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An integrated approach to modelling end-use energy and water consumption of Australian households

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ABSTRACT

To predict both end-use energy and water consumption of households, an integrated approach was developed by adding water module into the AusZEH design tool, which was a physically-based model to simulate energy consumption of residential buildings considering building envelop, appliance characteristics, local climate and occupant behaviour. Water and its associated energy consumption includes indoor and outdoor water systems considering actual operation of the water systems. Monte Carlo approach was applied to simulate both energy and water use patterns of appliances considering uncertainties. The comparisons between simulation and actual data show the model can track both energy and water consumption and usage patterns.

1. Introduction

Cities are large consumers of both energy and water, and efficient use of energy and water is crucial to city resilience. It is understood that water and energy consumptions interacted with each other, i.e. a massive amount of water is required to generate electricity, while a large amounts of electricity is required to treat, process and transport water. This energy-water nexus implies that water saving can reduce energy consumption and vice versa. However, there is little attention is paid to the interactions between energy and water savings (Young, 2014).

Currently, residential sector is responsible for around 30% of the energy consumption in developed countries (Vieira, Beal, & Stewart, 2014). In Australia, residential buildings accounted for about 20–30% of the total electricity consumption and 30–50% of the total peak demand (Wood, Carter, & Harrison, 2014). Meanwhile, Australia is the driest inhabited continent on earth, which can yield only a limited amount of freshwater (Australian Government Department of Industry, Innovation and Science, 2015). With climate change, available freshwater is expected to decline due to the change in rainfall patterns. To reduce energy and water consumption in residential buildings, Australian government has developed relevant policies and regulations, such as Nationwide House Energy Rating Scheme (NatHERS, 2015), the Equipment Energy Efficiency (E3) program (2015) and Water Efficiency Labelling and Standards (WELS) scheme (2015).

Some household appliances for residential buildings, such as shower, washing machine, dishwasher and evaporative cooling system, consume considerable energy and water. Water efficiency may have a significant effect on the energy consumption of those appliances. Information with an insight knowledge into the linkage between energy and water use is useful to identify more cost-effective options for saving.

A range of approaches has been established to investigate whole-house energy consumption (including water heating) patterns, such as in UK (Richardson, Thomson, Infield, & Clifford, 2010; Wood & Newborough, 2003; Yao & Steemers, 2005), in Italy (Capasso, Grattieri, Lamedica, & Prudenzi, 1994), in the USA (Christensen, Horowitz, Givler, & Barker, 2005; Chiou, 2009; Mills, 2004; Florida Solar Energy Centre, 2015), and in Australia (Newton and Tucker, 2009; Ren, Foliente et al., 2013). To predict household water use and conservation potential, various types of models have been developed, which are based on either empirically estimated data, water consumption device turnover rates, or regression analysis. The potential issues to use those models can be referred to Cahill, Lund, DeOreo, and Medellin-Azuara, (2013). In fact, energy savings as a result of water conservation can't be directly modelled using any of those models, considering that the interaction between energy and water was not taken into account.

To look for more opportunities for greater savings in energy and water, better understanding of their interactions is required (Copeland, 2013). Meanwhile, there is a growing interest in energy

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consumption related to water use. For examples, based on the data provided by water utilities, water energy intensity and energy for residential water heating were investigated for major cities of Australia (Cook, Hall, & Gregory, 2012; Kenway et al., 2008). Young (2014) drew existing data reported for water use and its related energy consumption in USA and estimated national energy savings in relation to water savings that includes hot water use reduction in buildings.

With the key planning policy (the Building Sustainability Index-BASIX policy) introduced in 2004 by New South Wales State Government in Australia, an online assessment tool – BASIX was developed to assess whether the design meets its water, energy and thermal comfort targets. The targets are based on the State's average water and energy consumptions per capita from FY 2002–03. It is required that all new homes to be designed to use less potable water up to 40% and generate fewer carbon emissions than the average NSW home at the same percentage (NSW Government Department of Planning and Environment, 2015). BASIX can be used to assess household energy and water consumption, and carbon reductions. However, it has the following limitations:

- Occupant behaviours and occupancy time that have significant impacts on household water consumption were not explicitly considered;
- Interdependencies between water and energy system (e.g., a rainwater tank can be installed to achieve potable water savings but this might have a very inefficient pump that increases overall energy intensity of water services for the household) is not considered;
- The estimation of energy and water uses for equipment and appliances is too general (i.e., based on typical or average values), and subsequently, it cannot take into account the effect of specific equipment/appliances or new technologies.

This study aims to develop an integrated approach to predict total energy and water consumption by Australian households. It is done by implementing modules of water use and its related energy consumption into the AusZEH design tool (Ren, Foliente et al., 2013). The main contributions are:

- Considering occupancy behaviours and appliance performance, a water module is developed and implemented;
- The hot water module developed to improve energy consumption prediction based on the actual hot water use;
- Based on published data on water energy intensity, water related energy consumption is considered;
- Based on the Australian Bureau of Statistics (ABS) survey *How Australians use their time* (ABS, 2006), electricity and water use patterns (half-hourly data over a period of one year) of appliances is assessed using Monte Carlo simulation technique (Doucet, Freitas, & Gordon, 2001);
- The integrated capability to predict water consumption, and electricity and water usage patterns of households are validated against the actual monitoring data.

2. Methodology

2.1. Estimation of total annual water consumption of individual households

The end-use of water is associated with both appliances and user behaviours, which is described as

$$V = F \times t \times f \tag{2.1}$$

Or

$$V = W_v \times f \tag{2.2}$$

Where V is the volume of water end-use (L/day), F the flow rate (L/min), t the duration of the appliance use (min), f the frequency of the appliance used (1/day) and W_v the volume of the event (L).

Eq. (2.1) is applied for the fixtures and appliances (such as shower and tap) when the end-use volume depends on the flow rate, duration and frequency, and Eq. (2.2) applied for the fixtures and appliances (such as clothes washer, dishwasher, toilet and sink) when their end-use depends on the volume of each cycle/event and use frequency. If data are available, the calculation of the end-use water volume is straightforward.

A water module, based on the House Water Expert (HWE) software (Grant, Mitchell, & Dell'Oro, 2004), has been implemented into AccuRate, a software for house sustainability assessment in Australia (Ren, Chan, & Chen, 2009a). The modelling platform of HWE was originally based on the National Water Conservation Rating and Labelling Scheme ('A ratings'), which specifies the range of flow rates (L/min) for each 'A rating'. The 'A rating' was replaced by the WELS scheme from 1st July 2006 (WELS, 2015). The new label scheme has a zero to six star rating. The range of water flow rate (L/min) is specified in each star level. This type of capacity model is useful to educate and guide users to save water through adoption of water efficient fixtures and appliances in terms of their water efficiency ratings. However, typically householders don't run their water appliances at their full capacities (Athuraliya, Gan, & Roberts, 2008). For actual water consumption estimation, it requires to provide actual input data of the flow rate (F) or the volume (W_v) and the occupant behaviour data (t and f). These actual data can be obtained from measurement and/or survey studies.

Across the Melbourne region, Yarra Velley Water undertook a series of research projects to investigate residential water usage at the end-use level by measurements (Anthuraliya, Roberts, & Brown, 2012; Roberts, 2005; Roberts, Athuraliya, & Brown, 2011) and Surveys (Roberts, 2004; Athuraliya et al., 2008; Roberts, 2012). Table 1 summarizes the measurement results of the main indoor water end uses for Year 2004 (Roberts, 2005), winter 2010 (Roberts et al., 2011) and summer 2012 (Anthuraliya et al., 2012).

Beal and Stewart (2011) made a comprehensive monitoring study for South East Queensland (SEQ), in which a total of 252 homes were monitored for the period over winter 2010 as part of the SEQ Residential End Use project. This comprised 87 in the Gold Coast, 61 in Brisbane, 67 in Sunshine Coast and 37 in Ipswich. The average metered results are shown in Table 2.

A summary of recent studies conducted both in Australia and internationally can be found in the paper by Beal and Stewart (2011).

Water leakage of fixtures and appliances were detailed in the report (Ren et al., 2009a). Table 3 summarized the default values used in this model when specified values are not available.

The implementation of the water module on water consumption and leakage is described in Section 2.4.

2.2. Modelling diurnal patterns of end-use electricity and water

Peak demand management of electricity is one of key drivers of investment in networks and/or power plants (Ren, Paevere, & McNamara, 2012). Diurnal patterns and peak demand of water provide valuable information for water utilities planning, engineering and billing functions. It is essential before optimised management of urban water could be implemented in the future. Significant research efforts have been focused on reducing the total energy and water consumption of buildings, but little research attention was paid to the synergies between whole housing stock energy and water consumption and their peak demand management.