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

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ABSTRACT

Energy use in households, including private transport, accounts for about 30% of primary energy use in industrialised countries. Therefore, households are important key drivers of energy use and related greenhouse gas emissions. In order to understand energy use related to water in households 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 determined 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. The study showed that for this 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.

1. Introduction

The consumption of energy and the associated greenhouse gas emissions are very high in industrialised countries. In Australia, primary energy consumption in 2007–2008 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 1 kW per person corresponds to 8760 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 6800 kWh (or 10%) of total primary energy per person (0.78 kW/person). Households account for about 30% of water-related energy consumption. This amounts to 2040 kWh per person and year (0.23 kW/person) of primary energy (10% of household primary energy use).

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).

Abbreviations: 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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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 to 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, and (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 a hot water system (HWS) running on either (i) electricity, (ii) gas storage or (iii) instantaneous 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. Energy use for water heating 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 when an electric hot water system was used. This was due to the high greenhouse emissions intensity of the electricity source. 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.

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 appropriate balance volumes and flows have to be defined. The aim was to describe not only one specific household but also 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. 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.

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