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Water-related energy in households: a model designed to understand the current state and simulate possible measures

Kenway, Steven. J.; Scheidegger, Ruth; Larsen, Tove A.; Lant, Paul; Bader, Hans-Peter.

Abstract

Energy use and the associated greenhouse gas emissions are very high in industrialised countries. Energy use in households, including private transport, accounts for about 30% of primary energy. Therefore households are important key drivers of energy use and related greenhouse gas emissions. To influence household consumption, it is important to gain an insight into the different uses within the household. One of these uses is water and water-related energy, which is the topic of this paper.

To address this topic, a detailed mathematical flow analysis of materials, energy, CO_2 emissions and costs (MMFA) for household water use was set up and tested for a specific family household in Brisbane, Australia. The simulation results for the current state of this household were well within 20% of the monitored data. After calibration, a detailed scenario investigation was performed to determine the impact of (i) potential and (ii) realistic reduction values for all relevant (a) behavioural and (b) technical parameters, including a shift from gas to a solar hot-water system. The reduction potentials for water use, greenhouse gas emissions, water-related energy consumption, water costs and water-related energy costs were 4-77%, 14-85%, 15-93%, 1-31% and 13-90% respectively, depending on the measures taken. The study showed that for this specific household, technical improvements alone, without changing to a solar hot-water system, result in less than a 15% change in terms of energy and greenhouse gas emissions. In contrast, combined behavioural and technical changes have a much higher reduction potential. The model is designed so that it can also be used to simulate other household types as well as whole cities.

Keywords: Water, energy, greenhouse gas emissions, material flow analysis, modelling.

1. Introduction

The consumption of energy and the associated greenhouse gas emissions are very high in industrialised countries. In Australia, primary energy consumption in 2007-08 was about 8 kW per person (around 68,000 kWh per person and year or 1,463,900 GWh/year of total domestic use [1, 2]). This is around four times higher than the global average of 2 kW per person [3]. This figure has been suggested as the future goal for countries currently consuming high amounts of energy. The unit of W per person is a convenient way to measure and compare energy consumption. A figure of 1kW per person corresponds to 8,760 kWh per person and year. This consumption unit was introduced in the "trilennium symposium" held in Japan in 1996 [4] to characterise a society according to its energy consumption.

The corresponding figure for greenhouse gas emissions (from energy consumption) for Australia is about 26,500 kg CO_2 equivalent per person and year (576×10^6 t per year for the whole country [5]).

Like other countries, Australia has set targets for reducing these emissions. In order to reduce energy consumption, an overview and insight into its different contributions is necessary. Private households in Australia consumed about 19,700 kWh/person and year of primary energy corresponding to about 2.2 kW/person. This includes private transport, which accounts for about 11,000 kWh/person and year (1.3 kW/person) [1]. Industry consumed about 32,600 kWh/person and year of primary energy (3.7 kW/person), including industry-related transport. Commercial and public services, agriculture and forestry, fishing and non-energy use account for the rest (1.8 kW/person).

According to [6], water-related energy consumption in Australian cities accounts for about 6,800 kWh (or 10%) of total primary energy per person (0.78kW/person). Households account for about 30% of water-related energy consumption. This amounts to 2,040 kWh per person and year (0.23 kW/person) of primary energy (10% of primary household energy).

Private households are important key drivers since they can determine their consumption in two ways: i) directly by regulating their direct energy consumption (mobility, heating/cooling, housing etc.), and ii) indirectly by regulating their grey energy consumption (amount, origin, quality and lifetime of everyday products).

This study consequently focuses on private households, and in particular on their water-related energy consumption and greenhouse gas emissions. Unlike sectors such as mobility, heating/cooling and communications, water-related energy consumption in households has not been studied very intensively. Household water use is very important in itself quite apart from the aspect of energy consumption. From 2001-2008, the historic "millennium" drought [7] made the citizens of Australia even more aware of their limited water availability. Water consumption was drastically cut from about 300 to about 220 l per capita and day. More sustainable water consumption would have many advantages: a) reduction of water-related energy use and greenhouse gas emissions, b) lower costs for freshwater and wastewater, c) less infrastructure and lower costs for water infrastructure.

In the past ten years, few studies have been undertaken that focus on water-related energy in households. Cheng [8] investigated the relationship between water use and energy consumption in buildings. He found that 84% of water-related energy (including energy for treatment and transport of water and wastewater) is used for water heating, and the largest share comes from taking showers. He also suggested that energy loss (water cooling in pipes, boilers) could be significant. Arpke [9] used data mining to model four household types in the US Midwest to show that energy uses for heating water comprised 97% of water-related energy.

Flower [10] developed a model based on data mining to simulate three "average" household types in Victoria, Australia, having an instantaneous hot water system running on either i) electricity, ii) gas storage or iii) natural gas. The model was based on the work of Arpke [9], other previous studies [11-17] and data mining. He found that 86-90% of the energy consumed in the urban water cycle is used for water heating in households. The operation of mechanical appliances accounted for 6-8%. Less than 4% of the energy was associated with the treatment and transport of water and wastewater. The hot water energy use was dominated by showers followed by washing machines and indoor taps. Greenhouse gas emissions were also dominated by showers, followed by washing machines. Showers and washing machines constituted a particularly large fraction of total water-related greenhouse gas emissions in households with an electric hot water system. In households with a natural-gas hot water system, the greenhouse gas burden of showers and washing machines was followed much more closely by emissions from dishwashers and evaporative air-conditioners. Flower extended his findings for the three household types to a city-scale assessment using probability distributions to include variations between single households.

The aim of this study is to develop and apply a model for water use, water-related energy as well as related CO_2 emissions and costs that is applicable to any single household as well as on a city scale. The model should take into account all relevant contributions to residential water use. It should provide a system understanding of water-related household activities and should answer the following questions:

(1) What are the most relevant contributions to water use, water-related energy use and greenhouse gas emissions in households?
(2) What are the key drivers of these flows?
(3) What possible measures could be applied to reduce these flows?

Moreover, the model should improve the basis for household monitoring and contribute to the development and design of more sustainable homes of the future.

The model is a systematic description of all residential water and water-related energy use. Each use was broken down in terms of its key driving factors. This provides a profound system understanding and allows any change in technology and behaviour to be analysed at household level.

2. Research Method and Model

In this study, we used a mathematical material flow analysis (MMFA) to quantify the household flows of water and energy. The approach is an extension of the classical MFA developed in the economic sector in the 1950s [18] and later adapted to regional investigations [19]. More recently, it has been applied to solving diverse environmental problems [20-22]. As pointed out by Schaffner et al. [22], the key benefit of the method is its ability to provide an understanding of the system based on current knowledge using often scarcely available data rather than conducting large monitoring and data collection campaigns. The method further aims to identify the key parameters (driving forces) involved. This is crucial for discussing possible measures (scenarios) to reduce the flows. The MMFA comprised the following steps:

1) System analysis
2) Mathematical model
3) Data collection and calibration
4) Simulation including uncertainty analysis, sensitivity analysis and scenario calculations.

2.1 System analysis

The system border and the balance volumes and flows appropriate to the system have to be defined. The aim was to describe not only one specific household but the most common types found in Australian cities. Therefore the system had to be designed to include different supply systems (electricity, gas, etc.) for the equipment as well as different equipment (e.g. top or front-loading washing machines). On the basis of our analysis, we set up the system shown in Fig. 1. The core of the system comprises ten "service" subsystems shaded in grey. The subsystems provide the households with water-related services such as drinking water, water for laundering and dishwashing, water to flush toilets etc. The exception is the “other energy” subsystem which captures all other major household energy-using services. The “service” subsystems are supplied with water and energy from the supply subsystems.

Wastewater from the “service” subsystems is discharged to the wastewater subsystem. The associated major flows of cold and hot water, energy and wastewater were identified. In order to validate the findings against household water and energy use records, all significant water and energy uses in the household must be included in the analysis.

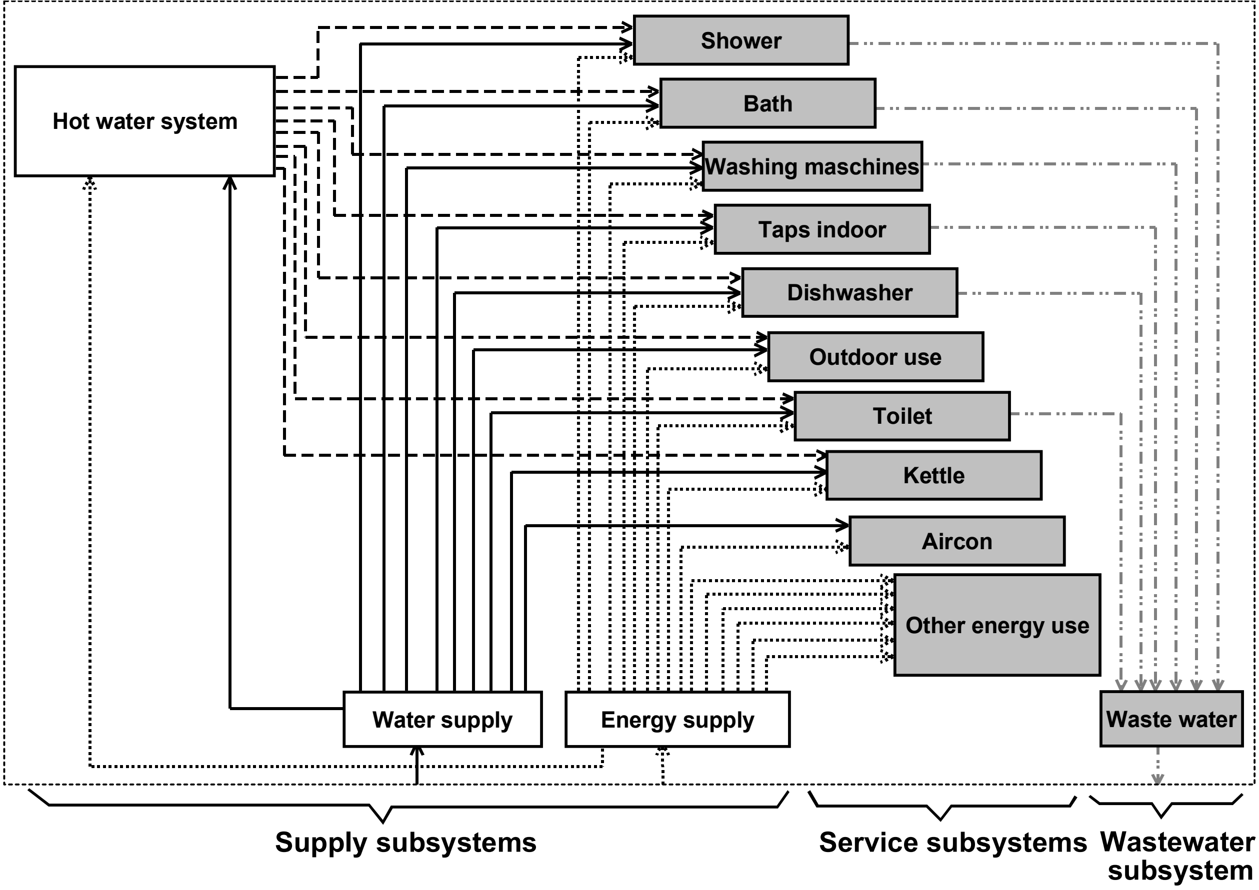

Figure 1: Scheme of the system showing tracked service, supply and wastewater subsystems and flows including cold water, hot water (dashed), energy (dotted), and wastewater (greyed).

Importantly, by tracking each individual flow, the approach creates a wide ability to assess and consider the influence of detailed alterations at subsystem level, such as including altered technologies, behaviours or environmental conditions.

2.2 Mathematical model

The model equations describe the present knowledge of the system.

We have chosen a “demand-driven” approach. This means that the specific demands on cold and hot water of the different subsystems providing the service required by the households are at the core of the model. For example, each individual resident requires a certain “shower service” characterised by duration, temperature of water, flow rate and frequency per day (shower parameters). This detailed approach is challenging as it requires information on a large range of parameters. Clearly, each subsystem can be influenced by a) the behaviour of the residents, b) water-using technologies and fittings, c) physical environments, d) plumbing configurations, e) building design and associated losses or gains, and f) water heating systems and energy sources. In combination, this diversity demands the systematic assessment of a wide range of parameters in order to thoroughly understand water-related energy use and greenhouse gas emissions.

According to this approach, the equations can be classified as follows:

i) “Demand” equations: (see Appendix A for the example of showers)

The water demand to provide the service required by the residents is formulated as a function of the parameters describing the amount per day per person or household (split into sub-parameters such as amount per service, frequency of service) and the temperature of the water. The corresponding energy demand is simply calculated from the calorimetric equation for water.

ii) "Supply" equation:

The supply of water and energy is exactly the sum of the demands by the individual subsystems.

iii) "Loss" equation: (see Appendix B)

Physical equations are used for the energy loss in storage and pipes.

In mathematical terms, this set of equations is an appropriate parameterisation of the water, related energy, CO_2-equivalent and cost flows. The parameters represent either the behaviour of the residents (such as shower duration, frequency or temperature), the technical state of the water and energy system (such as heat loss coefficients) or environmental conditions (such as cold-water temperature). The selected approach is a stationary one, since we are interested in daily flows averaged over one year or one season. A dynamic approach would be required to simulate the time when water and energy are needed for the different household activities, but that is not the focus of this study.

Some water use was modelled as being directly proportional to household occupancy numbers, e.g. showering, bathing and teeth cleaning, whereas other water uses were considered to be "collective" or better characterised at household level. Examples include the number of cleaning events, the number of dishwasher or washing machine cycles, lawn watering or swimming pool filling. We adopted this approach because it identifies underlying system drivers and enables detailed changes in policy, technology, environment or behaviour to be analysed.

The washing machine subsystem was considered in particular detail because it had been identified as having significant water and energy use and was recommended for detailed analysis [10]. This system was characterised by (i) technology type (front or top-loading), (ii) number of cycles per day, (iii) cycle temperature, (iv) cycle water volume (v) and cycle mechanical/pumping energy use. Washing machines and dishwashers required case-specific demand equations to identify if the machine was plumbed to cold water only, or to both hot and cold water. In the latter case, the appliance itself uses less energy because it draws on the hot water system. In the former case, the operational energy is much higher and includes the heating of water by electricity within the appliance.

The model was structured to accommodate households which use instantaneous hot water systems as well as storage heaters to enable better characterisation of losses. Because some household functions (e.g. cooking) draw on both electricity and gas energy sources, a parameter was included to identify the relative proportion or "split" between these two. This enabled more accurate characterisation of total household gas and electricity use, which could then be compared with household records.

As already emphasised in Section 2.1, the model approach is general in the sense that it applies to the most common types of households. The model for the different household types is the same, only the set of parameters changes across different household types. This was the challenge for the development of the model, and led to a large set of parameters.

The model was implemented in the simulation program SIMBOX [23]. A Newton-Raphson iteration algorithm was used to solve the equations.

3. Data collection and calibration for the case of the "Milton Household"

In this study the model will be calibrated for a specific household, known as the "Milton household". The procedure would be the same for a different type of household.

3.1 Data collection

Parameters were characterised according to the best available information for a specific household in Milton, Brisbane. A period of relatively uniform water use (2007-2009) was selected (Figure. 2). Level 2-6 water restrictions were in place in Brisbane during this time. At Level 2, most outdoor water use (e.g. irrigation) was banned. At Level 5, residents were encouraged to reduce their use to 140 l/cap·d.

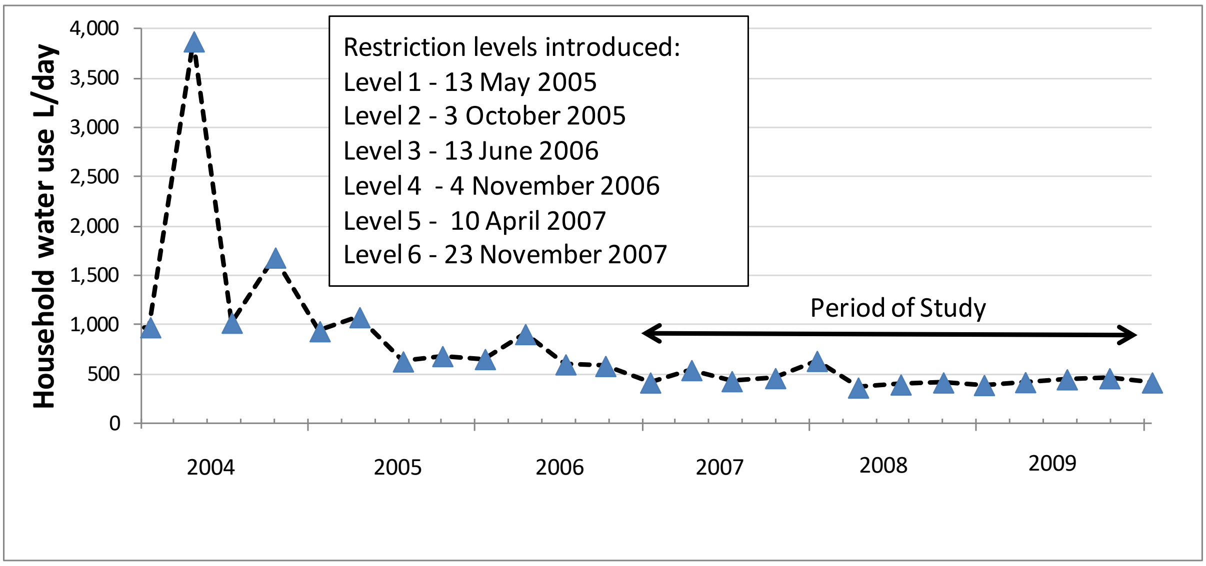

Figure 2: Water use in the household studied. A new water meter was installed in January 2003.

The calibrated parameter values describe an "average day". In this context, this means that the water and energy use over long periods (a month to a year) is divided by the numbers of days in the period. To determine these parameter values required accounting for "average" behaviour and conditions over the three years, and representing this as a daily value. We took this approach because long-term trends were more important than day-to-day changes for our purpose. However, day-to-day changes are addressed by the variability from day to day (see below). We used time-series data for parameters such as cold-water temperature, number of showers per day and number of washing machine cycles per day. In the first case, these time series were available from the bulk water supplier (SEQ Water). In the latter case, they were based on information such as "how many warm front cycles per week" and "on which days per week was the front loader used". For data where no time series were available such as the shower flowrate, average values were estimated as described below.

Two adults and two children (aged 6-10) occupied the typical "Queenslander" five-bedroom house. Periods during which household members were absent or visitors were staying were accounted for in the total mean population of adults and children. The two-storey house (longitude: 153.03 degrees East; latitude: 27.48 degrees South, elevation: 15m) experiences a subtropical climate with an annual mean of 21.3 +/- 3.6℃ and a mean monthly minimum of 15.5 and maximum of 25.6℃.

Household members were interviewed to determine usage patterns and behaviours. Repeated measurements were performed for the shower and bath temperatures of adults and children, washing of dishes by hand and shaving water (Table 2). Appliance efficiency data was recorded from manuals or similar appliance data available on-line. Appliance plumbing to either the cold or both hot and cold water supply was confirmed by inspection. The natural gas hot-water storage was located outside. The front-loading washing machine and dishwasher are both plumbed to cold water only, and were 7 and 12 years old respectively at the start of the period.

Natural gas (37.7 MJ/m^3) is used in a cooker top. A small gas heater is used for a total of approximately 40 hrs per year during winter. Electricity from coal-fired plants meets all other energy demands including microwave and oven cooking, air heating and cooling. The household has no pool, spa, aquarium, or water-chilling devices.

Literature values are relied on for the relatively small number of parameters that could not be determined using the above measures. For example, carbon dioxide equivalents were determined on the basis of current rates for electricity supplied from coal-fired power plants (1.04 kg CO_2-e/kWh) and natural gas (0.197 kg CO_2-e/kWh), which are the average estimates in Queensland for the full fuel cycle [24].

The costs for water, electricity and gas were calculated according to the current tariff in Brisbane as shown in Table 1. In principle, the stepped tariff for gas is calculated quarterly. For reasons of simplicity we converted it to an annual tariff.

Table 1: Costs for Water, Gas and Electricity for Residential use in Brisbane, Australia.

	Fixed costs	Step 1	Step 2	Step 3	Reference
Water	155 $/y	0-255 m^3/y 0.62 $/$m^3$	255-310 m^3/y 0.66 $/$m^3$	>310 m^3/y 1.17 $/$m^3$	[25]
Gas*	186 $/y	0-20,278 kWh/y 0.083 $/kWh	>20,278 kWh 0.074 $/kWh	-	[26]
Electricity*	90 $/y	0.194 $/kWh	-	-	[27]

**Excluding the 10% Goods and Services Tax (GST).*

Note that in Australia the specific costs for water increase the more you use, in contrast to gas use. Electricity costs per kWh are not use-dependent.

3.2 Uncertainties of the data

As already mentioned above, the parameter values are daily averages. Nevertheless we calculate the uncertainty for an "**average day**" as well as for a "**single day**". According to their behaviour as a function of time, the parameters can be classified into three groups. The first group are parameters which are constant over time such as heat coefficients, radius and length of hot water pipes etc. The second group are parameters which fluctuate randomly around their average such as numbers of showers per day or loads of clothes washes per day. The third group are parameters which fluctuate around a function with a seasonal pattern such as the cold-water temperature.

To characterise the uncertainty of the parameters, we calculated or estimated the standard deviation (STDV), which is the square root of the variance. In the following, we call the STDV of an average day "STDV-average-day" and the STDV of a single day "STDV-single-day". The first quantity characterises the uncertainty of the annually averaged day and the second the uncertainty of a single day. As is well known from basic statistics, the STDV-average-day is the STDV-single-day divided by $\sqrt{N_{size}}$, where N_{size} is the number of data points (see Appendix C). Therefore for parameters of Group 1, where only one or a few data points are available, the STDV-average day and the STDV-single-day are identical. For parameters of Groups 2 and 3 however, where time series of at least a year are available, the STDV-average-day is at least $\sqrt{365}$ times smaller than the STDV-single-day. The reason for this is that for parameters in Group 2 the STDV-single-day represents the variability from day to day, which is "smoothed out" in the STDV-average -day by the factor $\sqrt{365}$ (see Appendix C). For parameters of Group 3, the STDV-single-day is in a good approximation of the superposition of the variability from day to day and the "seasonal variability" (see Appendix C).

Where data was available, standard deviations were calculated to obtain an estimate. In other cases, standard deviations were estimated after discussions among the authors based on their knowledge of the household, its occupants, technologies and prevailing conditions. Estimates for appliances considered the performance range of similar technologies of similar ages. Maximum and minimum values were estimated by considering typical extremes averaged over a large sample. A conservative approach was taken, so if the uncertainty estimate (deviation and upper and lower bounds) was questioned, it was broadened until better information became available.

3.3 Probability distribution of the parameters

Normal distributions were used for parameters with fluctuations such as indoor and outdoor temperatures or household occupancy numbers. Truncated normal distributions were used for fluctuating parameters whose lower and upper bounds were known, such as the temperature of the cold and hot water, and heat coefficients.

Log-normal and truncated log-normal distributions are used for parameters which are known to show an asymmetrical distribution towards higher values. Examples are the number of washes per household and day or the duration of cooling. Finally, uniform distributions are used for parameters which show a uniform probability within a certain range and zero outside it, such as the number of stand times in hot-water pipes. For uniform distributions, it can be shown that the minimum / maximum boundaries depend as follows on the mean and STDV: $X_{min} = Mean - \sqrt{3} * STDV$, $X_{max} = Mean + \sqrt{3} * STDV$.

3.4 Simulations of current state

The model equations were solved for the parameter set described above. Water, electricity and natural gas for the house considered were obtained from the local water and energy providers. This data served to validate the model. The results of the data collection and calibration are presented in Table 2 for all 132 parameters used to characterise the stationary model that was developed. Besides the average values, the standard deviation "STDV-average-day" and "STDV-single-day", the type of distribution, and for truncated distributions the lower and upper boundaries, are also shown.

Table 2: Calibrated parameters for the household. The table shows the distributions, means, STDV-average-day, STDV-single-day, lower and upper boundaries for truncated distributions, potential and realistic values for scenarios and the data source. Parameters marked with a "T" (red shaded) are "technical", "B" (blue shaded) are behavioural and "TB" are "technical with behavioural assistance" (green shaded). The terms "technical" and "behavioural" parameters are explained below in the scenario analysis section.

No.	Unit	Description	Probability distribution	Mean	STDV-average-day	STDV-single-day	Lower boundary (trunc)	Upper boundary (trunc)	P Value Potential	P Value Realistic	Data source and notes
	Parameters for the household										
1	[-]	Number of adults per household	tnormal	1.92	0.03	0.61	0	6	1.92	1.92	Survey, includes guests and absences.
2	[-]	Number of children per household	tnormal	1.93	0.03	0.58	0	6	1.93	1.93	Survey, includes guests and absences.
3	[°C]	Temperature cold water	tnormal	21.3	0.2	3.6	15.5	25.6	21.3	21.3	[28]
4	[°C]	Temperature hot water at HWS	tnormal	55	5	5	45	65	55	55	Measured
5	[°C]	Average indoor temperature	normal	25	3	3			25	25	Measured
6	[°C]	Ambient air temperature at HWS storage	normal	21.3	0.13	3.9			21.3	21.3	[28],[29]
7	[m]	Ave. length of wastewater pipes	tnormal	5	3	3	3	12	5	5	Estimate
8	[m/s]	Velocity of wastewater	tnormal	0.1	0.05	0.05	0.05	0.3	0.1	0.1	Estimate based on radius (P13) and flow of 30L/min.
9	[m]	Radius of wastewater pipe	tnormal	0.045	0.005	0.005	0.03	0.06	0.045	0.045	Estimate
10	[W/(m^2 °K)]	Heat coefficient wastewater pipe	tnormal	2	1	1	0.5	4	2	2	PVC, [30]
11	[m]	Ave. length of hot-water pipes (storage to tap)	tnormal	7	2	2	2	10	7	7	Estimate
12	[m/s]	Velocity of hot water	tnormal	2.3	0.5	0.5	0.5	3	2.3	2.3	Estimate based on radius (P13) and flow of 8L/min [31]
13	[m]	Radius of hot-water pipe	tnormal	0.005	0.002	0.002	0.003	0.006	0.005	0.005	Rheem Stellar Manual 850330
14-T	[W/(m^2 °K)]	Heat coefficient of hot-water pipe	tnormal	2	1	1	0.5	5	0	0.2	Estimate using [30] for copper pipe through air.
15-T	[W/(m^2 °K)]	Heat coefficient of hot - water storage	tnormal	0.5	0.5	0.5	0.2	1.5	0	0.1	Estimate.
16	[m^2]	Surface of hot water storage	tnormal	3.04	0.304	0.304	1	4	3.04	3.04	Rheem Stellar Manual 850330
17	[-]	Split of hot water system: share of gas use	uniform	1	0	0			1	1	Gas system.
18	[-]	Number of stand times in hot-water pipes	uniform	3	1	1			3	3	
19	[m]	Thickness of hot-water pipe	tnormal	0.001	0.0001	0.0001	0.0005	0.002	0.001	0.001	
20-T	[-]	Switch: hws standard(0)/ solar heat (1)	uniform	0	0	0			1	1	
	Parameters for showers										
21-B	[min]	Flow duration per shower for adults	tnormal	4	0.28	1.3	1	5.5	2	3	Estimated based on measurements
22-TB	[l/min]	Flowrate per showers for adults	tnormal	11	2	2	3	25	4	6	Estimated based on measurements.
23-B	[-]	Number of showers per adult per day	tnormal	1.5	0.03	0.5	1	2	0.071	0.643	Counted
24-B	[°C]	Temperature of showers for adults	tnormal	41	2	2	30	45	35	38	Measured
25-B	[min]	Flow duration per shower for child	tnormal	5.5	0.6	1.65	1	8	2	3	Estimated based on measurements
26-TB	[l/min]	Flowrate per showers for child	tnormal	9.5	1	1	7	12	4	6	Estimated based on measurements.
27-B	[-]	Number of showers per child per day	tnormal	0.21	0.02	0.41	0	2	0.071	0.071	Counted
28-B	[°C]	Temperature of showers for child	tnormal	38	2	2	25	42	34	35	Measured
29	[-]	Fraction of instantaneous shower heating	uniform	0	0	0			0	0	Not relevant to this household
30	[-]	Split of instant. Shower: share of gas use	uniform	1	0	0			1	1	Not relevant to this household
	Parameters for bath										
31-B	[l]	Volume per bath per adult	tnormal	50	7.5	20	20	120	20	30	Measured
32-B	[-]	Number of baths per adult per day	tnormal	0.18	0.02	0.38	0	0.4	0.571	0.071	Measured
33-B	[°C]	Temperature of baths for adults	tnormal	41	2	2	37	45	39	40	Measured
34-B	[l]	Volume per bath per child	tnormal	37	5.55	10	20	90	20	30	Measured
35-B	[-]	Number of baths per child per day	tnormal	0.89	0.016	0.32	0.5	1.2	0.571	0.79	Estimated
36-B	[°C]	Temperature of baths for child	tnormal	38	3	3	27	42	36	37	Measured
37	[-]	Fraction of instantaneous bath heating	uniform	0	0	0			0	0	Not relevant to this household
38	[-]	Split of instant. bath share of gas use	uniform	1	0	0			1	1	Not relevant to this household

	Parameters for clothes wash									
39-B	[-]	Number cycles cold top per day	uniform	0	0	0			0	0	Not relevant to this household
40-B	[-]	Number cycles warm top per day	uniform	0	0	0			0	0	Not relevant to this household
41-B	[-]	Number cycles hot top per day	uniform	0	0	0			0	0	Not relevant to this household
42-B	[-]	Number cycles cold front per day	uniform	0	0	0			0	0	Not relevant to this household
43-B	[-]	Number cycles warm front per day	tnormal	0.93	0.07	1.33	0	1.43	0.5	0.643	Estimated
44-B	[-]	Number cycles hot front per day	tnormal	0.066	0.013	0.25	0.05	0.4	0.022	0.033	Estimated
45-T	[l]	Volume per cycle cold top	uniform	0	0	0			0	0	Not relevant to this household
46-T	[l]	Volume per cycle warm top	uniform	0	0	0			0	0	Not relevant to this household
47-T	[l]	Volume per cycle hot top	uniform	0	0	0			0	0	Not relevant to this household
48-T	[l]	Volume per cycle cold front	tnormal	62	9.3	10	50	90	40	40	[32], estimate
49-T	[l]	Volume per cycle warm front	tnormal	62	9.3	10	50	90	52	52	[32], estimate
50-T	[l]	Volume per cycle hot front	tnormal	62	9.3	10	50	90	47	47	[32], estimate
51-T	[kWh]	Energy per cycle cold top (excl. water heating)	uniform	0	0	0			0	0	[10]
52-T	[kWh]	Energy per cycle warm top (excl. water heating)	uniform	0	0	0			0	0	[10]
53-T	[kWh]	Energy per cycle hot top (excl. water heating)	uniform	0	0	0			0	0	[10]
54-T	[kWh]	Energy per cycle cold front (excl. water heating)	tnormal	0.35	0.0525	0.1	0.1	0.6	0.2	0.225	[32], estimate
55-T	[kWh]	Energy per cycle warm front (excl. water heating)	tnormal	0.35	0.0525	0.1	0.1	0.6	0.2	0.225	[32], estimate
56-T	[kWh]	Energy per cycle hot front (excl. water heating)	tnormal	0.35	0.0525	0.1	0.1	0.6	0.2	0.225	[32], estimate
57-B	[°C]	Temperature cold cycle top	uniform	0	0	0			0	0	[10]
58-B	[°C]	Temperature warm cycle top	uniform	0	0	0			0	0	[10]
59-B	[°C]	Temperature hot cycle top	uniform	0	0	0			0	0	[10]
60-B	[°C]	Temperature cold cycle front	normal	30	3	3			25	25	Program value
61-B	[°C]	Temperature warm cycle front	normal	40	3	3			35	40	Program value
62-B	[°C]	Temperature hot cycle front	tnormal	65	5	5	50	95	55	65	Program value
63-T	[min]	Duration average cycle top	uniform	0	0	0			0	0	[10]
64-T	[min]	Duration average cycle front	tnormal	60	9	20	20	90	60	60	[32]
65-T	[W]	Standby energy top	uniform	0	0	0			0	0	[33]
66-T	[W]	Standby energy front	tnormal	4	1	1	1	8	0	0	[33]
67-T	[-]	Connected to hot+cold (0) or only cold (1) water (SWITCH)	uniform	1	0	0			1	1	Only cold water connection
	Parameters for taps									
68-B	[-]	Number hand wash per person per day	tnormal	12	0.157	3	4	18	9	11	Estimate
69-TB	[l]	Volume per hand wash	tnormal	0.83	0.125	0.3	0.2	2	0.1	0.3	Estimate
70-B	[°C]	Temperature hand wash	tnormal	32	5	5	20	42	21.3	21.3	Estimate
71-B	[-]	Number teeth brush per person per day	tnormal	2	0.05	0.05	0	3	2	2	Estimate
72-TB	[l]	Volume teeth brush	tlognormal	0.3	0.045	0.1	0	2	0.05	0.1	Estimate
73-B	[°C]	Temperature teeth brush	tnormal	27	2	2	20	32	21.3	21.3	Estimate
74-B	[-]	Number shave per adult per day	tnormal	0.5	0.01	0.18	0	1	0	0.4	Estimate
75-B	[l]	Volume per shave	tnormal	2.5	0.375	1	1.5	5	0.1	1	Measured
76-B	[°C]	Temperature shave	tnormal	45	2	2	40	55	21.3	35	Measured
77-B	[-]	Number dish wash (by hand) per hh per day	tnormal	2	0.1	0.5	0	4	2	2	Estimate
78-B	[l]	Volume dish wash (by hand)	tnormal	7	1	1	5	12	4	5.5	Manual
79-B	[°C]	Temperature dish wash (by hand)	tnormal	46	4	4	42	60	39	43	Manual
80-B	[-]	Number clothes wash (by hand) per hh per day	tnormal	0.033	0.01	0.18	0	0.2	0.005	0.01	Estimate
81-B	[l]	Volume per clothes wash (by hand)	tlognormal	15	5	5	5	40	10	12.5	Estimate
82-B	[°C]	Temperature clothes wash (by hand)	tnormal	35	5	5	25	45	25	25	Estimate
83-B	[-]	Number cleaning per hh per day	lognormal	1	0.06	1.2			0.33	0.37	Estimate

84-B	[l]	Volume cleaning	lognormal	7	1.05	5			7	7	Estimate
85-B	[°C]	Temperature cleaning	tnormal	47	5	5	35	65	40	45	Estimate
86-B	[-]	Number other use per person per day	lognormal	10	1.5	3			4	5	Estimate
87-B	[l]	Volume other use	lognormal	1.3	0.2	0.2			1	1	Estimate
88-B	[°C]	Temperature other use	lognormal	30	5	5			21.3	21.3	Estimate
89	[-]	Fraction of instantaneous tap water heating	uniform	0	0	0			0	0	Not relevant to this household
90	[-]	Split of instant. taps share of gas use	uniform	1	0	0			1	1	Not relevant to this household
	Parameters for dishwasher										
91-B	[-]	Number cycles dishwasher per day	tnormal	1	0.02	0.38	0	2	1	1	Estimate
92-T	[l]	Volume per cycle dishwasher	tnormal	18	4	4	10	30	7	7	Estimate for 12-setting, 1995 Blanco machine
93-T	[kWh]	Energy per cycle dishwasher (excl. water heating)	tlognormal	0.33	0.0495	0.1	0.2	0.4	0.3	0.3	Estimate for 12-setting, 1995 Blanco machine
94-B	[°C]	Temperature dishwasher cycle	tnormal	50	5	5	40	70	40	45	Estimate for 12-setting, 1995 Blanco machine
95-T	[min]	Duration average cycle dishwasher	tnormal	100	10	10	30	200	100	100	Estimate for 12-setting, 1995 Blanco machine
96-T	[W]	Standby energy dishwasher	tnormal	2	0.5	0.5	0.5	4	0	0	Estimate for 12-setting, 1995 Blanco machine
97-T	[-]	Connected to hot+cold (0) or only cold (1) water (SWITCH)	uniform	1	0	1			1	1	Only cold water connection
	Parameters for outdoor use										
98-B	[l]	Pool volume per day	uniform	0	0	0			0	0	Not relevant
99-B	[l]	Irrigation per day	tnormal	0	0	0	0	0	0	0	Irrigation not allowed.
100-B	[min]	Duration pool filtration per day	uniform	0	0	0			0	0	Not relevant
101-T	[kW]	Power of pool filter	uniform	0	0	0			0	0	Not relevant
	Parameters for toilet flush										
102-B	[-]	Number toilet flushes per person per day	tlognormal	3.7	0.555	1	2	10	2	3.3	[15]
103-TB	[l]	Volume per toilet flush	tnormal	4.7	0.705	1	2	9	0.75	3.3	[15]
	Parameters for kettle boil										
104-B	[-]	Number of kettle boils per person per day	tnormal	2	0.3	1.2	0	6	2	2.5	Estimate
105-B	[l]	Volume per boil	tnormal	1.2	0.18	0.5	0.5	1.8	0.5	1	[34]
	Parameters for aircon										
106-T	[l/min]	Water use aircon evap.	tlognormal	1.5	0.225	1	0.2	13	1.5	1.5	[15]
107-B	[min]	Duration use aircon evap.	uniform	0	0	0			0	0	[15]
108-T	[W]	Energy used aircon evap.	lognormal	800	120	300			800	800	[33]
109-T	[W]	Standby energy aircon evap.	uniform	0	0	0			0	0	Estimate
110-B	[min]	Duration use aircon rest	tnormal	13	1.95	5	4	20	0	2	Estimate
111-T	[W]	Energy used aircon rest	tnormal	4500	675	1500	2000	20000	4500	4500	[35], ductless mini system
112-T	[W]	Standby energy aircon rest	tnormal	10	5	5	2	18	0	0	Estimate
	Parameters for other energy use										
113-B	[min]	Duration use cooking	lognormal	120	18	30			120	120	Estimate
114-B	[W]	Energy used cooking	tnormal	1389	208.35	300	500	2500	1000	1100	[33]
115-T	[W]	Standby energy cooking	tnormal	5	2	2	1	10	0	0	[33]
116-B	[min]	Duration use fridge	uniform	1440	0	0			1440	1440	Operates 24hrs per day
117-T	[W]	Energy used fridge	tnormal	140	30	30	90	170	40	47	Estimate, 2 fridges (600L and 100L). [33].
118-T	[W]	Standby energy fridge	uniform	0	0	0			0	0	Estimate, fridge always on
119-B	[min]	Duration use TV	tnormal	120	18	60	0	300	0	60	Estimate
120-T	[W]	Energy used TV	lognormal	150	22.5	50			67	115	[33]
121-T	[W]	Standby energy TV	lognormal	3.4	1	1			0	0	Estimate
122-B	[min]	Duration use light	tnormal	1800	270	750	200	5000	1800	1800	Estimate
123-T	[W]	Energy used light	lognormal	30	4.5	10			20	30	Mix of 40-60w and compact fluorescent lights.
	[W]	Standby energy light	uniform	0	0	0			0	0	Not relevant

124-T											
125-B	[min]	Duration use PC	lognormal	171	25.65	60			60	171	Estimate. Two laptops.
126-T	[W]	Energy used PC	lognormal	250	37.5	100			30	130	[36]
127-T	[W]	Standby energy PC	lognormal	10	3	3			0	0	[33]
128-B	[min]	Duration use heating	lognormal	3.9	0.585	2			0	0	Estimate
129-T	[W]	Energy used heating	lognormal	2400	360	1000			2400	2400	[33]
130-T	[W]	Standby energy heating	uniform	0	0	0			0	0	Estimate
131	[-]	Split of cooking energy: share of gas use	tnormal	0.5	0.1	0.1	0.25	0.75	0.5	0.5	Estimate
132	[-]	Split of heating energy: share of gas use	tnormal	0.5	0.1	0.1	0.25	0.75	0.5	0.5	Estimate

**Note for parameters P23, P32, P35 and P78 are based on samples of N=6,7,4 and 3 respectively. Total shower flow volume was measured 16 times for adults and 9 times for children.*

Remark: Some parameters in Table 2, such as P17, P20, P29, P30, P37, P38 and P67 are switches rather than parameters in a strict mathematical sense. However, for reasons of simplicity they are included in the parameter list for the simulations. These parameters are used to distinguish between different types of appliances in the households.

4. Results and Discussion

4.1 Validation with data about current water, gas and electricity use and data from other studies

Table 3 shows a comparison of the simulated results with measurements and data from other studies for water, gas and electricity use. Simulated water and electricity use are in good agreement with the measured data. The simulated gas use is 30% higher than the measured use. The parameters for the shower (most important hot water consuming subsystem), such as the flowrate and duration, may have been slightly overestimated. Compared to the average Australian household, the Milton household uses significantly less water and energy, namely 50% less water and 60% less energy on a per person basis. One reason may be that the average Australian household counts 2.6 persons per household whereas the Milton one comprises four persons including two children who consume less. Another reason could be that Brisbane had stricter levels of water restrictions than many other Australian areas. The household members are also generally proactive with regard to water and energy conservation.

Table 3: Modelled and measured water, electricity and natural gas use and data from other studies. The grey-shaded values represent the simulated and measured values for the Milton household.

	Unit	Source	Mean	STDV-average-day	Remarks
Total water use	l/(hh·day)	Model	464	33	Milton 4-person household
	l/(hh·day)	QUU [a]	451	74	Milton 4-person household
	l/(cap·day)	QUU [a]	113	19	Milton 4-person household
	l/(hh·day)	[10]	490		3-person household
	l/(hh·day)	Australian average [37]	548		2.6 persons per household
	l/(cap·day)	Australian average [37]	203		
	$/(hh.d)	Model	0.71	0.02	Milton 4-person household
	$/(hh.d)	QUU [b]	0.68	0.10	Milton 4-person household
Total gas use	kWh/(hh·day)	Model	9.1	2	Milton 4-person household
	kWh/(hh·day)	AGL [c]	7.4	2.9	Milton 4-person household
	kWh/(hh·day)	AGL [c*]	7.0	0.15	Milton 4-person household
	kWh/(cap·day)	AGL [c*]	1.8	0.7	Milton 4-person household
	kWh/(hh·day)	Australian average [d][1]	17.7		2.6 persons per household
	kWh/(cap·day)	Australian average [d] [1]	6.8		
	$/(hh.d)	Model	1.36	0.2	Milton 4-person household
	$/(hh.d)	AGL [c]	1.13	0.50	Milton 4-person household
Total losses alone	kWh/(hh·day)	Model [e]	1.4	1.3	Milton 4-person household
Total electricity use	kWh/(hh·day)	Model	12.1	1.0	Milton 4-person household

	kWh/(hh·day)	Energex [f]	12.3	1.2	Milton 4-person household
	kWh/(cap·day)	Energex [f]	3.1	0.3	Milton 4-person household
	kWh/(hh·day)	Australian average [1]	19.4		2.6 persons per household
	kWh/(cap·day)	Australian average [1]	7.4		
	$/(hh.d)	Model	2.59	0.20	Milton 4-person household
	$/(hh.d)	Energex [g]	2.34	0.18	Milton 4-person household
Hot water system (gas)	kWh/(hh·day)	Model	7.6	2	Milton 4-person household
Hot water system gas	kWh/(hh·day)	Flower [10]	15.5		3-person household
Hot water system electric	kWh/(hh·day)	Flower [10]	12.6		3-person household
Total water-related greenhouse gas emissions	kg CO_2-e / (hh.day)	Model	5.4	0.5	Milton 4-person household

[a] Data from Queensland Urban Utilities covering 12 quarters from 16/01/2007 to 16/01/2010. [b] Based on 6 bills from Urban Utilities from 13/07/2007to 14/07/2009. In addition to the costs stated in Table 1, there was a "state water charge" which was not considered in the model. [c]AGL data is based on 10 bills from 22/05/2007 to 9/04/2010. [c] AGL data is based on two complete years' data from 20/02/2008 to 22/02/2010. [d] Data for Australian average includes LPG usage in addition to natural gas. Data based on 8,235,000 households and 21,498,500 persons. [e] Includes heat losses from the (gas) hot water system and pipes. [f] Energex data is from 13 records from 12/02/2007 to 9/02/2010. [g] Energex financial data is based on 5 bills from 14/08/2008 to 9/02/2010.*

While total water use was highly comparable to Flower's 3-person household, modelled and measured natural gas usage was approximately half the result found by Flower [10]. This is probably because shower water use in Flowers' [7] work was higher (209 l/hh.d for three people in Flower's model; 76,000 l/year). Simulated electricity and gas costs were highly comparable with results from available bills. Water-related greenhouse gas emissions accounted for about 2 tons of CO_2 emissions per household and year.

4.2 Contributions of single service subsystems

Figure 3 shows a value-proportional water flow scheme for the cold, hot and wastewater flows for the Milton household. Of the 470 l/hh and day, 310 l are used as cold water and the rest, namely 160 l, as hot water. The dominant service subsystems in terms of wastewater flows are the shower, bath, taps, washing machine and toilet flushing. Note that the total wastewater flow is slightly lower than the total water inflow since the water uses for outdoor use, kettle and air conditioner are not directly connected to the wastewater flows.

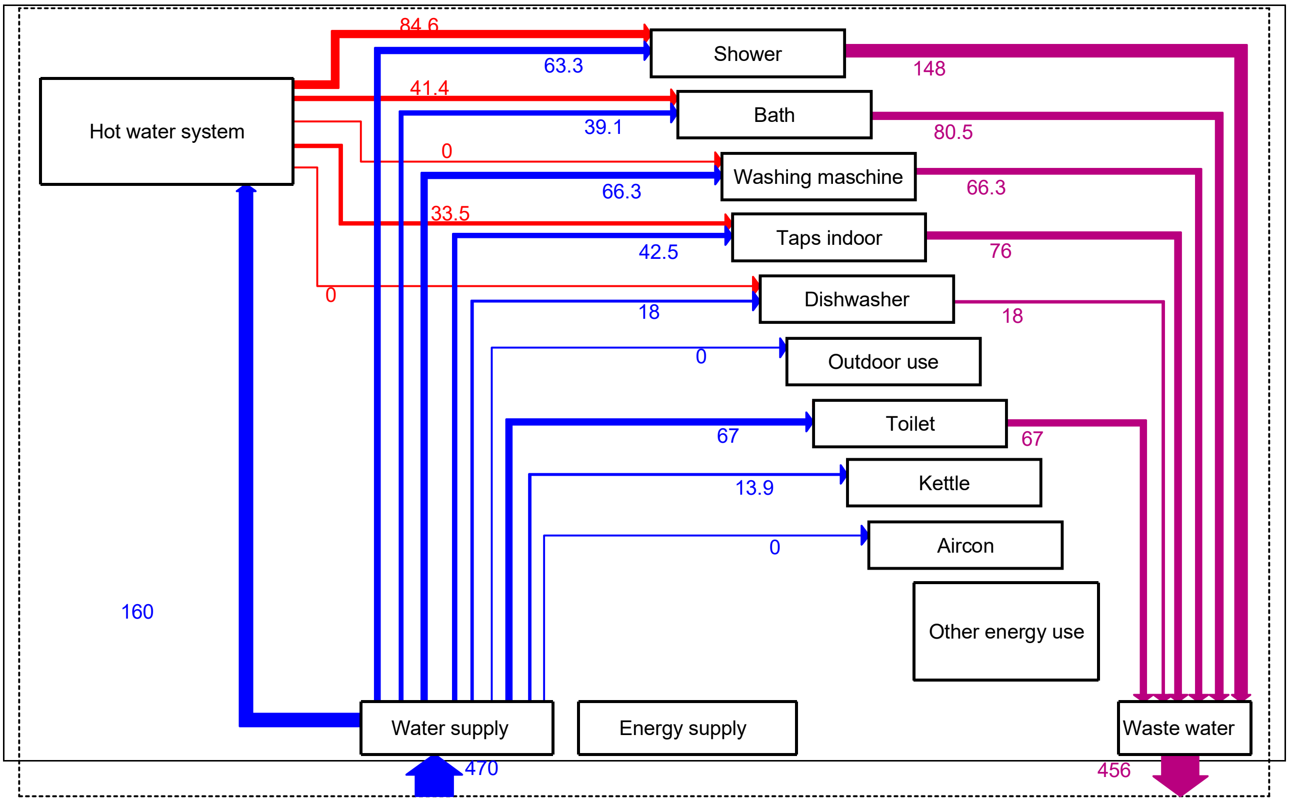

Figure 3: Value-proportional water flow scheme for the cold, hot and wastewater flows for the Milton household.

Figure 4 gives a more detailed analysis of the water flows and the connected energy flows, greenhouse gas emissions and costs including the “STDV-average-day” and “STDV-single-day”.

The hierarchy in the energy flows and costs is similar to that of the water flows except that no energy is used for the toilet. The picture for greenhouse gas emissions is different, since the specific CO_2 emissions per kWh for electricity (from coal-fired power plants) and gas differ by a factor of 5.3. The contributions of the gas-operated shower, bath and taps are consequently much lower than of the electrically operated washing machine, dishwasher and kettle. This would obviously change if power plants with lower carbon emissions were used for the electricity.

The total costs of water and energy in Fig. 4 at first sight show a similar pattern to the water flows. However, a closer look reveals that washing machines and dishwashers as well as kettles have higher costs due to a disproportionately greater use of electricity.

The water-related greenhouse gas emissions are 5.4 kg CO_2/(hh and day), including losses of 0.27 kg CO_2/(hh and day). This corresponds well with the value of Flower [ref.], who found water-related full-fuel cycle greenhouse gas emissions of 5.56 kg CO_2-e/hh.d for a household using natural-gas water heating. However, unlike Flower’s “average” household, in which 37% of water-related emissions were associated with shower-water use, the water-related greenhouse gas emissions from the Milton household were dominated by the use of electrical energy by the washing machine for heating water (37%). In Flower’s household, the washing machine drew hot water from the natural-gas hot-water system. Consequently, even though the two households appear similar, the sources of their water-related emissions are fundamentally different and substantially influenced by the plumbing configurations of the washing machine.

Uncertainty

The standard deviations for the daily average value (STDV-average-day) and for the single day (STDV-single-day) are shown in Fig. 4. Figure 5 presents the probability density distribution for 6 key variables calculated using Monte Carlo techniques for a sample size of 100,000. Again the probability distributions for the daily average values and for the single day are shown. As expected, the uncertainty for the average is much smaller than for the single day because of the large day-to-day and seasonal variability. In fact, the relative width in Figure 5 (see Schaffner et al. [19]) varies from 3% to 12% for the daily averages and from 10% to 35% for the single day.

The added value of a probability density distribution compared to a simple calculation of the mean is as follows: it allows the ranges of the variables as well as the probability that they are below or above a certain target value to be calculated. For example, Fig. 5 shows that average daily water use lies between 424 and 510 l/hh and day with a probability of 80%. The water use for a single day lies between 336 and 634 l/ hh and day, respectively, with the same probability. The same applies to the other key variables shown in Fig. 5.

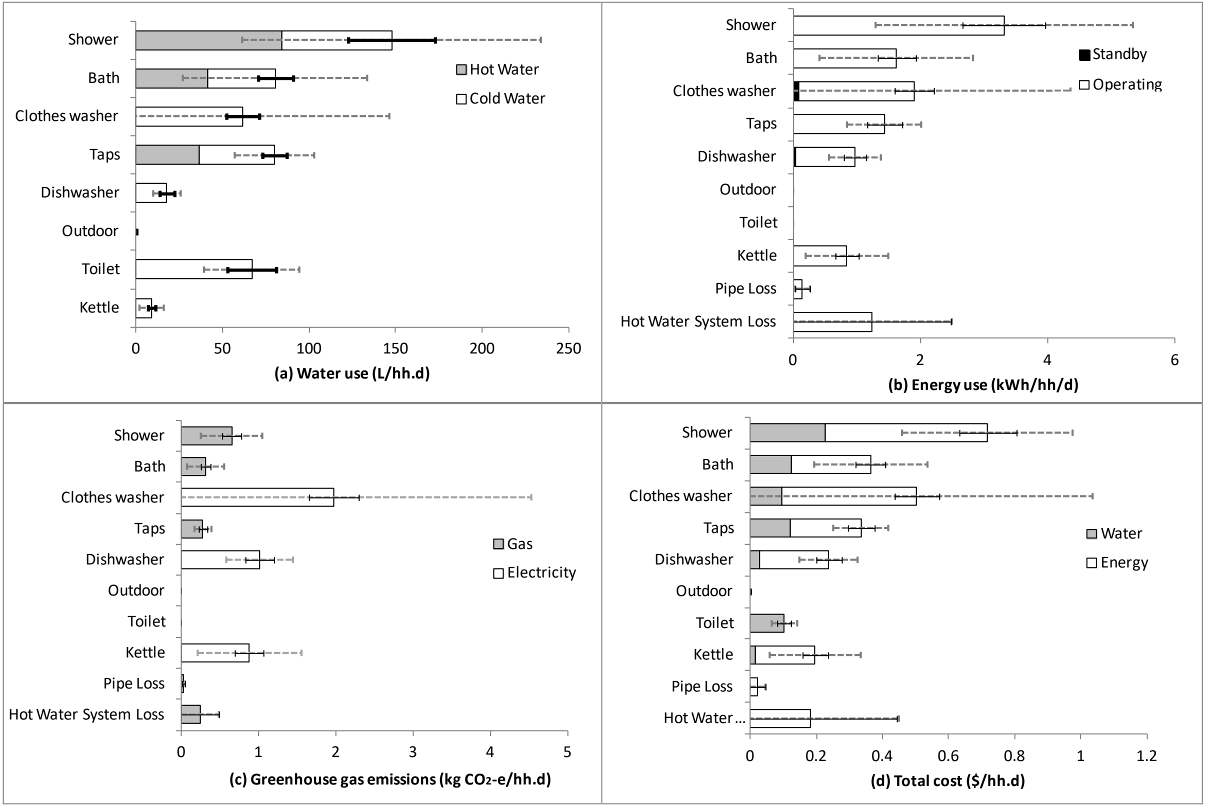

Fig. 4: *Water use, energy use, greenhouse gas emissions and total costs for the shower, bath, ...kettle subsystems. The smaller black error bars represent the "STDV-average-day" and the larger grey ones the "STDV-single-day".*

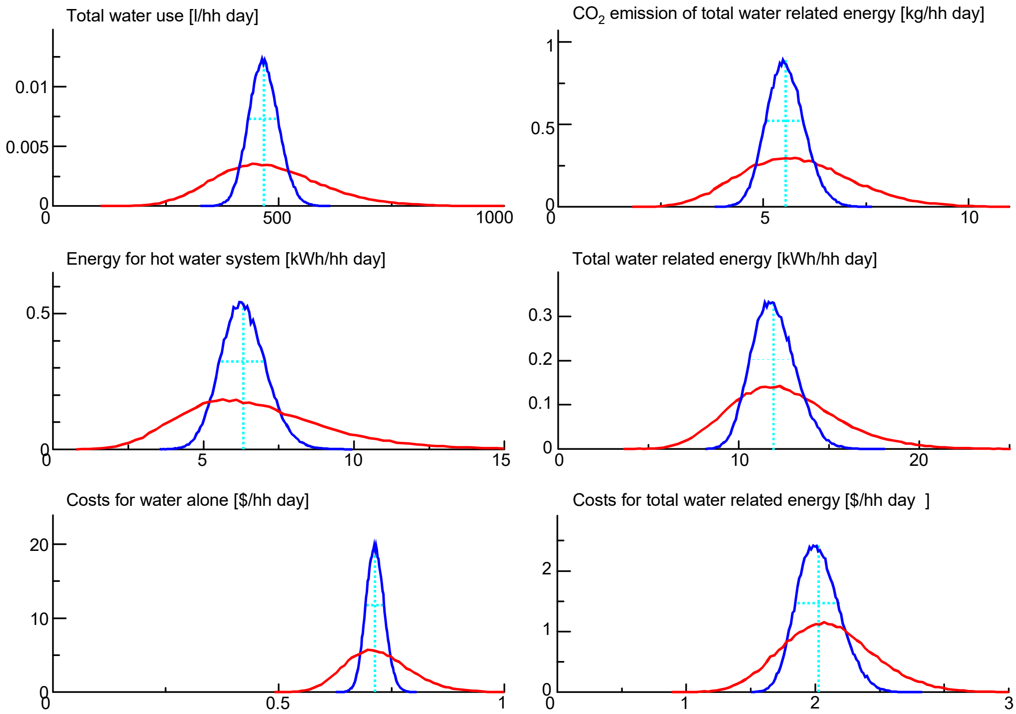

Figure 5: Probability density distributions for selected key variables. The narrower distribution shows the daily averages and the broader one the distribution for a single day. The dashed line represents the mean and standard deviation.

It's important to determine which parameter uncertainties are most responsible for the uncertainties of the selected variables. A parameter uncertainty ranking (Brun et al. [38]) showing which parameter uncertainty contributes how much to the STDV of a certain variable provides the answer.

As expected, the result of the analysis presented in Table 4 shows that the parameters for which no time series were available (P15, P22, P24, P70, P36, P4, P61, P49) dominate the uncertainty for the case of the STDV for the "average day". It should be pointed out that the figure for the "STDV-average-day" is quite small with 10%. If a further reduction should be needed, time series measurements for the above parameters would be required.

Table 4: Cumulative uncertainty rankings for the "STDV-average-day" and "STDV-single-day" for water-related energy

Average day		Single day	
Parameter	Cumulative uncertainty ranking in %	Parameter	Cumulative uncertainty ranking in %
P15 Heat coefficient hot water storage	64.6	P43Number of cycles warm front per day	28.4
P22 Flowrate per showers for adults	76.5	P1 Number of adults per household	44.1
P24 Temperature of showers for adults	80.2	P3 Temperature of cold water	59.3
P70 Temperature of hand wash	82.3	P15 Heat coefficient hot water storage	67.8
P36 Temperature of baths for child	84.4	P23 Number of showers per adult per day	73.0
P4 Temperature of hot water at HWS	86.3	P21 Flow duration per shower for adults	78.0
P21 Flow duration per shower for adults	88.0	P44 Number of cycles hot front per day	82.2
P61 Temperature of warm cycle front	89.8	P32 Number of baths per adult per day	86.2
P49 Volume per cycle warm front	91.3	P27 Number of showers per child per day	89.8

For the "STDV-single-day", the parameter uncertainty ranking in Table 4 shows that the uncertainty is dominated by parameters with large daily variability (P43, P1, P23, P21, P44, P32, P27) and those with large seasonal variability (P3). It should be pointed out that the variability cannot be reduced by collecting larger datasets or more accurate measurements as opposed to the uncertainty of the daily average.

4.3 Sensitivity analysis and scenarios

A first insight into possible reduction measures of water and energy use is provided by a local sensitivity analysis showing the local change of the variables for small changes in the parameters. This analysis allows those parameters with the greatest influence on key variables to be identified and is basic for a careful scenario analysis yielding possible reduction measures (see Schaffner et al. [22]). However, the local sensitivity analysis works only for continuous parameters but not for discrete ones such as the switch between standard (gas/electric) and solar hot-water systems (P20). Accordingly, we do not show the results of the sensitivity analysis but will proceed straight with the scenario analysis.

For the various scenarios, the parameters have been classified into the following four groups:
1) Parameters which were not changed either because we did not want to change them such as occupancy or length of pipes, or because they are environmental parameters such a temperature of cold water, ambient temperature.
2) Technical parameters such as heat loss coefficients and the energy used for washing machines.
3) Technical parameters with behavioural assistance such as flowrates per shower for adults and children.
4) Behavioural parameters such as flow duration and temperature of showers.
For each parameter of Groups 2 and 3, both the potential and realistic reductions have to be found (see Schaffner et al. [22]).

The basic assumption for the scenarios was that the "level of service" remains at least on the current level. Examples include that personal hygiene remains on an accepted level, clothes are still washed, cooling / heating is still possible and watching TV remains enjoyable (same screen size, quality).

The difference between potential and realistic reductions is that the latter mean no change in comfort and service (whereas potential reductions may cause a slight decrease in comfort but not in service). For example, the temperature of showers for adults is currently 41°C, whereas the realistic value was seen as 38°C and the potential one as 35°C.

The realistic and potential values for the "technical" parameters were carefully evaluated with the manufacturers of household appliances. The corresponding values for the "behavioural" parameters were estimated by discussions among selected stakeholders. Those for the "technical parameters with behavioural assistance" were evaluated with manufacturers and stakeholders. It should be pointed out that the realistic values are rather conservative in the sense of providing the same comfort. The resulting parameters for the scenarios are also shown in Table 2. A total of 107 parameters were evaluated for potential and realistic reduction measures. Each combination of these 107 parameters leads to a specific scenario. These can be classified into the groups of "1-parameter", "2-parameter", ... and "107-parameter" scenarios. The "n-parameter" scenario means that n parameters out of the 107 parameters are changed. The total number of scenarios is exactly the sum of the number of scenarios in each group, namely $\sum_{n=1}^{107}\binom{107}{n}=2^{107}-1$ which is a huge number.
where $\binom{107}{n}$ are binomial coefficients.

It is clear that it is impossible to calculate each of these scenarios. However, in order to get an insight into the possible reduction potential, we calculated the "1-parameter" scenarios and the scenarios including all technical and behavioural changes and the combination of both respectively. Table 5 presents the results for the "1-parameter" scenario with a solar HWS and for the combined scenarios. The six selected key variables defined above, namely total water use, CO_2 emission of total water-related energy, energy for hot-water system, total water-related energy, costs for water alone and costs for total water-related energy are shown.

Table 5: Results of scenario analysis. Selected key variables for the scenarios discussed above. For the parameter values (P) refer to Table 2.
-* In principle, the household uses the same amount of energy for heating up the water with a solar HWS. However, as solar energy is not relevant to primary energy and CO_2 emissions, it is omitted from the table

Scenario	Total water use		CO_2 emission of total water-related energy		Energy for hot water system		Total water-related energy		Costs for water alone		Costs for total water-related energy	
	[l/hh day]	%	[kg/hh day]	%	[kWh/hh day]	%	[kWh/hh day]	%	[$/hh day]	%	[$/hh day]	%
Current state	464		5.40		6.37		11.5		0.71		1.95	
Technical potential	444	96	4.57	85	6.25	98	9.46	82	0.70	99	1.66	85

Technical realistic	444	96	4.65	86	6.25	98	9.73	85	0.70	99	1.69	87
Solar HWS	464	100	3.87	74	-*	-*	3.72	32	0.71	100	0.80	41
Technical +solar HWS potential	444	96	3.34	62	-*	-*	3.21	28	0.70	99	0.73	37
Technical +solar HWS realistic	444	96	3.37	62	-*	-*	3.24	28	0.70	99	0.72	37
Technical+solar HWS+washer/dishwasher connected to hot and cold water potential	444	96	1.84	34	-*	-*	1.77	15	0.70	99	0.42	22
Technical+solar HWS+washer/dishwasher connected to hot and cold water realistic	444	96	1.86	34	-*	-*	1.79	16	0.70	99	0.41	21
Technical with behavioural assistance potential	279	60	4.89	91	3.8	60	8.9	77	0.6	85	1.73	89
Technical with behavioural assistance realistic	353	76	5.04	93	4.55	71	9.64	84	0.64	90	1.79	92
Behavioural potential	185	40	2.53	47	1.22	19	4.53	39	0.54	76	1.25	64
Behavioural realistic	281	61	3.89	72	2.24	35	6.66	58	0.60	85	1.52	78
Technical+behavioural potential	108	23	1.63	30	1.09	17	2.46	21	0.49	69	0.71	36
Technical+behavioural realistic	202	44	2.83	52	1.80	28	4.37	38	0.55	77	1.08	55
Technical+behavioural+ solar HWS+washer/dishwasher connected to hot and cold water, potential	108	23	.79	15	-*	-*	0.76	7	0.49	69	0.20	10
Technical+behavioural +solar HWS+washer/dishwasher connected to hot and cold water, realistic	202	44	1.39	26	-*	-*	1.33	12	0.55	77	0.32	16

Table 5 shows that the reduction potential for water, CO_2 emissions, water-related energy, water costs and water-related energy costs are 4-77%, 14-85%, 15-93%, 1-31% and 13-90% respectively depending on the measures taken. Technical measures alone, i.e. without changing to a solar HWS, lead to the smallest reduction whereas the combined scenario, namely technical + behavioural + solar HWS + connection of washer/dishwasher to the HWS, naturally lead to the highest reduction. Technical changes with behavioural assistance have the potential to save a lot of water, namely up to 30%. Behavioural changes alone are very effective. In fact, they account for up to 75% of the whole possible reduction of water and water costs, two-thirds of CO_2 emissions and water-related energy and just over one-third of the water-related energy costs.

Remark: In Table 5, the costs for the water-related energy for the “Technical + Solar HWS potential” scenario are slightly higher than for the realistic scenario, which seems rather strange. In fact the total electrical energy costs are lower for the potential case than for the realistic one, as expected. However, the water-related energy is 3% higher for the potential than for the realistic case, which explains this unexpected fact.

5. Conclusions

Systematic application of the mathematical material flow analysis to the problem of water-related energy in households permitted a detailed analysis of the services and activities in the Milton household that account for specific amounts of water, energy, CO_2 emissions and related costs. The model developed allowed us to investigate and discuss possible reduction measures in detail.

The method represents a complementary approach to huge “data-mining” and monitoring programs. In fact, it offers the benefit of gaining a system understanding from a rather limited database (the current system knowledge) without conducting extended measurement campaigns.

The study showed that technical improvements alone without changing to a solar HWS in the Milton household result in a less than about 15% reduction in energy and CO_2 emissions. This is because this is already equipped at a high technical level. The technical improvements required for other types of household might be much greater. Technical improvements with behavioural assistance offer a large potential for water saving.
Behavioural changes have the potential to be very effective in terms of water saving and reduction of water-related energy and CO_2 emissions, namely by about 50% or even more. The major advantages of behavioural changes are a) no additional costs are involved, b) no change in installations or infrastructure is needed, c) they can be applied immediately, and d) each individual can apply them independently.

The most effective technical measure would be the installation of a solar HWS combined with the connection of washing machines and dishwashers to a hot water source (rather than using coal-fired electricity to heat water within the machine). This would lead to a reduction of about 70% in water-related energy and about 25% in CO_2 emissions. However, this measure would require changes in installations and associated costs.

It should be pointed out that replacing a washing machine connected to a natural-gas operated HWS to a water-efficient washing machine using coal-fired electricity to heat the water internally would result in an increase in greenhouse gas emissions.

The analysis presented in this paper underlines the importance of detailed household analyses in order to understand key factors determining the water, water-related energy and CO_2 emissions of households. Since households are the building block of cities, acquiring a high understanding of them is crucial to understanding the cities themselves. Therefore the next step is to extend the analysis to the different types of households in a city, which is currently in progress. (The model has been designed so that it can be applied to a whole city.)

6. Abbreviations and acronyms

a	annum (year)
CO_2-e	carbon dioxide equivalent
d	day
hh	household
HWS	hot water system
kWh	kilowatt hour
l	litre
MFA	Material Flow Analysis
t	tonne

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8. Appendix A. Equations for the shower subsystem.

Water used for shower:

$$X_w = X_w^{(Adult)} + X_w^{(Child)} \tag{1a}$$

$$X_w^{(Adult)} = P_1 \cdot P_{21} \cdot P_{22} \cdot P_{23} \tag{1b}$$

$$X_w^{(Child)} = P_2 \cdot P_{25} \cdot P_{26} \cdot P_{27} \tag{1c}$$

Where $X_w, X_w^{(Adult)}$ and $X_w^{(Child)}$ is the total water used by adults and children.

Energy used for shower:

$$E_w = X_{hw} \cdot (P_4 - P_3) \cdot c_p \tag{2a}$$

$$X_{hw} = X_{hw}^{(Adult)} + X_{hw}^{(Child)} \tag{2b}$$

$$X_w^{(Adult)} = X_{hw}^{(Adult)} + X_{cw}^{(Adult)} \tag{2c}$$

$$X_{hw}^{(Adult)} = \frac{P_{24} - P_3}{P_4 - P_3} \cdot X_w^{(Adult)} \tag{2d}$$

A similar set of equations was used for children.

E_w is the energy used for the shower, X_{hw} the hot water, $X_{hw}^{(Adult)}$ and $X_{hw}^{(Child)}$ the hot water used by adults and children and c_p the specific heat of water (0.001103 kWh/kg·°K).
Refer to Table 2 for the parameter values.

Appendix B: Loss equations

Energy loss by water storage system:

For the case of stored water held at a constant temperature T_{hws} the losses in the time interval Δt are:

$$\Delta E_{storage\_loss} = \Delta t \cdot h \cdot O \cdot (T_{hws} - T_{env}) \tag{3a}$$

For the case of stored water heated up periodically to a temperature T_{hws} the losses in the time interval Δt are:

$$\Delta E_{storage\_loss} = h \cdot O \cdot (T_{hws} - T_{env}) \cdot \frac{(1 - e^{-\alpha \cdot \Delta t})}{\alpha} \tag{3b}$$

where:

$$\alpha = \frac{h \cdot O}{m \cdot c_p}$$

$h = P_{15}$	Heat coefficient of hot water storage
$O = P_{16}$	Surface of hot water storage
$m =$	Water capacity of storage [kg]
$T_{hws} = P_4$	Temperature of hot water
$T_{env} = P_6$	Ambient temperature of the hot-water storage system

Energy loss by hot water pipes:

Hot water in pipes loses energy through:

1) Heating up the pipe
2) Convection and radiation from the pipe
3) Cooling off of standing water in the pipe.

More precisely, when hot water is used, first of all the pipe is always heated immediately, secondly it loses energy to the environment, and thirdly the standing water in the pipe cools off.

1) Heating up the pipe:
To a very good approximation, the energy loss is:

$$\Delta E_{heat} = \upsilon \cdot 2\pi \cdot r \cdot d \cdot l \cdot \rho_{co} \cdot C_{co} \cdot \left[T_{hws} - T_{env}\right] \tag{4a}$$

$\upsilon = P_{18}$	Number of cycles
$r = P_{13}$	Radius of the pipe
$d = P_{19}$	Thickness of the pipe
$l = P_{11}$	Length of the pipe
ρ_{co}	Density of the pipe
c_{co}	Specific heat of the pipe

2) Cooling and radiation from the pipe:

$$\Delta E_{conv} = h_{pipe} \cdot 2\pi \cdot r \cdot l \cdot \left[T_{hws} - T_{env}\right] \cdot \frac{V_{hw}}{\pi r^2 \cdot v_0} \tag{4b}$$

$h_{pipe} = P_{14}$	Heat coefficient of the pipe
V_{hw}	Volume of hot water used per day
$v_0 = P_{12}$	Velocity of hot water

3) Cooling of the standing water in the pipe:

$$\Delta E_{stand} = \upsilon \cdot c_p \cdot \left[T_{hws} - T_{env}\right] \cdot \rho_w \cdot \pi \cdot r^2 \cdot l \tag{4c}$$

$\rho_w = 1000 \frac{kg}{m^3}$ Density of water

Clearly, (eq. 4c) is only valid if the cooling off of the standing water is complete. For shorter cooling times, the loss is smaller.

It can easily be seen that eq. (4a) – (4c) represent upper limits for the energy loss of a hot water pipe.
In the simulations, eq. (4a)-(4c) were used, representing an **upper** limit for the loss of hot water pipes.

Appendix C: Basic statistical formulas:

$P_i^{(n)}$: n=1,….,N : data points for parameter P_i

a) Average:

$$\overline{P}_i = \frac{1}{N}\sum_{n=1}^{N} P_i^{(n)} \tag{5a}$$

b) Variance of a single day:

$$\sigma^2 = \frac{1}{N-1}\sum_{n=1}^{N} (P_i^{(n)} - \overline{P}_i)^2 \tag{5b}$$

c) Variance of an average day:

$$\sigma_{\overline{P}}{}^2 = \frac{1}{N}\sigma^2 \tag{5c}$$

d) Variance of Group 3 parameters:

$$\sigma^2 = \frac{1}{N-1}\sum_{n=1}^{N} (P_i^{(n)} - \overline{P}_i)^2 \approx \frac{1}{N-1}\sum_{n=1}^{N} (P_i^{(n)} - P_{Seas,i}^{(n)})^2 + \frac{1}{N-1}\sum_{n=1}^{N} (P_{Seas,i}^{(n)} - \overline{P}_i)^2 \tag{5d}$$

where : $P_{Seas,i}^{(n)}$ is the (smoothed) seasonal trend of $P_i^{(n)}$, namely:

$$P_{Seas,i}^{(n)} = \frac{1}{N_0} \sum_{m=n-\Delta n}^{n+\Delta n} P_i^{(m)} \cdot e^{-\frac{(t_n - t_m)^2}{2\sigma^2}}$$

$N_0 = \sum_{m=n-\Delta n}^{n+\Delta n} e^{-\frac{(t_n - t_m)^2}{2\sigma^2}}$ is the normalisation factor and Δn and σ are 20 and 10 days respectively for our time series of air and drinking-water temperatures.

The first term on the right hand side of eq. (5d) is the variability from day to day and the second term the seasonal variability.

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