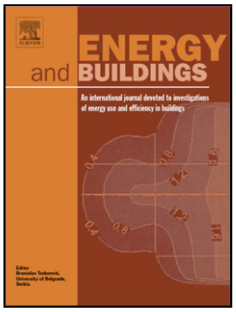

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PII: S0378-7788(16)30808-8
DOI: http://dx.doi.org/doi:10.1016/j.enbuild.2016.09.008
Reference: ENB 6997

To appear in: *ENB*

Received date: 7-1-2016
Revised date: 8-8-2016
Accepted date: 5-9-2016

Please cite this article as: Steven J.Kenway, Amanda Binks, Ruth Scheidegger, Hans-Peter Bader, Francis Pamminger, Paul Lant, Thomas Taimre, Household analysis identifies water-related energy efficiency opportunities, Energy and Buildings http://dx.doi.org/10.1016/j.enbuild.2016.09.008

Household analysis identifies water-related energy efficiency opportunities

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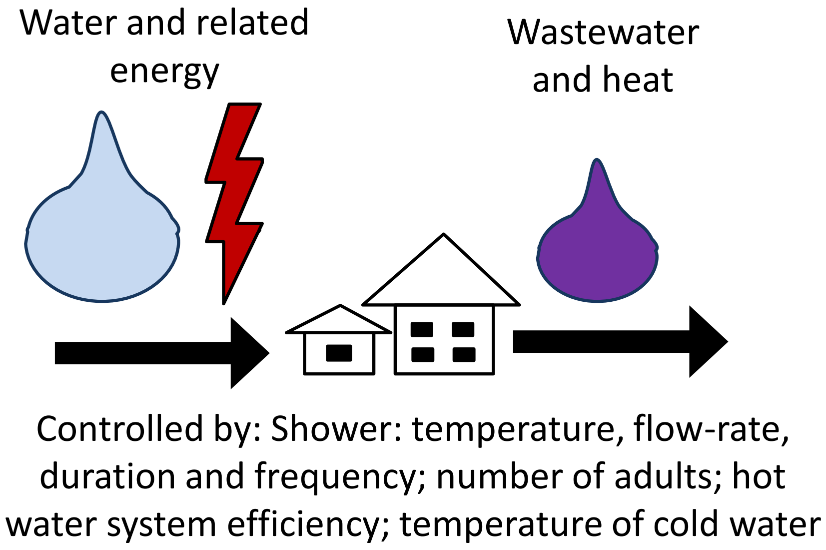
Graphical Abstract:



Highlights:

- Detailed modelling of water-related energy in seven households.
- Identifies key factors of influence, and the significance of shower systems.
- Uses data from 5,399 shower events from 94 households to simulate ranges.
- Identifies strongest scope for influence in shower flow rate and duration.
- Identifies implications for city-scale analysis and management.

Abstract: Water heating accounts for around one third of household direct energy use. This energy demand is some four times greater than lighting. Here we use detailed monitoring and modelling of seven individual households to quantify major factors. Using normalized sensitivity results we demonstrate (i) high variability and (ii) a large and consistent influence of shower duration, flow rate, frequency and temperature along with hot water system efficiency, adult population, and the temperature of cold water. A 10% change in these factors influenced 0.1–0.9 kWh/hh-person.d, equivalent to a 2–3% of total household energy use. We draw on 5,399 shower events from a further 94 households, and 491 shower temperature measurements to understand the scope for changes to the households. Individual parameters variation guided by these larger datasets demonstrated shower duration and flow rate offer most scope for change. The work helps guide city-scale analysis of household water-related energy demand. It also supports the tailoring of behavioural and technological water-efficiency programs towards those with strongest potential to influence energy. Strong interaction between parameters suggests that programs aiming to influence water-related energy need to be aware of how this interplay either amplifies, or diminishes, the intended energy savings.

Abbreviations

GHG	greenhouse gas
HH	a specific, studied household (e.g., HH1)
hh	households generally
kWh	kilowatt hour (3.6 megajoules (MJ))
kWh/hh.d	kilowatt hour per household per day
kWh/p.d	kilowatt hour per person per day
L/hh-p.d	litres per household-person per day (household data normalised by occupancy)
kWh/hh-p.d	kilowatt hour per household-person per day (household data normalised by occupancy)
L	Litre
P1, P2, etc.	Parameters 1, 2, etc. of the ResWE model
	“Behavioural” parameters are those most influenced by human choice (e.g. shower duration)
	“Technological” parameters are parameters influenced by appliance and fixture characteristics
	“Structural” parameters are parameters characteristic of the household (e.g. length of pipes, energy source for the hot water system)
	“Environmental” parameters are influenced by the ambient environment surrounding households (such as the temperature of cold water)
ResWE	The Residential Water-Energy model (refer to Kenway et al. 2013)

Keywords:

Urban metabolism, Urban systems, Key factor analysis, Mathematical Material Flow Analysis, Sensitivity analysis, Zero Energy Buildings

1. Introduction

Households in Australia, and many industrialised countries, use approximately one third of their direct energy use for heating water in hot water systems or appliances (Kenway et al., 2011a; Klein et al., 2005; Wolff and Wilkinson, 2011). Most of the energy used is for showers, baths, clothes-washers and dishwashing. In Australian homes, water-related energy accounts for over four times more energy use than lighting (Commonwealth of Australia, 2008). The proportion of household energy use in Australia which is influenced by water use is expected to grow. This is because other household energy demands are being more actively managed and reduced (Tiefenbeck et al., 2014).

Understanding water-related energy use is important for the design of efficient appliances, households and cities (AWE and ACEEE, 2011; PMSEIC, 2010; WBCSD, 2009). With energy use for urban water rapidly growing in Australia (Hall et al., 2011), improved understanding of water-related energy use helps find cost-effective solutions to reduce or offset this growth (Rothhausen and Conway, 2011). In 2007, water-related energy use in Australian cities accounted for 13% of total electricity use, plus 18% of natural gas energy use (Kenway, 2011). This includes energy for urban water use, supply, and wastewater services (Kenway et al., 2011a). Similar values are articulated for California (Klein et al., 2005; Wolff and Wilkinson, 2011). Water heating in homes and businesses requires 7–15 times more energy than the energy required for provision of water in Europe, the United States and Australia (Arpke and Hutzler, 2006; Cheng, 2002; Flower, 2009a; Kenway et al., 2015).

Despite acknowledgement of the significance of residential water-energy links, there is a paucity of quantitative analysis of key factors. By “key” factors we mean behavioural, technological, environmental, or structural (building envelope) conditions which, when varied within expected realistic ranges, can have strong effects on energy use. In the limited studies available, much of the effect of water-related energy in households is typically attributed to generic causes such as “shower water use” (Flower, 2009b; Kenway et al., 2013), giving limited guidance to solutions or policy. Most previous studies have relied on modelled results of the “average” household (e.g. a hypothetical household with attributes representing median values estimated from a range of sources) rather than evaluating potential variation across households. This is surprising given the wide range of assumptions evident in the literature, and the significant influence this is likely to have on water-related energy use. For example, cold water temperatures from 4.4°C (Arpke and Hutzler, 2006) to 20°C (Cheng, 2002) have been used.

Sensitivity analysis of residential water-related energy use is not described in the literature, other than by Flower (2009b), who did not identify key parameters. Flower considered all parameters to be of equal effect. Jacobs and Haarhoff (2004) recommended sensitivity analysis, but did not pursue this. Understanding of system sensitivity is critical to guide insight for management and policy. Sensitivity analysis can quantify the “levers of control”. As a result, strategies intended to influence residential water-related energy cannot be well targeted due to the high potential for household-to-household variability.

Consequently, the major objective of our work was to systematically identify, and quantify, key factors influencing household water-related energy use. We define water-related energy use here as household direct energy use which can change as a consequence of altered water use in households. Our research focussed on understanding key factors, and the scope for how much water-related energy can be influenced by changes to these factors.

In this paper we go beyond the existing literature to identify which factors have major impacts on water-related energy in households. This research has been undertaken as a component of a larger collaborative industry-government-university project, we build on the baseline characterisation of seven households (Binks et al 2016). We build on this work here to (i) systematically identify key sensitivities across all seven households using Material Flow Analysis, (ii) use additional data for 5,399 shower events from 94 households in the community and 491 new shower temperature records to (iii) undertake single parameter variation to understand scope for changing water-related energy. We also used combined (two-parameter) variation to investigate interactions, and we discuss the implications for city scale analysis, as well as potential implications for behavior and technology management.

Our work is a relatively rare example of an Integrated Component-based Water Model (Bach et al., 2014), with the research focusing not only on water, but also including “external” environmental factors, such as water temperature and related energy influences including heat losses. . The work contributes to an improved understanding of behavioural and technological factors influencing the flow of water, and related household energy consumption.

This work also aimed to contribute to urban metabolism theory by focusing on the *activities* and *processes* associated with water use within households. Metabolism studies consider the flows of water, energy, and materials through urban systems (Baccini and Brunner, 1991; Fischer-Kowalski and Huttler, 1998; Kennedy et al., 2011; Pamminger and Kenway, 2008). Wolman (1965) identified that water is by far the dominant material flow which passes through cities. Drawing on Wolman's work, Decker et al. (2000), suggested that water should be a priority in understanding the metabolism of cities.

Improved knowledge of water-related energy use, and its controls, will help water and energy managers, policy makers, appliance manufacturers, householders, and other stakeholders to reap full energy and cost benefits of efficiency investments.

2. Methodology, theory and calculation

This research has been conducted as a component of a larger research project undertaken collaboratively between The University of Queensland (Australia), the Melbourne water and energy sectors and related government agencies. The overarching project has principle goals including: (i) understanding water and energy connections in individual households and then city-scale water-related energy and (iii) identifying opportunities to cost-effectively reduce water-related energy. This paper focusses on the first of these aims.

This approach undertaken included (Figure 1): (1) household selection, recruitment, and baseline data collection processing and analysis in the individual households for relevant parameters, (2) collection of additional data specific to shower systems, (3) Mathematical MFA (MMFA) modelling to quantify water and energy flows (with attention to water-related energy), (4) results validation, (5) sensitivity analysis, (6) parameter variation informed by collection of additional data related to community-scale water use focused particularly on showering.

2.1 Household Selection and Baseline Data Collection

Seven households were selected in Australia, with five in Melbourne, (HH1-HH5) and two in Brisbane (HH6-HH7) to provide a geographic spread. Households were selected based on characteristics including (a) willingness for relatively intrusive surveys, installation of monitoring equipment, and questioning; (b) stable occupancy during the study period (April 2012 until March 2013); and (c) no solar Photo Voltaic (solar electricity supply) installed (due to its influence on electricity meter readings). The households were not intended to be particularly representative for water-related energy (or water use or energy use). Rather it was our aim to characterise a wide range of situations particularly with regard to water use patterns, and hot water systems and hence a potentially wider potential range of water-related energy characteristics.

Households were evaluated in detail for the period between 1 April 2012 and 30 March 2013; coincident with a period of stable water use and high data availability.

Detailed household surveys were undertaken including behavioural interviews; and audits of fittings, fixtures, appliances, and structural and overall household aspects. Parameters critical to the performance of water and energy use in the household were characterised according to the best information available by (i) measuring where possible for volumes, water flow rates and temperatures, (ii) interviewing household members regarding usage patterns and behaviours, (iii) sourcing water temperature and other data from water utilities, (iv) retrieving information from available manuals (e.g. Litres (L)/cycle, temperature/cycle, minutes/cycle for clothes-washing machines) or from similar manuals available from suppliers, (v) confirming by inspection the plumbing of clothes-washers and dishwashers to either the cold or both hot and cold water supplies, and finally (vi) estimating from literature the relatively small number of parameters that could not be measured directly. Binks et al. (2016) describe the data collection methodology in detail including fieldwork.

The present work builds on work in a larger project (Binks et al (2016), Kenway et al ref) with additional data collected specifically for shower systems and community water use to inform realistic parameter variation (Steps 2.2 and 2.3 in Figure 1). The principle innovations, and foci of this paper include (i) systematic sensitivity analysis (ii) normalisation of sensitivity analysis to enable comparison of sensitivities across households (iii) variation of individual key parameters to understand the scope for influencing water-related energy, (ivi) variation of key parameters in combination to improve understanding of interaction effects. These are shown as steps 5 and 6 in Figure 1. Collectively these innovations provide significant new, non-obvious information relevant to the management of behavioural and technological factors influencing water-related energy, and salient to the design of city-scale analysis and monitoring programs.

2.2 Characterisation of Shower Parameters

A range of strategies were implemented to source additional data to characterise shower parameters. This was undertaken both for (i) individual households and (ii) for the community in the vicinity of studied households. Shower meters (Amphiro), were deployed to measure the frequency, duration, and flow rate of each shower event over approximately a one-month period in individual households. A log-sheet was completed by each household member for each shower recording the date, time, and displayed shower volume for each shower event. This enabled subsequent identification of the shower temperature, duration and energy use associated with each individual shower event. Amphiro meters are powered by micro-turbines, and innovatively avoid the need for a supply of electricity to the shower space. They measure water flow and temperature. The Amphiro meters were installed in two households (HH4 and HH7), but could not be installed in five of the seven study households due to incompatibility with specific shower fixtures. For two additional households (HH3 and HH6), high resolution water end-use data from in-line meters enabled characterisation of shower frequency, duration, and flow rate. For all households, a thermometer measurement of shower temperature was taken after the household member had stabilised the water temperature to the level at which they typically shower.

For key parameters such as shower duration, flow rate, and number per day (P21–P23), data was sourced from the Amphiro records (in the studied households) and for data from 94 households in Melbourne (Roberts, 2012) based on high-resolution water-end use metering. Records from 94 households for winter water use, (2,755 shower events) were combined with data from 83 households for summer water use (2,644 shower events) to give a combined dataset of 5,399 shower events. This was used to create probability distributions of shower parameters for the “community” and estimates of the range of realistic values which could be expected for each parameter.

Shower temperature was also characterised across the “community” using data from the Amphiro meters installed in the study households, as well as installing one additional Meter (HH8, in Brisbane) which included 1 adult and 4 children (up to age 14). For shower temperature, a collective 491 shower events from 11 individual people (five adults and six children aged 14 or less) were obtained. This included 170 individual records for adult males, 100 for adult females and 221 for children.

2.3 Mathematical Material Flow Analysis Model Construction and Use

Construction and use of detailed Material Flow Analysis (MFA) models of each of the seven households was a core component of this research. A generic MFA modelling tool – The Residential Water Energy (ResWe) Model was completed prior to this project (Kenway et al., 2013), and was integral to the project. ResWE was further developed during the project, for example to account for multiple different types of hot water systems, including solar hot water, and to improve partitioning of results. Key benefits of MMFA are its ability to provide an understanding of the system based on current knowledge, and to systematically identify the key parameters (driving forces) involved (Huang et al., 2007; Kwonpongsagoon et al., 2007; Schaffner et al., 2009). This is crucial for discussing possible measures to reduce the flows.

Inputs to the ResWe model include distributions (mean, standard deviations, distribution type (eg normal, lognormal, truncated), upper and lower bounds) of 139 parameters describing sub-system level household behaviours, technologies, structural and environmental aspects of influence (See Supplementary Information). Fixed and variable water and energy costs, and GHG emissions intensities of fuel sources can also be input. Sub-systems focus on areas of key water-energy interactions (e.g. showers, baths, clothes-washers, taps, dishwashers, kettles and air-conditioners), other water using systems (outdoor water, toilets) and all other energy-using systems, plus estimates of losses (e.g. heat conversion losses, storage losses and pipe losses) (Figure 2).

The principle function of ResWe is to calculate, and enable simulation of “Water Related Energy” (WRE). By this we mean any household energy use influenced by water. This includes household direct consumption of electricity and natural gas, as well as the use of solar energy for heating water (which occurred in HH1 and HH2). It does not include energy used by water utilities in providing water or wastewater services to the household. For full details see Kenway et al 2013.

The ResWE model has 740 output variables exported as mean–standard deviation pairs or probability distributions, depending on the availability of input distributions. Outputs at sub-system level include use of water, electricity, natural gas, and related costs and GHG emissions, broken down by adults and children.

The ResWe model was run by loading input parameters and calculating output variable mean and standard deviations in order to characterise baseline performance of the households. For example, sub-system level water use, electricity, natural gas (and related GHG emissions and costs) were determined individually for each household. For the full baseline of the households studied and the related validation refer to Binks et al (2015 submitted).

2.4 Sensitivity Analysis and Normalisation

Sensitivity analysis was performed for each household individually. The objective of the sensitivity analysis was to systematically quantify the effects of small changes to all input parameters and to identify key parameters. This uses the validated MMFA model (Binks et al 2016) of each individual household, fully characterised for all parameters, by progressively changing each individual parameter (from P1 to P139) and determining the associated change for each ResWE output variable. The “relative sensitivity” of X_i with respect to parameter p_j is defined as:

$$\Delta X_{i,j} = \frac{\partial X_i}{\partial p_j} \cdot \Delta p_j \qquad (1)$$

where $\Delta p_j = \pm 0.1 \cdot p_j$, and $\Delta X_{i,j}$ is the linear approximation of the change in variable X_i if the parameter p_j is increased or decreased by 10%.

As an example of Equation 1, a 10% increase in adult occupancy for a household with 3.0 persons would increase by 0.3 “adults” per day (as an average over a year), i.e. to a total of 3.3 “adults” per day. Changing adult occupancy across households is particularly influential because in the ResWE model, water use for showering, bathing, and teeth cleaning was characterised as being directly proportional to household occupancy numbers. Other water uses such as number of cleaning events, the number of dishwasher or clothes-washing machine cycles, lawn watering or swimming pool filling were considered to be “collective” or better characterised at household level, rather than at the level of individual persons. We adopted this approach because it helps identify underlying system drivers and enables analysis of detailed changes to technologies, behaviours, environmental conditions or general structural (household) aspects.

Sensitivity analysis was conducted for all ResWE output variables with particular attention to (i) water use and (ii) water-related energy. As our aim was to identify the relative consistency of key parameters having the largest influence on these variables, the relative sensitivity $\Delta X_{i,j}$, was assessed.

In order to compare the sensitivities across households, and to determine the most significant parameters across all seven households, with different numbers of occupants, household sensitivities were normalised by occupancy (the sum of the adult and child population). This leads to units of “water”, or “water-related energy sensitivity”, in units per household-person, per day. The total (cumulative) value of the normalized sensitivity for each parameter, was used to identify those parameters of most consistent influence across the seven households. This simulated, for example, the cumulative impact on water use, and water related energy, if a parameter (say adult population, P1) increased 10% in all seven households. This process was undertaken for each of the 139 input parameters of the ResWE model. Parameters with the highest absolute cumulative influence across the seven households were identified as the key factors. In assessing cumulative sensitivity of energy use influenced by water, the absolute influence needed to be considered because some parameters, (such as the temperature of cold water), when increased, reduce household water-related energy, rather than increasing it.

2.5 Parameter Variation

Individual and combined parameter variation was undertaken to understand how changing key parameters (identified in the sensitivity analysis above), could influence water-related energy use.

Individual parameter variation was undertaken by varying key parameters systematically in the MMFA through a range of values identified from 5,399 shower records from 94 households. This provided insight into the potential range of water-related energy use representative of the broader population. In doing so, it created a range of possible behaviours– which could occur in each of the seven households – if an "attribute" of the surrounding population" moved into" the households studied. This method also enabled estimation of the potential influence of management programs such as behavior change.

For parameters with normal distributions, approximately 68% of observations would be expected to fall within one standard deviation of the mean, and 95% of values would fall within two standard deviations. We did not simulate all households shifting to the 2nd or 98th percentile. Rather, we used the "community" data, in order to understand how water-related energy would change energy use within the seven households studied (ie HH1-HH7). Effectively this is testing the scenario that a specific parameter value range (such as shower duration), typical of the community, "moved into" each of the seven households.

The rationale for undertaking this is that two factors could have similar mean values, but quite different overall distributions. For example, Factor A could be shower flow duration, and Factor B could be shower flow rate. While the mean value for each factor could be identical, and sensitivity of water-related energy for the factor could also be identical, the potential range of values could be quite different. This difference is represented with a higher standard deviation for the factors (Figure 3), which conceptually presents a wider range of potential within which Factor B could change (e.g. from 1 to 16) when compared with Factor A (4 to 9).

The combined effect of simultaneous changes to two important parameters — cold water temperature and shower duration — was studied by varying them simultaneously. This was also intended to help identify any potential interaction effect between the two parameters. Varying the temperature of cold water was undertaken to help compare results from studies of household water-related energy undertaken across areas with different cold water temperatures. Flow duration was selected as a key parameter to also vary, because it was identified as having a strong influence on water-related energy, and it is often a parameter targeted in water conservation strategies. Consequently, the combined analysis could help estimate the anticipated energy impact of changes in shower flow duration in areas with different cold water temperatures.

3. Results

A summary of the households, key parameters and performance relevant to this paper are provided in Tables 1, 2 and 3. Observed shower temperature distributions for adults and children from households characterised, are shown in Figure 4. They are also shown in Appendix A which contains the complete probability distributions for each individual adult and child surveyed for shower water temperature in the study. Full parameter lists characterised for each of the seven households is provided as supplementary information.

3.1 Overview

For the seven households investigated, water-related energy comprised 7–21 kWh/hh.d or 13–79% of total household energy use. While total water-related energy per person was relatively consistent 2.0-6.9 kWh/hh.d, the Melbourne households had a smaller fraction of total household energy use influenced by water. This is attributable to larger quantities of total energy use related to additional heating (largely natural gas) in Melbourne, compared to the warmer Brisbane climate.

Showers were the major component of water-related energy use, comprising over half of all water related energy use in four of the seven households. Low shower temperatures and low number of showers per day (HH3), low numbers of showers (HH4), and low shower flow duration (HH7) meant showers comprised a lower proportion of water-related energy use in those households. Hot water system conversion efficiency and storage losses, followed by clothes-washers attributed for the most household water-related energy after showers.

3.2 Sensitivity Analysis

As outlined in the methods section 2.5, sensitivities were normalized by occupancy in order to compare them, as “water”, or “water-related energy sensitivity”, in units per household-person, per day.

Key factors influencing household water use include the number of adults (P1) and shower flow duration (P21), flow rate (P22) and frequency (P23) (Figure 5). For water use impact, these factors were of consistently influential across all households studied. A 10% relative change in the occupancy of adults (P1) increased household water use between 2 and 20 L/hh-p.d.

Some parameters are unique to certain households and/or sub-systems. For example, only air conditioners (and households with air conditioners) will be influenced by changes to the “evaporative air-conditioner sub-system” (P106-107). As approximately 35% of Melbourne households have an evaporative air conditioner (Roberts 2012) changes to this system will not influence all households. Similarly, a 10% change in numbers of irrigation water use only influenced those households where irrigation is undertaken. Small changes in the number and volume of toilet flushes influenced up to 2 L/hh-p.d. This was a relatively consistent factor across all the households studied, however, the overall water consumption influence of the 10% change was relatively small on the households studied.

3.3 Key Factors Influencing Water-related Energy Use

Water-related energy use was most consistently and strongly influenced by parameters relating to shower temperature, shower water use, adult occupancy, the conversion efficiency of hot water systems and the temperature of cold water (Figure 6). These factors consistently influenced 0.1–0.6 kWh/hh-p.d (or ~0.5–1.5 kWh/hh.d) across the studied seven households when changed by 10%.

*Figure 6 only shows those pparameters (of the 139 tested) with substantial influence (i.e. more than a total of 0.15 KWh/hh.p.d across all seven households associated with a 10% change in the parameter). “Inverted” means a -10% effect, rather than a +10% (these parameters had to be inverted to be shown on the same axis as other parameters).

The temperature of showers for adults (P24) had a particularly consistent and strong influence on household water-related energy use. A 10% increase in this parameter influenced 0.1–0.9 kWh/hh-p.d or 0.2–2.6 kWh/hh.d energy use. This is an important finding not previously isolated as significant. As expected, shower temperature has more substantial influence on energy consumption in households which use significant quantities of water due to long showers, frequent showers, and/or showers with high flow rates.

The temperature of baths (P36), and the volume and regularity of baths for children (P34 and P35) was a reasonably influential parameter in the two households with children (HH3 and HH4), primarily as the children were bathing more regularly than showering. Likewise, results indicated that the shower temperature for children was generally lower than for adults and hence less significant as an overall factor.

Shower temperature analysis has received almost no previous attention in the characterisation of water-related energy use. Our analysis indicates that considerable shower temperature variability, both between and within households, is evident. Average temperatures for adult males and females were respectively 34–38ºC and 39–40ºC, and average temperatures of 32–41ºC recorded for children. This temperature range suggests that for accurate studies of water-related energy use, shower temperatures for each household occupant should be established, rather than assumed. Further analysis with a larger sample size could be instructive in differentiating the influence of age, gender, and other factors such as ambient air temperature, on results.

Some factors, such as hot water temperature of the hot water system (P4), had a more consistent, albeit low (~0.05 kWh/hh-p.d) influence on energy use across the seven households. Factors such as the heat transfer coefficient or area of hot water storage (P15 and P16 respectively) had influence only in households which have a storage hot water system (HH1,2,5,6,7).

3.4 The influence of changing shower behaviour

Probability distributions were created for key parameters identified as significant (primarily showers). The showering behaviour of the community in the vicinity of the studied households was determined based on 5,399 shower records from 94 households (Figure 7). These distributions were used to determine the impact on water-related energy by changing individual parameters in the households studied to values represented in the community.The change in water-related energy in each household, when individual parameters were varied from 2% through to 98% of the range observed in the surrounding community, is presented in Figure 8. This gives a measure of how "movable" water-related energy would be in each household – should the particular parameter change in a realistic way. Shower flow duration and flow rate for adults have more potential to influence water-related energy than the number of showers and shower temperature (both of which have a much smaller range on the y-axis).

The stronger potential influence of shower flow duration and flow-rate is attributed to the larger range of behaviours evident, for these two parameters, in the surrounding community. This, in combination with the strong impact of these factors on water-related energy, creates scope for reduction to (or increases in) water-related energy. This demonstrates that influencing shower duration and flow-rate are the levers that would likely have the most substantial impact on water-related energy in this 'community" because these parameters demonstrated (i) strong influence and a had (ii) a wide range over which to potentially be changed.

We also point out that, for the households studied, influencing the number of showers per day per adult, and the temperature of showers per adult, towards community median (50th percentile) values would have a more consistent influence of reducing water-related energy across the households studied. By this we mean, shifting these parameters in households to "community median value" would reduce household water-related energy in all the households we evaluated. This unusual finding occurs because the households studied displayed relatively high shower temperatures and shower frequencies when compared with the surrounding community.

It is also worth observing here that for the seven households studied, changing either the number of showers for adults, or shower temperature for adults – to a wide range of values represented in the community, generally reduced water-related energy use. This is largely because, for the seven households studied, have relatively high values for these parameters, when compared with the surrounding community.

*Note the values for community percentile values are from data presented in Figure 5 and represent observed behaviours in the community where the households are located.

The results also demonstrate:

- Varying the number of showers per day, and shower temperature, through the range of behaviour values observed in the community demonstrates less overall scope for impact (range of movement of water-related energy) in each of the seven households observed. For shower temperatures, this is potentially due to less variability in the range of shower temperatures when compared with other factors of influence. While this could be attributable to a smaller sample size (i.e., the distribution of shower temperatures was based on our survey of three households), other authors suggest that shower temperatures are less able to be "moved" than other parameters, such as shower duration (Tiefenbeck et al., 2014).
- For shower flow duration:
  - changing to the community 50th percentile (6.8 minutes) value reduced water-related energy for HH1, 2 and 5 (approximately 5 kWh/hh.d). However, it increased water-related energy for HH6 and 7 by about 2.5 kWh/hh.d.
  - reducing shower flow duration to the 2nd percentile (2 min) reduced water-related energy by 12.5 kWh/hh.d for HH2, 7.5 kWh/hh.d for HH1 and 5, and 2–4 kWh/HHfor all other households.
  - increasing shower flow duration to the 98th percentile (14 min) increased water-related energy use by 12.5 kWh (HH6), 5–10 kWh (HH2, 4 and 7), and 2–4 kWh for HH1, 3 and 5.
- For shower flow rate:
  - changing to the community "median" (2 L/min) reduced water-related energy for HH4, 7 and 2 (by approximately 2.5 kWh/hh.d), but increased water-related energy for HH1 and 3 (by 2.5–5.0 kWh/hh.d).
  - reducing shower flow rate to the 2nd percentile (2 L/min) reduced water-related energy by 12.5 kWh/hh.d for HH2 and 2.5-7.5 kWh/hh.d for all other households, excluding HH3.

  - Increasing shower flow rate to the 98th percentile (14 L/min) increased water-related energy use by 15 kWh (HH1), 5–10 kWh (HH2, 5 and 6), and 0–2.5 kWh for HH3, 4 and 7.
- Moving the number of showers per adult per day in the seven households, to the median value for the community (0.73 Showers/person.d), reduced water-related energy in five households (HH1, 2, 5, 6, 7) by 0.5–2.0 kWh/hh.d and made little change for HH3 or 4.
- Moving the temperature of showers per adult in the seven households, to the median value for the community (38 °C), reduced water-related energy in five households (HH1, 2, 5, 6, 7) by 0.5–2.0 kWh/hh.d and made little change for HH4. In contrast, moving to a community-median shower water temperature would increase energy use in HH3 by about 0.5 kWh/hh.d because the current shower temperature in HH3 is relatively low (32°C), compared with other observations.

Collectively, the research indicates that applying policy “blindly” to households — such as shifting all shower flow rates to 7 L/min will not necessarily reduce water-related energy in some households. That is, in the households observed here, such a move would reduce water-related energy, and in other households water related energy would increase. Consequently, in order to systematically reduce water-related energy across a community, it will be important to understand the individual household. In order to use water to influence household energy, campaigns should be targeted to the specific circumstances influencing individual households.

3.5 Combined Parameter Variation and Interaction of Key Factors

Varying the temperature of cold water and shower duration at the same time, revealed wide possible influence on household water-related energy use (Table 5). Varying parameters helps us understand combined influences which cannot be easily measured because it would be impossible to obtain two identical households, each showering for precisely the same durations, but located in areas where the water temperature was vastly different.

Assuming that each model is adequately representing each household, we can see that the combined influence of changing two variables simultaneously, has much greater influence on household water-related energy, than changing a single factor in isolation. That is, the combined influence of shifting from a 1minute shower with cold water temperature of 30 degrees to a 14 minute shower with cold water temperature of 5 degrees is an increase in water-related energy of up to 1,059%) (ie an increase from 1.7 kWh/hh.d to 19.7 kWh/hh.d) in HH5. This is far greater than is the sum of the influence of changing each factor (temperature and duration) individually. What is of particular interest, is that some households (e.g. HH5) display a far higher interaction effect than others. It is not immediately obvious why this is the case, however, it is likely to be associated with the combined influence of other parameters (factors) in conjunction with the two key factors examined in Table 5.

4. Discussion

We recognise that the seven households examined do not necessarily represent the wider community. In selecting the households we specifically sought a wide range particularly with regard to water use patterns and hot water system technologies.

With this caveat in mind, we explore below what could be inferred, should the results from these seven households (coupled with the dataset of 5,399 shower records from a further 94 households) be generally representative of community-scale patterns – or at least the potential range exhibited by the community. We note up front however, that a much more comprehensive city-scale analysis would need to be undertaken to in order to make city-scale conclusions. However, such city-scale analysis needs to be informed by studies such as the present work, in order to compile necessary information at adequate resolution to draw conclusions. Specifically, the present work demonstrates how individual households vary widely, and consequently city-scale analysis of water-related energy, which is often based on “averages” across household types, is very unlikely to account appropriately for the wide range of individual system performance observed in this research.

The potential benefit to a city to pursue efficiency improvements in water related energy is significant. For example, if a 10% efficiency gain could be achieved in all homes across a city of 1 million people, the energy gains to that city would be in the order of 15 MW, which is equivalent to 90% of hydroelectric power plants, or all gas reciprocating plants in the state of Victoria.

4.1 Implications for Behaviour

Behavioural traits were collectively more influential than technological parameters. This was particularly evident with water use, where nine of the thirteen most influential parameters were behavioural. For water-related energy use, behaviour influenced around half of the most significant parameters. Technological, structural and environmental factors collectively had less influence than behaviours.

More factors influence water-related energy use than water use alone. This occurs because every parameter that influences water use, also influences water-related energy, but additional parameters are also relevant to water-related energy (such as water temperatures, energy conversion efficiencies and loss factors). This observation gives insight that managing water-related energy use is more complex than solely managing water consumption in cities.

Considering that the residential sector is responsible for over half the water consumption of cities (National Water Commission, 2014) and that showers are the largest water users in residential homes, behaviour and/or technological changes within showers, and associated hot water systems, could have a significant influence on urban water flows and related energy.

Many water conservation programs target shower duration. This analysis demonstrates that of all parameters, shifting shower duration is likely to have the largest impact on water-related energy within households because (i) the parameter has a strong impact on energy and (ii) a wide range of behaviours are evident. This means shower duration is a strong lever which can shift energy use significantly. A similar, though a less striking influence was seen by changing shower flow rate and number of showers per day.

Shower temperature can also significantly influence household energy use. But how flexible are water users with regard to changing shower temperatures? Changes in temperature could influence the “enjoyment” of showering for some people and it is possible that there is relatively little scope to influence this parameter. The temperature of showers for adults is a parameter of strong effect which has largely been previously ignored, however, the temperature of showering appears quite specific for each individual. Our monitoring demonstrated a wide range of actual shower temperatures though relatively consistent temperatures for individual adults.

In general, shower temperatures for children were lower than shower temperatures for adults. Shower temperature profiles for individuals (Appendix A) indicates that the warmest overall showers were taken by a 14-year old girl. Consequently, for modelling shower energy use, a lower cut-off range for “children” would likely be more appropriate, e.g. perhaps at 12 or even 10 years of age.

Because showers influence a large proportion of water-related energy, showers are also responsibile for a larger proportion of energy losses (e.g. via hot water systems heating, storage and distribution losses). This makes showers also a good target to consider integrated assessment of water-related energy use and associated losses in order to identify least-energy, least-GHG, or least-cost solutions. For water conservation programs seeking to influence energy use, it would be strategic to understand the household behaviours and technologies in place, in order to have the greatest influence (i.e. to target specific solutions to specific households, based on their attributes).

Given the above, future more detailed studies could involve use of larger data sets focussed on the key parameters identified in this study. It could also include trials of behavioural change with related monitoring of energy consumption impacts. The work also suggests that improved monitoring of shower temperature and hot water system energy use would be of high value.

4.2 Implications for Technology

While behavioural changes may warrant consideration for combined water and energy savings programs, it is also possible that new technological solutions offer potential to minimise water-related energy without influencing shower enjoyment. For example, a range of high-efficiency showers with standard flow rates of 7-9 L/min are currently on the market, and most emphasise their potential to influence water use, however, impacts on household energy use are less clear.

Some new technologies claim significant savings to the shower water and energy consumption (up to 70-90% reduction in both). This is achieved by either recycling water, or enabling heat recovery, or both simultaneously. Rather than directing warm wastewater to sewer, some technologies recycle around 70% of the wastewater flow treating it rapidly and consequently reusing the heat stored in the wastewater. Such technologies differ to shower systems which focus on heat recovery alone, e.g. through the use of heat exchangers. It is also different to showers which recycle only the water, and not the embodied energy, for example by capturing waste shower water and reusing it after slower treatment, when the water has cooled.

In a recirculating shower, for example, in a six-minute shower, with a user flow-rate of say 10 L/minute, 7 L/minute would be reused each minute, meaning the effective draw of fresh water is only 3 L/minute. Further, the water recycled at 7 L/minute is typically warm ~35°C meaning less new energy is required for heating this fraction of water used in the shower. Detailed analysis of the operational and life-cycle costs and benefits of new shower technologies would appear strongly warranted given that this research has identified the strong significance of showers to water-related energy.

For global studies of the energy impact of existing and/or new technology showers, the combination of temperature of showers and cold water is expected to be particularly important. Considering both parameters would help differentiate the influence in colder areas (e.g. where water is also cold).

4.3 Implications for City-scale Analysis and Future Buildings

The results have implications for city-scale analysis and future buildings. Firstly, the strong influence of cold water temperature on household energy emphasises the need for consideration of this factor in any comparison of studies from different regions. As individual cities can span considerable areas and in some cases elevations, analysis of the spatial and temporal influence of cold water variability appears warranted. Managing variability. City-scale characterisation and quantification of water-related energy will be improved if it focusses on the parameters identified in this work. Water consumption, wastewater generation and water-related energy could be substantially influenced by programs focused on shower water use and related hot water systems efficiency losses. In addition to the household-specific factors identified here, there is a need to understand how cities perform and respond: how the mix of future building types will influence water-related energy.

The influence of temperature of cold water also suggests that technology options which pre-warm the cold water entering the hot water system (e.g., by using household waste heat such as in warm wastewater, for example by heat coils or exchangers), could influence household energy use. A range of companies using this, indicate that up to 70% less energy use is possible in the shower (and hot water system), when warm water can be rapidly recycled, effectively reusing the water and the energy embodied in the water. Finally, while it may appear self-evident to include the temperature of cold water in studies of energy use in water-using appliances, this is not evident in the few observable papers addressing, for example, global electricity consumption associated with clothes machines (Pakula and Stamminger, 2010). Additionally, taking into account the potential range and anticipated variability in shower water temperature (along with other key variables) will help improve estimates of water-related energy. It will also help improve estimates of the potential for energy, cost and GHG savings associated with technological or behavioural changes within households.

4.4 Limitations

This study has focused on modelling seven individual households in order to characterise a to extend knowledge of household water-related energy variability. These seven households have been “coupled” with observations of 5,399 shower events (a key factor influencing performance) in a further 94 households to extend the range of the observations of variability. However, we definitely make no claim that the selected households are “representative of the wider community”. Given the significance of the variability observed, our view is that it would be almost impossible for any study to identify a representative household. While the individual results are particular to the seven individual households studied, our identification of parameters which are consistently important across these households gives greater confidence that those parameters will be also of greater importance in the wider population. This hypothesis this needs to be confirmed with further more detailed city-scale analysis. Other households may perform differently and some will almost certainly fall outside the range of results identified in this study.

5. Conclusions

This research has identified the key factors influencing residential water-related energy in seven highly characterized individual households. Key factors of influence included shower temperature, shower flow-rate, shower duration, shower frequency and number of adults.

Energy use for showering varied from 0.2-4.6 kWh/person.d. Sensitivity analysis demonstrated how a 10% change in key shower parameters influenced 0.1–0.9 kWh/hh-person.d or 0.2–2.6 kWh/hh.d energy use. This is equivalent to a 2–3% of total household direct energy use.

Parameter variation (guided by results from 5,399 shower events in a further 94 households) demonstrated that shower flow duration, and shower flow rate have the most scope for change, in order to influence household water-related energy. High variability was observed. For example, in "moving" shower duration to the 50th percentile value of the 94 households (6.8 minutes) reduced water-related energy for three households by approximately 5 kWh/hh.d. However, it also increased water-related energy for two households by some 2.5 kWh/hh.d. Behaviours were shown to have the greatest number of factors influencing water-related energy. Small changes to existing technologies within the household can also influence water-related energy substantially.

The identification of key factors in this paper will help improve accuracy of city-scale modelling and management of water-energy. The high household-to-household variability observed suggests a thorough understanding of household-level factors is necessary to support robust city-scale analysis.

A strong and consistent influence of cold water temperature was demonstrated across all seven households studied. A shift in the temperature of cold water by 2.0°C was shown to influence 0.1-0.4 kWh.hh-person.d (or 0.5-1.0 kWh/hh.d). This suggests that further attention to the influence of water temperature on household energy use is warranted.

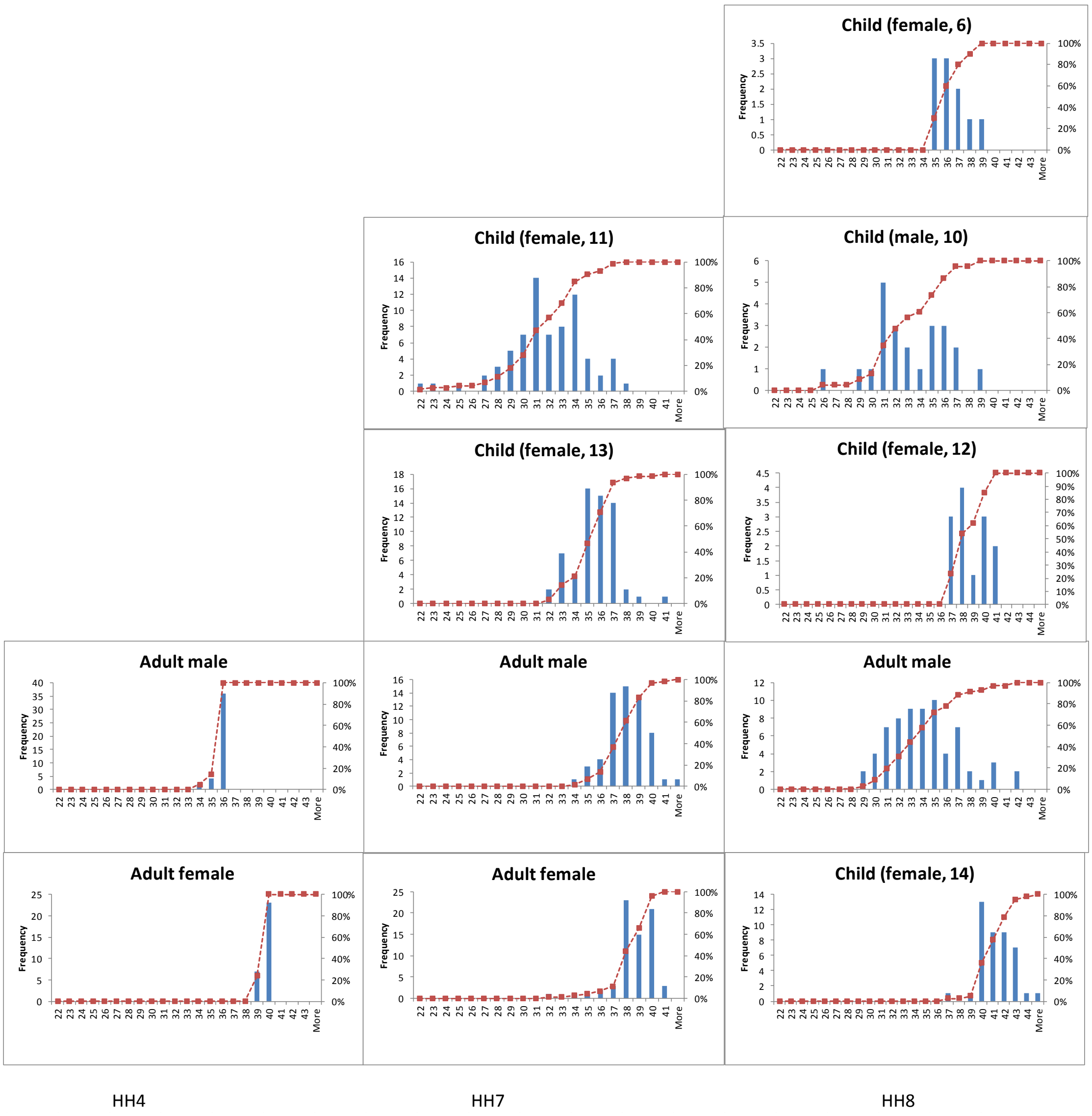
Combined parameter variation demonstrated a strong, and variable interaction effect, between shower duration and cold water temperature on household water-related energy. This suggests that programs aiming to influence water-related energy need to be aware of how the major factors of influence, interplay to either amplify, or diminish, the intended energy saving effect of water conservation measures.

Increased knowledge of water-energy interactions within households will contribute to a clearer understanding of the role of water demand management in reducing system-wide energy use and greenhouse gas emissions. It will also help in the design and management of future, low-energy households and cities.

6. Acknowledgements

The authors acknowledge the support of the Australian Research Council and Smart Water Research Fund (Grant Numbers LP120200745 and DE160101322). We thank ETH Bits to Energy Lab for provision of Amphiro Meters, our industry partners (Yarra Valley Water, South East Water, and City West Water) for input to the study, and Peter Roberts in particular. Kristiane Fox for her input to analysis of Amphiro data and several anonymous reviewers for comments on earlier drafts.

Appendix A: Probability Distribution Functions for Shower Temperatures for individuals.



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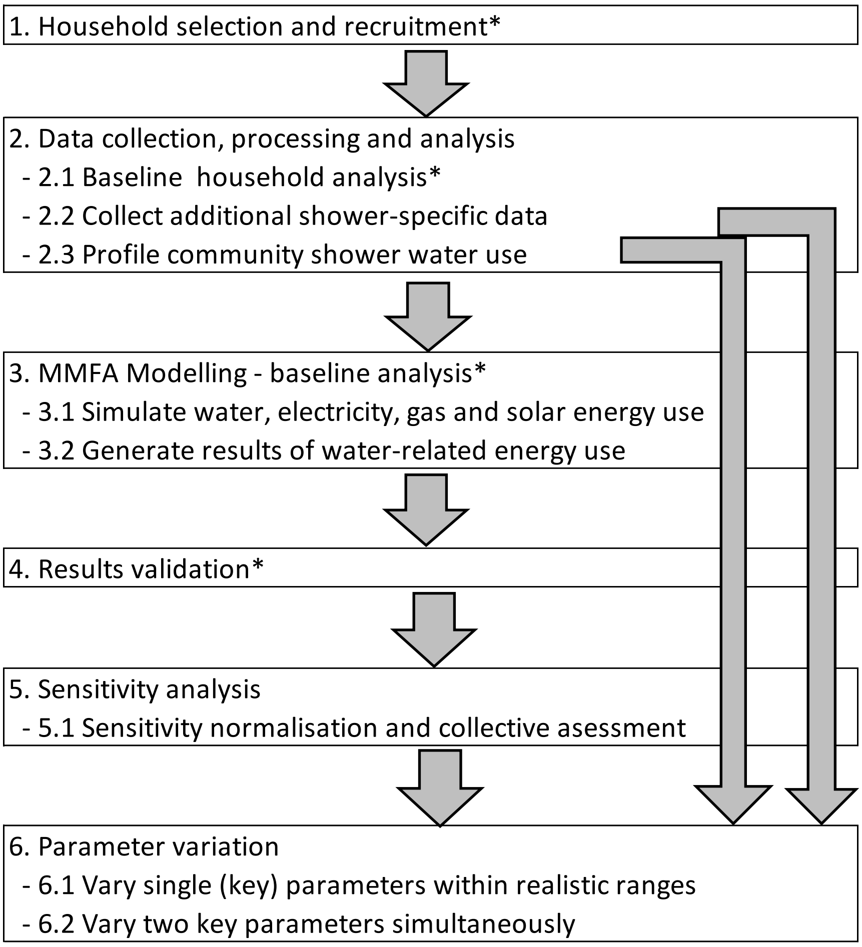


Figure 1: Overview of research and modelling process. *(See Binks et al 2016)

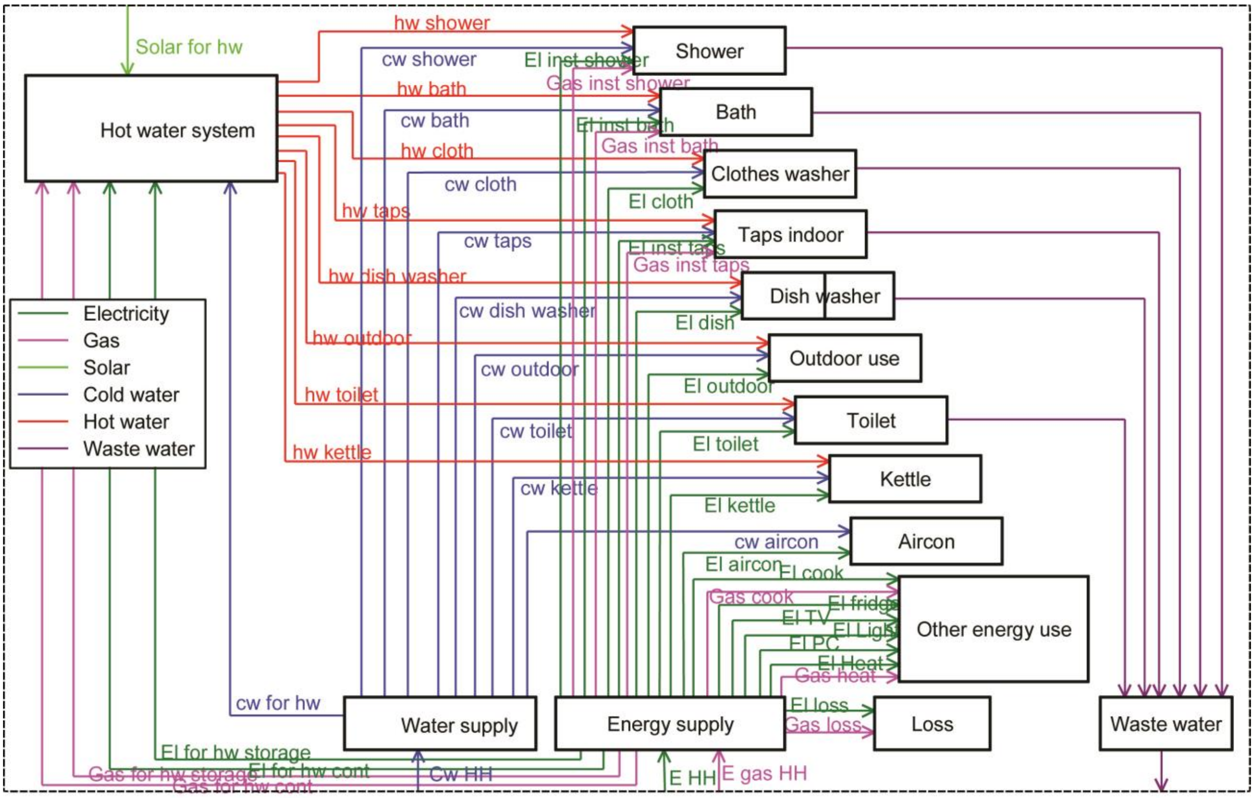


Figure 2: Overview of the ResWe model sub-systems and illustration of hot water (hw), cold water (cw) electricity (El) energy, gas energy (E gas), and wastewater flows.

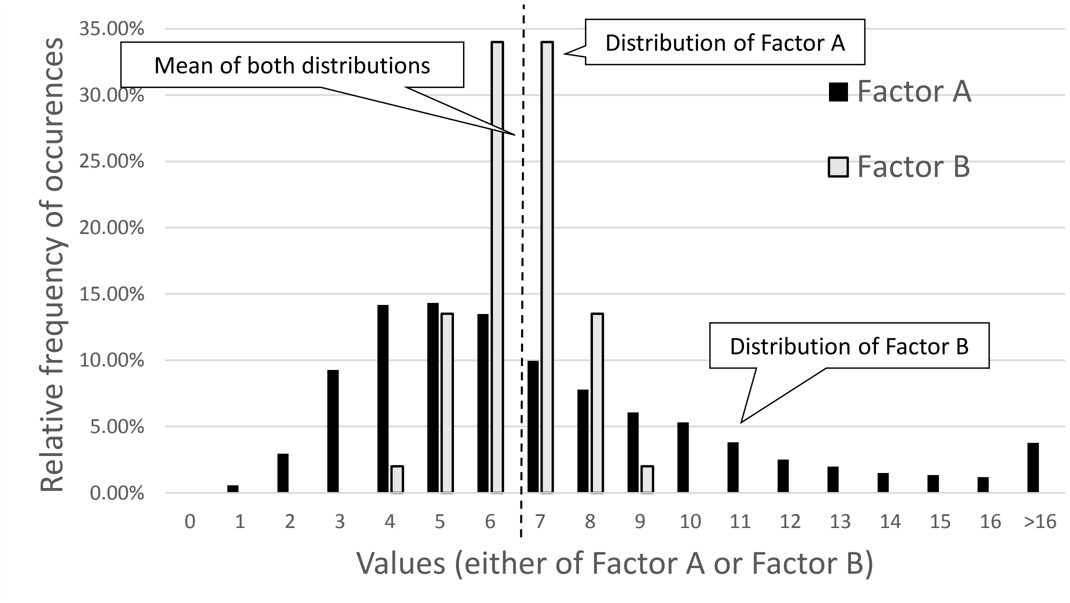


Figure 3: Illustrative example of probability distributions for two Factors (A and B), with the same mean, but different ranges.

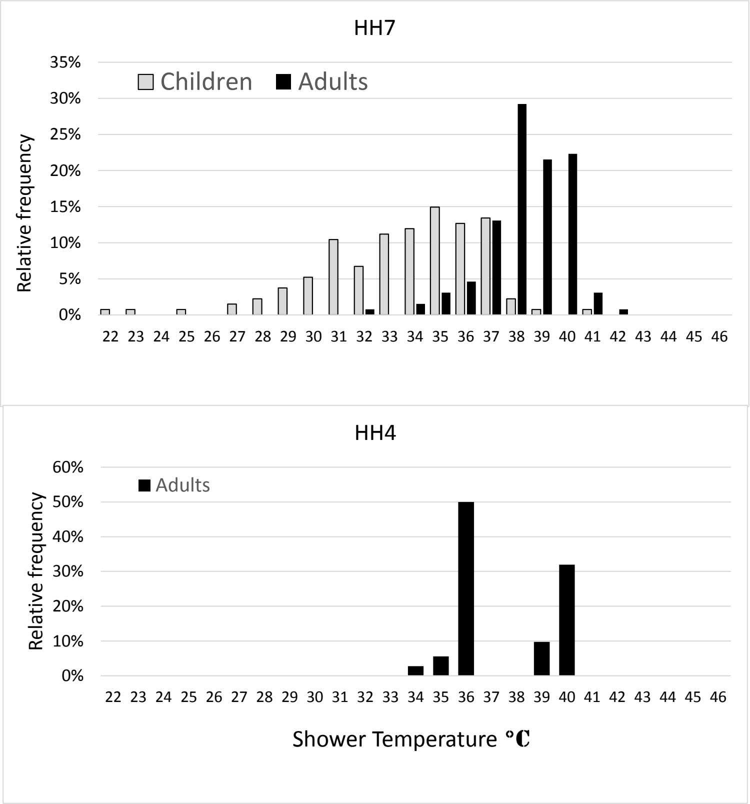


Figure 4: Shower temperature distributions for HH4 and HH7.

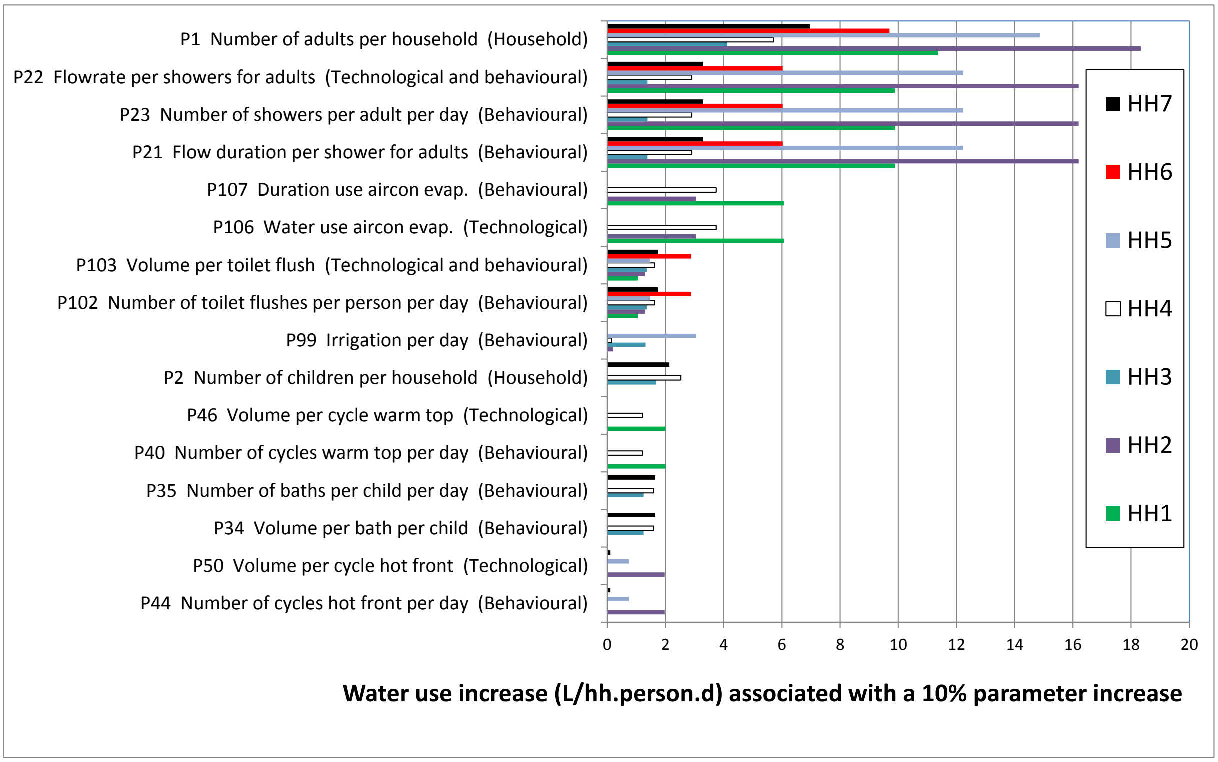
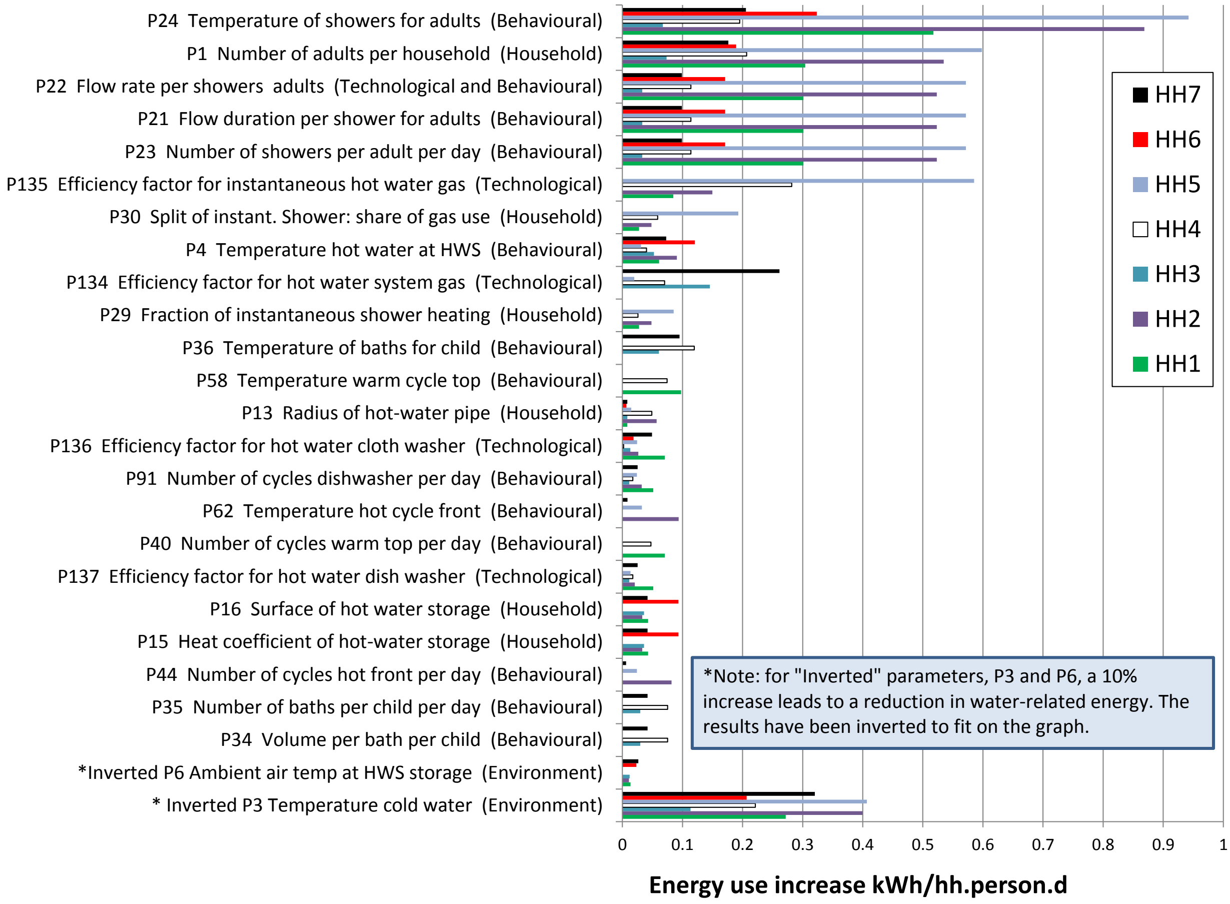


Figure 5: Household water use sensitivity normalised by occupancy.*

* Figure 5 only shows those parameters (of the 139 assessed) which had a collective influence of more than 3 L/hh.p.d (across all seven households) associated with a 10% change in the parameter).



*Note: for "Inverted" parameters, P3 and P6, a 10% increase leads to a reduction in water-related energy. The results have been inverted to fit on the graph.

Figure 6: Household water-related energy use sensitivity.*

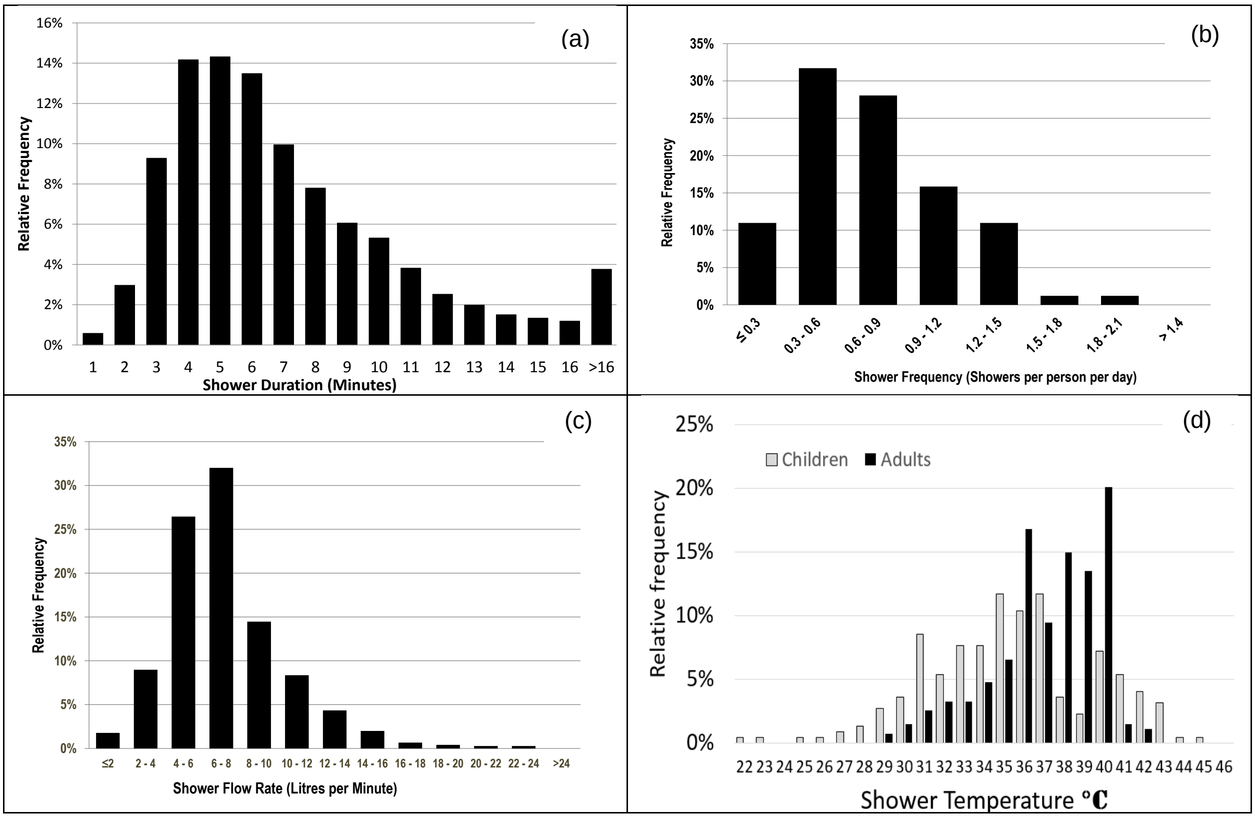


Figure 7: Shower (a) duration (b) flow rate (c) frequency and (d) temperature distributions for the community in the vicinity of the households studied (based on survey of 94 households (5399 shower events) for shower flow rate, shower flow duration and number of showers per day) (Roberts, 2012) and based on survey 491 shower events (three households) for shower temperature (refer to Table 4 of this present paper).

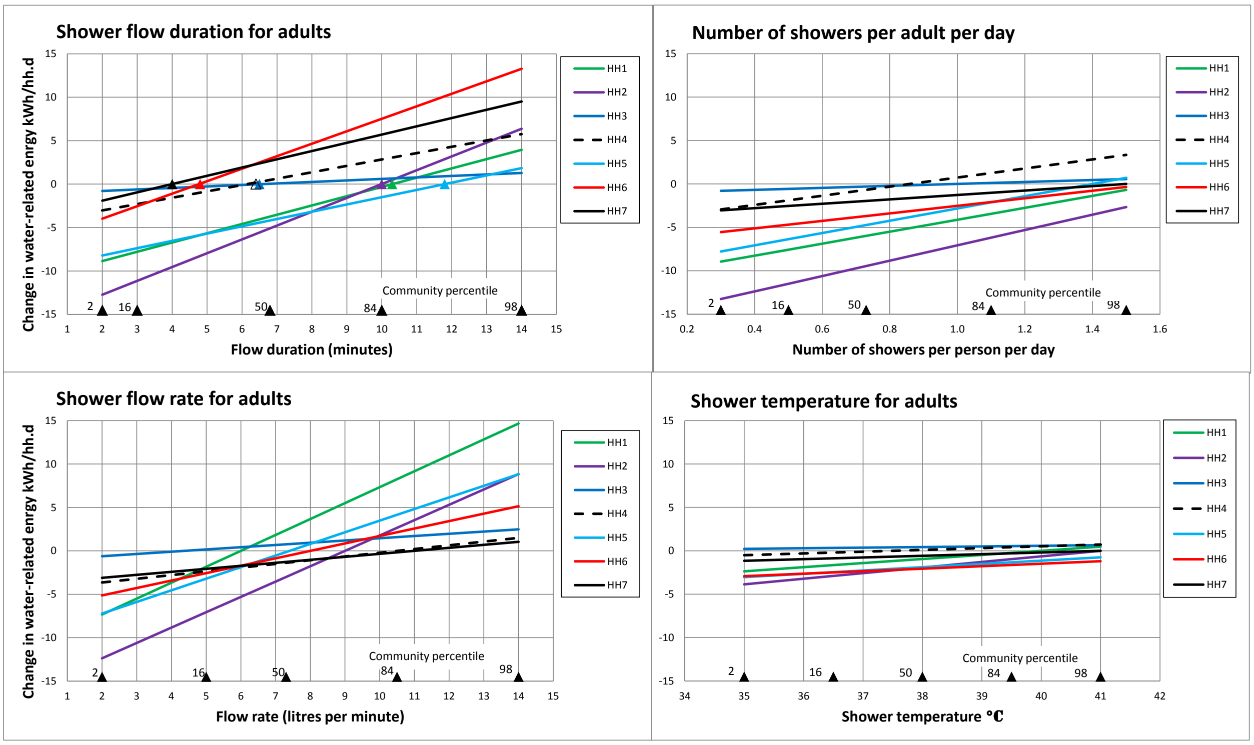


Figure 8: Energy use change in each household (kWh/hh.d) associated with changing key parameter values through the range observed in the community.*

Table 1: Summary of key household attributes*

ID	Residents (Adult **/Child**)**	**Type and Age of House**	**Hot Water System**	**Clothes Washer**	**Heating**	**Cooling**	**Cooking**	**Rain Water Tank**	**Outdoor Water Use**
HH1	4 / 0	Large brick, 2 storey, 50+ years	Solar storage + gas instant.	1 front load, 1 top load	Gas (central)	Evap (central)	Gas stove, Electric oven	No	Minimal hand watering
HH2	4 / 0	Large brick, 2 storey, 2 years	Solar storage + gas instant.	1 front load	Gas (central)	Evap (central)	Electric stove and oven	No	Drip irrigation
HH3	2 / 2	Small weatherboard, 1 storey, 20+ years	Gas storage	1 front load	Gas (central)	Electric (wall mount)	Gas stove, Electric Oven	Yes	Manual RWT**
HH4	2 / 2	Medium weatherboard, 1 storey, 58 years,	Gas instant.	1 top load	Gas (central)	Evap (central)	Gas stove, Electric oven	Yes	Manual RWT**
HH5	2 / 0	Large brick, 1 storey, 20+ years,	Gas instant.	1 front load	Gas (space)	None	Gas stove and oven	No	Drip irrigation
HH6	4 / 0	Medium weatherboard, 1 storey, 100+ years	Electric storage	1 top load	None	None	Electric stove and oven	No	None
HH7	2 / 2	Medium weatherboard, 2 storey, 100 years upper floor, 15 years lower	Gas storage	1 front load	Electric (reverse cycle), Gas (space)	Electric (wall mount)	Gas stove, Electric oven	Yes	No

*For details see Binks et al (2015 Submitted). **Children were considered as 14 years or younger. ***RWT Manual Watering from rain water tank.

Table 2: Summary of key parameters used**

Total Use	**Units**	**HH1**	**HH2**	**HH3**	**HH4**	**HH5**	**HH6**	**HH7**
P1 Number of adults per household**	Occupancy	3.65	3.04	1.65	2.07	1.73	4.01	1.92
P2 Number of children per household**	Occupancy	0	0	1.77	1.88	0	0	1.93
P3 Temperature of cold water	°C	16.7	16.3	16.3	15.6	16.9	21.3	21.3
P21 Flow duration per shower for adults	Minute	10.3	10.0	5.8	6.1	11.8	4.8	4.0
P22 Flow rate per shower for adults	Flow rate (L/min)	6.0	9.0	4.4	10.5	7.4	8.0	11.0
P23 Number of showers per adult per day	Showers/day	1.6	1.8	0.9	0.9	1.4	1.6	1.5
P24 Temperature of showers for adults	°C	40	41	32	38	43	45	41

* For details see Binks et al (2015 Submitted).**Fractions are based on periods of absence from the house (e.g. for holidays or travel).

Table 3: Summary of key modelled results*

Total Use	**Units****	**HH1**	**HH2**	**HH3**	**HH4**	**HH5**	**HH6**	**HH7**
HH location		**Melbourne**					**Brisbane**	
Water	L/hh.d	733	737	305	545	333	460	465
Electricity***	kWh/hh.d	12	20	12	14	7	17	12
Natural Gas***	kWh/hh.d	50	130	40	86	42	-	7
Solar Hot Water	kWh/hh.d	8	14	-	-	-	-	-
Total Energy	kWh/hh.d	70	164	52	100	49	17	19
Total WRE****	kWh/hh.d	16	21	7	15	12	13	15
WRE as % of total empirical energy use		23%	13%	13%	15%	24%	76%	79%
Shower WRE****	kWh/hh.d	9.8	14.1	0.8	4.5	6.4	6.7	4.0
Shower percentage of WRE		61%	67%	11%	30%	53%	52%	27%
Occupancy	Adults+Children	3.65	3.04	3.42	3.95	1.73	4.01	3.85
Total WRE****	kWh/pp.d*	4.4	6.9	2.0	3.8	6.9	3.2	3.9
Shower WRE****	kWh/pp.d*	2.7	4.6	0.2	1.1	3.7	1.7	3.6

*For details see Binks et al (2015 Submitted). **Per capita values are based on total occupancy (Adults + Children) from Table 2 accounting for absences and periods of extra visitors. ***Empirical results based on electricity and gas utility records.****WRE – water-related energy (household energy use influenced by water).

Table 4 Summary of results of shower water temperature characterisation.

Household	Subject	Sex	Age	Count	Avg. Volume Extracted (L)	Std Dev Volume	Avg. Temperature (◦C)	Std Dev Temperature (◦C)	Minimum Temperature (◦C)	Maximum Temperature (◦C)
HH7	Adult	M	>14	60	29	14	38	2	34	40
HH4	Adult	M	>14	42	38	9	36	1	34	36
HH8	Adult	M	>14	68	27	5	34	3	29	42
HH4	Adult	F	>14	30	104	26	40	0	39	40
HH7	Adult	F	>14	70	44	20	39	2	32	41
HH8	Child	F	14	42	55	16	41	1	37	43
HH8	Child	F	12	13	43	20	39	1	37	41
HH8	Child	M	10	23	27	7	33	3	26	37
HH8	Child	F	6	10	36	14	36	1	35	39
HH7	Child	F	13	62	39	14	36	2	32	37
HH7	Child	F	11	71	23	18	32	3	22	38
		Total		491						
Totals (Demographic)										
Adult male				170	31	9	36	2	32	39
Adult female				100	68	21	40	1	36	41
Child				221	34	14	35	2	22	43
		Total		491						
Total (Households)										
HH4				72	71	37	37	2	34	40
HH7				263	33	19	36	3	22	41
HH8				156	38	17	37	4	26	43
		Total		491						

HH4: Melbourne, sampling period: 18 August to 1 October 2013. HH7: Brisbane sampling period 8 September to 15 December 2013. HH8: Brisbane sampling period 18 September to 15 December 2013.

Table 5: Interaction between two key factors on household water-related energy.

	Cold Water Temperature				
	30°C		5°C		
	Shower Duration (minutes)				
Household number	1	14 (Ex)	1 (Ey)	14 (Exy)	Interaction Effect
HH3 (WRE (kWh/hh.d)	3.3	3.6	8.7	12.5	106%
% increase from 1 minute 30 °C		9%	164%	279%	
HH4 (WRE (kWh/hh.d)	6	9.3	15.7	29.9	182%
% increase from 1 minute 30 °C		55%	162%	398%	
HH5 (WRE (kWh/hh.d)	1.7	7.2	3.8	19.7	612%
% increase from 1 minute 30 °C		324%	124%	1059%	

*This is the difference between the combined effect (E (xy)) and the sum of the individual effects (E (x) +E (y)).