the potential key factors influencing heat loss from pipes. With further validation in future, these insights may be used to inform policy and regulation for behaviours and designs that enhance water and energy efficiency, consequently reducing carbon emissions and household costs.

CRediT authorship contribution statement

R. Hall: Conceptualization, Formal analysis, Methodology, Visualization, Writing – original draft. **K.R. O'Brien:** Conceptualization, Methodology, Writing – review & editing, Supervision. **S. Kenway:** Writing – review & editing, Supervision. **F.A. Memon:** Writing – review & editing, Supervision.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests:

Rebecca Hall reports financial support was provided by University of Queensland.

Data availability

Python code for DHW-HLP model will be made available on request. The authors do not have permission to share water consumption data.

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Supplementary materials

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References

Araújo, A., Pereira, V, 2017. Solar thermal modeling for rapid estimation of auxiliary energy requirements in domestic hot water production: on-off flow rate control. In: Energy, 119, pp. 637–651.

Australian Bureau of Statistics. 2022. *Housing: Census - Information on housing type and housing costs*. Available: https://www.abs.gov.au/statistics/people/housing/housing-census/latest-release [Accessed 10/4/24].

Australian Government - Bureau of Meteorology, 2023. Melbourne Airport. Daily Weather Observations, Victoria.

Beal, C.D., Bertone, E., Stewart, R.A., 2012. Evaluating the energy and carbon reductions resulting from resource-efficient household stock. Energy Build. 55, 422–432.

Binks, A.N., Kenway, S.J., Lant, P.A., Head, B.W., 2016. Understanding Australian household water-related energy use and identifying physical and human characteristics of major end uses. J. Clean. Prod. 135, 892–906.

Braas, H., Jordan, U., Best, I., Orozaliev, J., Vajen, K., 2020. District heating load profiles for domestic hot water preparation with realistic simultaneity using DHWcalc and TRNSYS. Energy 201, 117552.

ÇEngel, Y.A., Ghajar, A.J., 2020. Heat and Mass Transfer: Fundamentals & Applications. McGraw-Hill Education, New York, NY New York.

Chen, Y.C., 2020. System dynamics evaluation of household water use behavior and associated greenhouse gas emissions and environmental costs: a case study of Taipei city. J. Water Process Eng. 37, 101409.

Cholewa, T., Siuta-Olcha, A., Anasiewicz, R., 2019. On the possibilities to increase energy efficiency of domestic hot water preparation systems in existing buildings—long term field research. J. Clean. Prod. 217, 194–203.

de Oliveira, G.C., Bertone, E., Stewart, R.A., 2022. Challenges, opportunities, and strategies for undertaking integrated precinct-scale energy–water system planning. Renew. Sustain. Energy Rev. 161, 112297.

Genuardi, M.D., Wiegand, M., Opel, O., 2023. Installation of an ultrafiltration plant in a multi-family house to reduce the hot-water temperature and energy demand: a case study in Germany. J. Build. Eng. 66, 105898.

Guo, X., Goumba, A.P., 2018. Air source heat pump for domestic hot water supply: performance comparison between individual and building scale installations. In: Energy, 164, pp. 794–802.

Hadengue, B., Morgenroth, E., Larsen, T.A., 2022a. How to get your feet wet: integrating urban water and building engineering for low-energy domestic hot water systems. Energy Build. 271, 112318.

Hadengue, B., Morgenroth, E., Larsen, T.A., 2022b. Screening innovative technologies for energy-efficient domestic hot water systems. J. Environ. Manag. 320, 115713.

Hadengue, B., Scheidegger, A., Morgenroth, E., Larsen, T.A., 2020. Modeling the water-energy nexus in households. Energy Build. 225, 110262.

Hamburg, A., Mikola, A., Parts, T.M., Kalamees, T., 2021. Heat loss due to domestic hot water pipes. Energies 14, 6466.

Heidari, A., Maréchal, F., Khovalyg, D, 2022. An occupant-centric control framework for balancing comfort, energy use and hygiene in hot water systems: a model-free reinforcement learning approach. Appl. Energy 312, 118833.

Hofer, G., Kotik, J., Pröll, T, 2023. Heat loss reduction and tap temperature equalization of a centralized domestic hot water system in a modernized pre-WWI residential building. J. Build. Eng. 77, 107506.

IWU - Institute for Housing and Environment. 2014. *DE Germany - Country Page - Residential Building Typology*. Available: https://episcope.eu/building-typology/country/de/[Accessed 10/4/24].

Jiang, S., Wang, J., Zhao, Y., Lu, S., Shi, H., He, F., 2016. Residential water and energy nexus for conservation and management: a case study of Tianjin. Int. J. Hydrogen Energy 41, 15919–15929.

Kenway, S.J., Binks, A., Scheidegger, R., Bader, H.P., Pamminger, F., Lant, P., Taimre, T., 2016. Household analysis identifies water-related energy efficiency opportunities. Energy Build. 131, 21–34.

Kenway, S.J., Scheidegger, R., Bader, H.P., 2019. Dynamic simulation of showers to understand water-related energy in households. Energy Build. 192, 45–62.

Kenway, S.J., Scheidegger, R., Larsen, T.A., Lant, P., Bader, H.P., 2013. Water-related energy in households: a model designed to understand the current state and simulate possible measures. Energy Build. 58, 378–389.

Klein, G. 2013. Efficient hot water piping.

Ltd, B.-B.R.E. 2014. *GB Great Britain - Country Page - Residential Building Typology*. Available: https://episcope.eu/building-typology/country/gb/[Accessed 10/4/24].

Manouchehri, R., Collins, M.R., 2022. Investigating the impact of plumbing configuration on energy savings for falling-film drain water heat recovery systems. Energies 15, 1141.

Marini, D., Buswell, R.A., Hopfe, C.J., 2021. Development of a dynamic analytical model for estimating waste heat from domestic hot water systems. Energy Build. 247, 111119.

Marszal-Pomianowska, A., Jensen, R.L., Pomianowski, M., Larsen, O.K., Jørgensen, J.S., Knudsen, S.S, 2021. Comfort of domestic water in residential buildings: flow, temperature and energy in draw-off points: field study in two Danish detached houses. Energies 14, 3314.

Moss, R.W., Critoph, R.E., 2022. Optimisation of a recirculating domestic hot water system to minimise wait time and heat loss. Energy Build. 260, 111850.

Nguyen, K.A., Stewart, R.A., Zhang, H., Jones, C., 2015. Intelligent autonomous system for residential water end use classification: autoflow. Appl. Soft Comput. J. 31, 118–131.

Plastics Industry Pipe Association of Australia 2010. Thermal insulation of hot water pipes for plumbing applications.

Pomianowski, M.Z., Johra, H., Marszal-Pomianowska, A., Zhang, C., 2020. Sustainable and energy-efficient domestic hot water systems: a review. Renew. Sustain. Energy Rev. 128, 109900.

Riahi, K., Bertram, C., Huppmann, D., Rogelj, J., Bosetti, V., Cabardos, A.-M., Deppermann, A., Drouet, L., Frank, S., Fricko, O., Fujimori, S., Harmsen, M., Hasegawa, T., Krey, V., Luderer, G., Paroussos, L., Schaeffer, R., Weitzel, M., van der Zwaan, B., Vrontisi, Z., Longa, F.D., Després, J., Fosse, F., Fragkiadakis, K., Gusti, M., Humpenöder, F., Keramidas, K., Kishimoto, P., Kriegler, E., Meinshausen, M., Nogueira, L.P., Oshiro, K., Popp, A., Rochedo, P.R.R., Ünlü, G., van Ruijven, B., Takakura, J., Tavoni, M., van Vuuren, D., Zakeri, B, 2021. Cost and attainability of meeting stringent climate targets without overshoot. Nat. Clim. Change 11, 1063–1069.

Tanha, K., Fung, A.S., Kumar, R., 2015. Simulation and experimental investigation of two hybrid solar domestic water heaters with drain water heat recovery. Int. J. Energy Res. 39, 1879–1889.

United States Census Bureau. 2021. *American Housing Survey Table Creator*. Available: https://www.census.gov/programs-surveys/ahs/data/interactive/ahstablecreator.html?s_areas=00000&s_year=2021&s_tablename=TABLE1&s_bygroup1=1&s_bygroup2=1&s_filtergroup1=1&s_filtergroup2=1 [Accessed 10/4/24].

Victorian Building Authority. n.d. *Hot water safety*. [Accessed 23/02/2024].

Zhou, X., Tian, S., An, J., Yan, D., Zhang, L., Yang, J., 2022. Modeling occupant behavior's influence on the energy efficiency of solar domestic hot water systems. Appl. Energy 309.