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Understanding Australian household water-related energy use and identifying physical and human characteristics of major end uses

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ABSTRACT

Residential resource use efficiency and management is a subject of interest to a number of fields spanning the physical and social sciences. Energy use for residential water heating in Australia is some five to eleven times more than the energy required to deliver urban water services. However, little is known about which activities within households contribute most significantly to water-related energy use (WRE). This work quantifies WRE use in individual households, and identifies household characteristics which contribute significantly to variation. Empirical data were collected through in-home audits, interviews and high-resolution end-use water flow meters for five households in Melbourne, and two in Brisbane, Australia. This was used to characterise 139 parameters describing household occupancy characteristics, behaviours, technologies, and structural and environmental aspects of influence. Mathematical material flow analysis (MMFA) modelling was conducted for individual water and energy use subsystems within each household. WRE use ranged from 7 to 21 kWh hh^{-1} d^{-1} (13–24% of total household energy use in Melbourne and 76–79% in Brisbane). Detailed end use analysis of the five Melbourne households showed that shower use (11–61% WRE), hot water system efficiency losses (8–31% WRE) and clothes washer usage (4–17% WRE) contributed most to differences in WRE between households. Findings highlighted shower use as a consistent influence on WRE across households, and suggest further investigation of shower programs as a potentially effective demand management measure for both water and energy in households. The work highlights the importance of consistent messaging for both water and energy efficiency, and suggests that a focus on both human and technical characteristics of households is needed for effective management of combined water and energy use.

1. Introduction

Energy use associated with water end use is far more significant than that for the delivery of water and wastewater services (Kenway et al., 2008, 2011a; Rothausen and Conway, 2011). In Australia, for example, energy use for residential hot water is estimated to be between 5 (Adelaide) and 11 (Melbourne) times that required to deliver urban water services (Kenway et al., 2008). On average, it is estimated that residential end use of water is responsible for approximately 30% of energy used throughout the urban water cycle (Kenway et al., 2011b), and energy for water heating represents approximately 23% of total Australian residential energy consumption (Commonwealth of Australia, 2008).

This research aims to understand whether total water-related energy use varies significantly between seven different households, and to identify end-use characteristics responsible for greatest variation. Households and their component fixtures (permanently attached components such as a hot water system, or pipework), fittings (removable items such as shower heads, or light bulbs) and appliances are subject to a range of environmental policies and regulations targeting efficient water and energy end use. The potential for energy demand management through water efficiency measures has been recognised (Beal et al., 2012). If we are to maximise the advantages of synergies between water and energy management approaches, data are needed to ensure that our efforts are targeted in the right area and through the most effective pathways. Without an understanding of water-energy interactions, there is also a real risk that attempts to increase efficiency on one

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side of the linkage (e.g. water) will decrease efficiency of the other (e.g. energy and/or greenhouse gas emissions (GHG)) and lead to unintended consequences. (For an example of this, see (Kenway et al., 2013)). Current water- and energy-efficiency standards and codes are hard-wired into new residential developments (Beal et al., 2012). As population growth and urbanisation accelerate (e.g. the percentage of world population in urban areas is project to grow from 30% in 1950 to 66% in 2050, (United Nations, 2014)), in the absence of clear data and foundational knowledge on water and energy end-use interactions, cities may be at risk of unwittingly increasing their resource use intensity despite best efforts to the contrary. An understanding of influential end-use characteristics and their contribution to variation in water-related energy (WRE) use across households, is a significant knowledge gap for evidence-based policy and program development for water-related energy management (Head et al., 2013). Such an evidence base is needed to enable sustainable resource policy development to target areas with the greatest potential for effective change (Newton and Meyer, 2012). In the absence of data, the extent to which policy interventions can be effective in managing water-related energy use is unclear, and resource managers risk problem-shifting between the water and energy spheres (Kenway et al., 2011c).

1.1. Background

The urban water-energy system can be described in terms of both 'human' attributes (e.g. behaviours, rules, economics, governance) and 'physical' attributes (e.g. technologies, fittings, structures, environmental factors, infrastructure issues). These exist at varied scales, from micro (individual end use) to macro (institutional) scales, with a high degree of interaction. Combined, these attributes describe the way we manage and use water and energy. Knowledge of these factors, and their interactions and effect on water-related energy use, is an important foundation for the design of integrated management measures.

The influences of human habits and behaviours on household water and energy use have been noted in qualitative literature (Strengers, 2011; Strengers and Maller, 2012; Martinez-Espineira et al., 2014; Fielding and Head, 2012; Beal et al., 2013; Gilg et al., 2005; Kurz et al., 2005; Hansen, 1996; Jeong et al., 2014). Similarly, the impacts of physical characteristics of households have been assessed, with a focus on key individual components such as hot water system design and efficiency (Kar and Kar, 1996; Parker, 2003; Boait et al., 2012; Hernandez and Kenny, 2012; Bohm, 2013; Lai et al., 2014). However, few studies consider the potential for water-related energy management across multiple end uses within a household, or consider both human and physical characteristics of these end uses.

Table 1 provides a summary of literature focused on quantification of water-related energy use in households, summarised according to the impacts assessed, the human and physical characteristics of households considered, and the scale or resolution of results. Most quantitative water-related energy studies assess either total household water or hot water use (Parker, 2003; Zhou et al., 2013; Nasrabadi et al., 2013; Vieira et al., 2014; Shimoda et al., 2010; Kuusk et al., 2014), or a single end use (e.g. showers, (Slys and Kordana, 2014; Giglio et al., 2014)). Studies which include some consideration of human as well as physical factors included consideration of the effect of varied occupancy on optimal hot water system design (Parker, 2003; Shimoda et al., 2010) and domestic hot water consumption (Kuusk et al., 2014), and the impact of shower duration on the cost-effectiveness of a heat recovery unit (Slys and Kordana, 2014). Vieira et al. (Vieira et al., 2014) demonstrate that energy tariffs impact upon optimal energy and service performance for residential hot water systems. Giglio et al. (Giglio et al., 2014) further consider human factors in detail through economic clustering analysis to assess impact of solar hot water systems on energy savings, finding that human factors significantly influence effectiveness. This concurs with work by Kenway et al. (Kenway et al., 2013), who demonstrate that physical management measures alone resulted in less than 15% reduction in household water-related GHG emissions and energy consumption,[1] whereas combined physical and behavioural measures had the potential to achieve 85% (GHG emissions) and 93% (energy) respectively.

Only two studies were found to assess multiple end uses (Beal et al., 2012; Kenway et al., 2013). Kenway et al. (Kenway et al., 2013) contribute a validated model of the energy effect of water for each individual end use within a household. The first principles 'ResWE' (Residential Water-Energy) model estimates water use based on fundamental parameters such as the flow-rate, duration and frequency of showering. Heat energy is then estimated based on thermodynamics of heating water from one temperature to another, rather than, for example, using energy estimates based on "standard" appliance efficiencies. These allow estimation of water flows, which in turn drive thermodynamic relationships based on water supply and end use temperatures, operational energy requirements, heat transfer coefficients, hot water pipe lengths and stand times, and energy conversion efficiencies, allowing prediction of energy use associated with each water end use. Beal et al. (Beal et al., 2012) also assess energy demands for individual water end uses (showers, taps, clothes washers, and dishwashers), based on empirical data for average water end use and technology choice (hot water systems and washing machines). While contributing a valuable assessment of hot water energy demands, the study does not enable insight into non-technological management levers such as the impact of occupancy, behaviour, environment, or structural aspects of the household. Beal et al.'s work also focused on energy demand for hot water use, and does not include assessment of the energy conversion efficiency of different hot water heating systems.

Of the studies reviewed, none considered both human and physical influences on individual water-related energy end uses across more than one household. This study aims to provide further insight into Beal et al.'s (Beal et al., 2012) and Kenway et al.'s (Kenway et al., 2013) findings by quantifying variation in water-related energy use across multiple households, and considering both human and physical characteristics which contribute to this variation.

2. Methods

2.1. The water-energy-carbon links in households and cities project

This paper has been conducted as a component of a larger research effort undertaken collaboratively between The University of Queensland (Australia) and the Melbourne water sector and related State agencies. The overarching project has four principal goals: (i) understand water and energy connections in individual households, (ii) characterise "household types", (iii) understand city-scale water-related energy use and greenhouse gas emissions, and finally (iv) identify opportunities to manage water-related energy use. This will include quantification of the water and greenhouse gas reduction potential of a range of management options including technological, behavioural and policy changes.

This paper reports upon work towards goal (i) outlined above, aiming to understand water and energy connections in individual households. Outcomes of this work will inform the definition of "household types" for water-related energy use and underpin

[1] Excluding a switch to a solar hot water system.