DETAILED CHARACTERISATION OF WATER-RELATED ENERGY USE IN HOUSEHOLDS

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ABSTRACT

Households are the target of a broad range of water and energy efficiency policies and programs. Limited quantitative data currently exists however to describe the impacts of interaction between water and energy efficiency measures. This can result in problem shifting between the water, energy and carbon spheres, and limits opportunities to capitalise on measures which improve both water and energy efficiency simultaneously.

This paper presents first stage outcomes of a project focused on detailed characterisation of water-related energy use in households. Water, electricity and gas usage, costs and emissions have been quantitatively defined and validated for seven households, and the sensitivity of each to key household characteristics has been analysed. Defined linkages will improve policy outcomes for water, energy and greenhouse gas efficiency in households.

INTRODUCTION

Background

Urban water use indirectly influences 13% of Australia's electricity and 18% of Australia's natural gas use, corresponding to 9% of greenhouse gas emissions (Kenway 2011). A large proportion of urban water use is residential, and significant work has been done by industry and government to increase water and energy efficiencies in households. End use research has enabled utilities to refine conservation messages, and has informed customers where to target change. Industry has responded through innovation to improve appliance efficiencies. High uptake of efficiency measures such as low-flow shower heads and front loader washing machines (Beal 2010), and energy saving light bulbs have achieved considerable water and energy savings

Recent research has shown, however, that some efficiency measures can result in perverse outcomes. For example, Kenway et al (2013) shows that shifting from a top loading washing machine (plumbed to gas-heated hot water) to a water-efficient front-loading machine (plumbed to cold water only with internal electric heating) can significantly increase greenhouse gas emissions by shifting the energy source for water heating from gas to coal-fired electricity. When small changes at the household level are translated to city scale, impacts can be considerable. Households therefore offer great opportunity to influence water-related energy use within cities.

Existing data on the interaction of water and energy use within households is limited. Although research exists on the impacts of residential water use on energy use much is limited to consideration of 'hypothetical' systems, and few studies have quantified linkages or identified key causal factors of change (Kenway 2011).

Research Objectives

The University of Queensland, with the Smart Water Fund, are conducting a three-year study into water-energy-carbon links in households and cities as an Australian Research Council Linkage project. The objectives of the study are to: (a) understand water-energy connections in individual households; (b) describe a set of household 'types' based on influential technical, behavioural, structural and environmental characteristics; (c) understand water-related energy (WRE) use, greenhouse gas (GHG) emissions and costs at a representative area (e.g. city scale); and (d) identify opportunities to reduce water-related energy, including quantification of water, energy and GHG reduction potential of a range of technical and behavioural policy options.

This paper presents outcomes of the first stage of the project which focuses on detailed characterisation of individual households. Water and energy use, costs and GHG emissions have been quantified for seven households, including an analysis of the sensitivity of WRE, costs and GHG emissions to changes in behaviours, technology choices and structural aspects.

METHODOLOGY

Approach

The study approach builds on the development of a mathematical material flow analysis (MMFA) model for residential water and energy use by Kenway et al (2013). The MMFA model is a bottom-up material and energy balance model of a single household, based on 132 input parameters. Input parameters have been designed to take into account the influence of behaviours (e.g. shower frequency and duration), water-using technologies and fittings (e.g. washing machine specifications, shower head flow rate), physical environments (e.g. average air temperature), plumbing configurations (e.g. hot and cold tap connections), building design and associated losses or gains (e.g. distance from hot water system to taps), and water heating system types and energy sources. Each parameter is assigned a probability distribution function to account for uncertainty during simulation.

The MMFA model returns a detailed set of over 400 output metrics describing water use, energy use (by individual energy source), WRE, costs and GHG emissions for each subsystem (e.g. shower, washing machine) within the household. Results are validated against historical water, electricity and natural gas usage records for each household. The model also allows for testing of the sensitivity of each output to changes in each input parameter, to identify which parameters have the most significant impact on overall water and energy use, costs and GHG emissions.

The aim of this research is to further test and validate the MMFA model by characterising an additional five Melbourne households (further to two Queensland households), results of which will be used to describe a set of household 'types'. These will then be used to scale up to a regional analysis and test a range of water and energy efficiency policy scenarios. The overall goal of the work is to better understand the trade-offs between water and energy efficiencies, and to identify opportunities to reduce water-related energy including quantification of water, energy, cost and GHG reduction potential.

Model Development and Validation

Individual household data has been collected through detailed surveys including behavioural interviews and technical audits of fittings, fixtures, appliances, and structural and environmental aspects. Key attributes of surveyed households are summarised in Table 1. This information has been used to generate probability distribution functions for all 132 water and energy use input parameters for MMFA modelling.

Model outputs include end-use breakdowns of water-related energy use, natural gas use, electricity use, greenhouse gas emissions and costs for each household modelled.

To test the accuracy of the model, modelled outputs for total water use, electricity use and natural gas use are compared against annual average consumption from actual water, electricity and natural gas billing data for each household. The aim of this process is to validate the model, by showing that the sum of individual end use estimates generated by the model for water, electricity and natural gas equals the total actual use for the modelled period. The validation process is iterative, as better information is collected to refine model input parameters and increase model accuracy.

First pass modelling has been conducted for the households based on data collected during household audits and behavioural interviews. Validation outcomes are presented in Table 2 with the corresponding model outputs presented in Table 3.

Model development and validation is ongoing, focused on the collection of more detailed datasets to increase accuracy in model input parameters. This processs will conclude with well-validated models for each household, providing confident estimates of individual household end uses and in particular detailed information on the interactions between water, energy and carbon.

A sensitivity analysis has also been performed on the first pass model to understand which technical and behavioural characteristics have the greatest impact on total water, electricity and gas use and water-related energy use, costs and GHG emissions. Table 4 presents an overview of the model parameters for which a 10% change in input value results in a greater than 5% change in total modelled water, electricity or natural gas usage.

Application of Model Outcomes

Validated model results for the seven case studies will provide a detailed set of output metrics related to water and energy use for each household, based on bottom-up physical relationships. This will allow for fine-scale exploration of complex relationships between water and energy use at the household level and enables tracking of flow-on effects of changes in the system. Results of the sensitivity analysis will allow identification of key behavioural and technical 'levers' in water-related energy use in households. This will inform definition of a set of 'household types' describing variations of influential water and energy use characteristics.

Detailed regional level data sets are being collated to apply these household types for city-scale analysis, including appliance stock and usage data and residential end use monitoring data from water utilities, suburb level aggregated smart energy meter data from energy distributors and retailers, and census demographic data.

RESULTS

First Pass Model Results

The results of modelling based on household survey data indicate that water-related energy use within the sampled households ranges from 5 to 20 kWh/hh.day (corresponding to 2.5-5.0 kWh/person.day) (Table 3). These figures comprise between 15% and 50% of total household energy use.

Estimates of greenhouse gas emissions resulting from water-related energy use range between 3 to 15 kg CO_2-e/hh.day (corresponding to a range of 1 to 3.5 kg CO_2-e/person.day), representing 10% to 45% of total estimated household greenhouse gas emissions.

Outcomes of the sensitivity analysis suggest that frequency of showers and clothes-washer usage are consistently influential on water and energy use across almost all households (Table 5). Cold water temperature is also indicated as a driver for water-related energy usage.

Data Accuracy

While significant effort was devoted to accurately estimating household water and energy end use characteristics during the household surveys, participant understanding of behaviours (such as frequency and duration of usage) is imperfect and contributes to model inaccuracies. Additional work is being undertaken to improve confidence in this data, and detailed data from a number of sources has been compiled to this end.

Yarra Valley Water have contributed high-resolution water meter data for each of the participating households, to which pattern recognition software will be applied to disaggregate the data into individual water end use events. This will significantly improve the statistical accuracy of water end use frequency, duration and usage volume parameters for input into MMFA modelling. Households participants have also provided detailed smart energy meter data, which will be compared against high-resolution water meter data to improve understanding of energy intensity of water end uses.

First pass results suggest that shower input parameters have significant impact on model results (Table 4). To improve confidence in these parameters, through collaboration with Eawag (Switzerland) a number of Amphiro meters have also been installed in households. The Amphiro is a self-powered water and energy meter for showers, logging detailed data for up to 400 shower events. This has enabled collection of data on frequency, duration, temperature and flow rate of individual shower events, which will be used to refine model inputs including parameter probability distribution functions.

The high resolution datasets described above will allow for a high degree of accuracy in model results, in particular for outcomes of the sensitivity analysis. This will facilitate confident identification of parameters of key influence ('levers') in water-related energy use, associated costs and emissions. Understanding of these factors will inform the development of household 'types' which will form the basis of larger scale analysis of a representative city area in further stages of the project.

Limitations

The MMFA model currently facilitates static analysis for a single day. Analysis to date has focused on an 'annual average' day for a specified year of collected data, with probability distribution functions assigned to each input parameter indicating likely range of variability in outputs. A summer and winter average day analysis is currently being undertaken for all households to improve understanding of temporal variability in water-related energy use.

Households surveyed to date are all detached dwellings and do not include multi-unit residences. The objective of this stage of the project was further testing and validation of the MMFA model, and sample data was not intended to represent all household types. It is recognised that different residential types will vary in key characteristics, and further work will adress this.

DISCUSSION

Implications of Results

Results of this research will have implications for the residential sector, water industry, energy industry, building industry, appliance manufacturers, efficiency labelling, environmental agencies and social welfare organisations.

Of relevance to the water industry, increased knowledge of water-energy interactions within households will contribute to a clearer understanding of the role of demand-side management in reducing system-wide energy demand and carbon footprints. This will provide the opportunity to target investment for increased efficiency in water service provision. It will quanitfy the impact that demand-side management options may provide compared to supply side infrastructure management. It will also quantify current efficiency programs, which can all contribute to improving customer messaging to provide options to decrease water use, energy use, GHG emissions, and ultimately utility bills.

Insight into the role of water and energy end uses in driving household costs will be particularly pertinent for social welfare organisations and will assist in identifying initiatives to help households, particularly lower income and concession holders, to limit living costs.

Improved information on the role of water-use in driving peak energy demand will be of interest to the energy sector, as they seek demand-management solutions to defer costly infrastructure investment. One hypothesis is that incentives for indirect energy management through water demand management at peak times may prove equally or more effective than those targeting direct energy end uses.

Environmental regulators, the green buildings industry and appliance efficiency bodies will have an interest in detailed information regarding the impact of appliance specifications, plumbing configurations and structural design features on household GHG intensity, as it will have implications regarding the effectiveness of benchmarking, rating and labelling schemes and environmental design codes.

Further Work

Results of the sensitivity analysis from the first stage of this project will be used to inform the definition of household ‘types’, which will be defined by combinations of the most significantly influential input parameters upon water-related energy use.

Based upon these household types, water-related energy use characteristics for a representative area (e.g. city-scale) will be modelled. Analysis will draw on detailed regional-level datasets including appliance stock and usage data and residential end use monitoring data from water utilities, suburb level aggregated smart energy meter data from energy distributors and retailers, and census demographic data.

Scaled up modelling for the representative area will be used to test the efficacy of a range of water and energy efficiency policy scenarios, including quantification of water, energy, cost and GHG reduction potential. An industry consultation group from a broad range of sectors including water supply, energy supply, environmental regulation, building regulation, technology development, efficiency labelling, social welfare and behaviour change stakeholders has been formed to contribute to design of policy scenarios for analysis.

CONCLUSION

The first stage of this project provides significant insight into key levers of influence for water-related energy in households and cities, including detailed quantification of WRE. This insight has potential implications for the rigorous identification of least-cost solutions across water and energy for cities today and into the future.

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Table 1: Summary of key household attributes

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

Table 2: First pass model validation outcomes

Parameter	Source	Units	HH1	HH2	HH3	HH4	HH5	HH6	HH7
Water Use, Total	Model	L/hh.d	730	860	410	650	175	460	465
	Actual	L/hh.d	540	610	310	440	290	500	450
	Model / Actual	**%**	**135%**	**140%**	**130%**	**150%**	**60%**	**90%**	**105%**
Electricity Use, Total	Model	kWh/hh.d	10	15	10	10	10	30	10
	Actual	kWh/hh.d	15	20	10	15	10	20	10
	Model / Actual	**%**	**65%**	**75%**	**100%**	**65%**	**100%**	**150%**	**100%**
Natural Gas Use, Total	Model	kWh/hh.d	90	20	30	50	20	NA	10
	Actual	kWh/hh.d	TBC*	130	40	85	40	NA	10
	Model / Actual	**%**	**TBC***	**15%**	**75%**	**60%**	**50%**	**NA**	**100%**

**To be confirmed – inaccuracies with billing data received to date*

Table 3: First pass model outputs: Summary of key water, electricity, natural gas and WRE use breakdowns

Parameter	Units	HH1	HH2	HH3	HH4	HH5	HH6	HH7
Analysis Period	Start	Apr-12	Apr-12	Apr-12	Apr-12	Apr-12	Oct-11	Jan-07
	End	Mar-13	Mar-13	Mar-13	Mar-13	Mar-13	Sep-12	Dec-09
Water Use, Total	L/hh.d	730	860	410	650	175	460	465
Water Use, Shower	L/hh.d	360	490	130	165	100	240	150
Electricity Use, Total	kWh/hh.d	10	15	10	10	10	30	10
Natural Gas Use, Total	kWh/hh.d	90	20	30	50	20	NA	10
Solar Energy Use, Total	kWh/hh.d	10	15	NA	NA	NA	NA	NA
Energy Use, Total	kWh/hh.d	110	50	40	60	30	30	20
Water-related Energy Use, Total[a]	kWh/hh.d	15	20	10	10	5	10	10
	% of total	15%	40%	25%	15%	20%	30%	50%
Energy GHG, Total	kg CO_2-e /hh.d	30	45	15	25	10	35	15
Water-related Energy GHG, Total	kg CO_2-e /hh.d	5	5	4	5	3	15	5
	% of total	15%	10%	25%	20%	30%	45%	30%

[a] Includes solar component of water-related energy use

Table 4: Preliminary results: Parameters with greatest impact on total water, electricity and gas use

	Water, Electricity and Gas Use						
Household **Input Parameter**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
Cold Water Temperature	□Δ	□Δ	□Δ	Δ	□Δ	□	Δ□
Hot Water System Temperature	Δ		Δ				
Number of Adults in Household	○□Δ	○□Δ	○□Δ	○Δ	○□Δ	○□	○Δ
Number of Children in Household			○□Δ	○			○Δ
Shower Flow	○Δ	○Δ	○	○Δ	○Δ	○□	○Δ
Shower Duration	○Δ	○Δ	○	○Δ	○Δ	○□	○Δ
Shower Frequency	○Δ	○Δ	○	○Δ	○Δ	○□	○Δ
Shower Temperature	Δ	Δ	Δ	Δ	Δ	□	Δ
Bath Temperature			Δ	Δ			Δ
Bath Volume			○Δ	○			○Δ
Bath Frequency			○Δ	○			○Δ
Toilet Flush Volume	○		○	○	○	○	○
Toilet Flush Frequency	○	○	○	○	○	○	○
Clothes Washer Temperature	□	□	Δ		□		□
Clothes Washer Volume	○□	○	○	○	○□	○	○□
Clothes Washer Frequency	○□	□	○	○	○□	○	○□
Clothes Washer Power							
Dishwasher Power				□			
Dishwasher Frequency	□		□	□			□
Dishwasher Temperature	□		□				□
Dishwasher Volume							
Air Conditioner Duration	○□	○□		○□			□
Air Conditioner Water Use	○	○		○			
Air Conditioner Energy Use	□	□		□			□
Volume Kettle Boil			□	□	□		□
Frequency Kettle Boil			□	□	□		□
Dish Washing (Hand) Temperature		Δ					

LEGEND:

- ○ Total water use impact (greater than 1% change in response to 10% increase in input parameter)
- □ Total electricity use impact (greater than 1% change in response to 10% increase in input parameter)
- Δ Total gas use impact (greater than 1% change in response to 10% increase in input parameter)