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# Evaluating the energy and carbon reductions resulting from resource-efficient household stock

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## Abstract

The nexus of water and energy and greenhouse gas emissions is now well recognised, and the adoption of water-efficient technologies is viewed as imperative in reducing residential water end use related energy demand. However, quantifying the energy savings from (hot) water-efficient technologies has been largely based on modelled or assumed consumption data from water use appliances and fixtures, the type of hot water system and percentage use of hot water. The aim of this paper is to determine water, energy and greenhouse gas emission savings from resource-efficient household stock using empirical water end use data and detailed stock specifications and usage patterns for homes in south-east Queensland, Australia. Hot water system type and clothes washing machine configuration (e.g. load type and number of tap connections) is also considered with comparisons made between intervention scenarios with and without inclusion of a low energy heating system. Results confirm the significant impact that electric storage water heating has on total household energy consumption. Substantial energy savings can be achieved by substituting water (e.g. high star rating clothes washers and shower heads) and energy (e.g. solar hot water system) efficient appliances in the home. Results suggest that retrofitting cheaper resource-efficient technologies such as tap aerators and low flow shower heads are still a relatively effective means of reducing both water and energy consumption regardless of HWS type. Future research includes consideration of all thermal losses from heating systems and the use of empirical energy end use data.



**Keywords**: water end uses, micro-components, climate change, climate adaptation, energy-efficient technology, carbon footprint, intervention strategies, greenhouse gas, water heating

## 1. Introduction

*1.1 The water-energy-carbon footprint nexus*

Scientific research continues to provide evidence of the detrimental impacts that consumption of non-renewable resources are having on global climate patterns [1]. Further, it is becoming increasingly accepted that the simultaneous management of water and energy efficiency is essential in addressing future management climate change adaptation strategies [2-4]. The conflict between water use and associated energy consumption is often referred to as the water/energy nexus. This is particularly relevant in an urban context as studies continue to demonstrate the significant role that the urban resident plays in consuming water and energy resources [5-7]. Managing such interconnected resources has significant implications on the savings (or production) of greenhouse gas emissions [8-10]. As Fidar et al. [11] and Maas [12] observe, managing water demand through water-efficient technology and behavioural changes has strong implications for reducing greenhouse gas emissions as well as conserving potable water supplies. This argument becomes stronger when one considers the acceleration of economic development and subsequent rise in living standards some developing countries [13,14].

*1.2 Quantifying energy demand and carbon emissions from residential water end uses*

To quantify and manage the water-energy nexus, accurate knowledge on domestic energy and water uses can be used to predict carbon emissions and climate change impacts from the urban water cycle. While there has been a number of residential energy [7] and water [11, 15,16] end use studies, there is a lack of measured data on simultaneous water and energy consumption from residential end uses such as shower, washing machines and taps. This is especially important in jurisdictions where all new developments require the installation of energy and water-efficient fixtures to achieve a more sustainable water and carbon footprint. These government mandates are being implemented increasingly as part of the suite of climate change adaption strategies [10, 17,18].

A review of literature revealed that much of the work to date examining the energy demand from residential water end uses has taken the approach of modeling the energy demand from total water consumption data with the end uses of water inferred rather than measured. Further, the range of hot water systems available and the percentage of hot water used for tap, shower and clothes washer end uses is often unknown. Despite this, studies have yielded some valuable data and trends on the relationships between water use, energy demand and carbon emissions [9,19,20]. However, a consistent finding of the reviewed water and energy investigations was the absence of up to date empirical data underlying the calculations for the operational life cycle stage of residential water-use energy household stock and associated GHG emissions for urban dwellings. In many cases, water heating was assumed to be from electric water heater rather than other sources. Further, the impact of water-efficient technology on water-related energy in households has usually relied on modelled or low resolution water use data [11,21]. Thus, the aim of this study is to determine energy demand and their associated carbon emissions based on empirical, high-resolution water end use data and detailed stock specifications including water heater type and hot water usage from residential appliances and fixtures. Building on this, a second aim is to explore a range of efficient technologies and strategies that can be used to reduce household water and energy consumption and can underpin the decision making process for sustainable management of existing and new developments.

## 2. Methods

There were two major components to the methods: (1) determining water, energy and carbon emissions from measured water end uses; (2) and calculating the reductions in water, energy and carbon emissions from various resource-efficient household stock. Both components were based on an existing inventory of water end use data and detailed stock information and usage patterns generated from the South East Queensland Residential End Use Study (SEQREUS).

### *2.1 End use data acquisition*

The water end use data for this study was obtained from the SEQREUS (n=252 homes) using smart meters that measured flow to a resolution of 72 pulses/Litre (L) or a pulse every 0.014 L [15]. The smart meters were connected to data loggers that wirelessly transmitted the data weekly to a central computer. This data was then disaggregated into end uses using trace flow analysis software (Trace Wizard™). After eliminating homes with no consumption data and the total number for this study was n=211 homes, although in some cases the sample was lower (n=189) due to some missing stock appliance data (e.g. information on clothes washer cycle temperatures). Further discussion on the research methods in obtaining and analysing the end use data is provided in Beal et al. [15] and Beal and Stewart [22].

### *2.2 Determining energy demand for water appliances and HWS*

The measured end use data was used as a basis for determining energy and carbon emissions from clothes washers, dish washers, taps (hot water use) and showers (hot water component). Calculations used in determining energy demand are provided in Table 1.

Energy end use data for heating was available from a small pilot study sample which metered the electricity usage of an electric hot water system (HWS) as well as its hot water end uses (i.e. hot water going to shower) [23]. The heating electricity and distribution of hot water enabled the heating energy of individual water end uses to be determined (i.e. energy of morning shower by Adult A). In addition, completed water use diaries for each home in the SEQREUS also assisted in providing valuable information on water use patterns and often provided additional estimates on the proportion of hot and cold water tap usage. Finally, published values on hot water end uses were used to confirm the data from the trial study. A water use audit had been undertaken for each home in the SEQREUS, where the model and make of every water use appliance and fixture was recorded along with the water and energy-efficient star ratings. Information on clothes wash temperature (i.e. cold, warm or hot wash cycle) and number of washes per day were also known. Using this information, the energy demand from each water use appliance was determined using published values in the literature or from manufacturers' datasheets. While this approach may be potentially skewed by biased reporting of the energy usage, it was sufficient to give an indication of energy demand from the appliances in the absence of measured data available in the SEQ region.

**Table 1**

Summary of calculations used to determine the specific energy consumption from water use appliances and fixtures

| Water end use | Equations[1] | |
|---|---|---|
| | Total energy use (kWh/p/y) | Energy intensity (or specific energy) (kWh/kL) |
| Clothes washer | TOT EN = ME + $HWE(HWS)$ [Eq 1] | AWSE = $\frac{TOT\ EN}{LpW}$ [Eq 2] |
| Dishwasher | ME information from Australian Government [24] | $DSE = \frac{EC}{LpdW}$ [Eq 3] |
| Tap | $DECt = \frac{\%HWt \cdot TWC \cdot HWSen \cdot n}{\eta_{HWS}}$ [Eq 4] | $TSE = \frac{DECt}{TWC \cdot n}$ [Eq 5] |
| Shower | $DECs = \frac{\%HW(HWS)s \cdot SWC \cdot HWSen \cdot n}{\eta_{HWS}}$ [Eq 6] | $SSE = \frac{DECs}{SWC \cdot n}$ [Eq 7] |

[1] where: *TOT EN* = total energy consumption, *ME* = machine (appliance) energy demand, *HWE* = hot water energy (kWh/wash), *CWE* = cold water energy (kWh/wash), *HWE(HWS)* = hot water energy needed by the hot water system (kWh/wash), *LpW* = clothes washer water consumption in litres per wash (L/wash), *AWSE* = average washing machine specific energy, *DSE* = dishwashing specific energy, *DSE* = dishwasher specific energy (kWh/kL), *EC* = dishwasher energy consumption (kWh/use) obtained by dividing the overall energy consumption [24] by 365 days, *LpdW* = dishwasher water consumption in litres per cycle (L/cycle), *DECt* = daily energy consumption for taps (kWh/day), *%HWt* = percentage of tap hot water used, TWC = tap water consumption in litres per person per day (L/p/day), $HWSen =$ hot water system specific energy (kWh/kL), $\eta_{HWS}$ = efficiency of the hot water system, TSE = tap specific energy (kWh/kL), *n* = number of people living in the house, *DECs* = Daily Energy Consumption for Shower (kWh/day), *% HW(HWS)s* = Percentage of hot water used during a shower event, $HWSen =$ hot water system specific energy (kWh/kL), $\eta_{HWS}$ = efficiency of the hot water system, SSE = shower specific energy (kWh/kL), SWC = shower water consumption (L/p/day).

Calculations shown in Table 1 were applied to the measured and published water and energy data described above to predict energy consumption for each end use in each household in the study. The mean, median, standard deviation and 95% confidence intervals are reported for each end use to characterise the variation and uncertainties of energy demand data across households and end uses. Units are reported in kilowatt hours per person per year (kWh/p/y). Note that the source of data for calculations were taken from Australian Government [24-26] and Kenway et al. [27] when not provided directly from household water stock audit.

### 2.2.1 Clothes washer

Clothes washers (CW) are one of the most ubiquitous household appliances in the western world and are in use in an estimated 97% of Australian homes [13]. There are some important aspects to consider when calculating energy demand from clothes washers. Many of the later model machines are either horizontal axis (or front loading) machines that only have a single, cold water tap connection to the machine and thus source hot water from internal heating. Older models tend to be vertical axis (or top loading) machines that have a larger capacity and have dual water connections (e.g. hot and cold tap connection to the machine), where hot water is sourced from the external hot water service. The wide variety of heating, water connection and loading configurations mean that the water and energy demand can vary markedly between machines, as also observed by others [13, 27,28]. The proportion of hot and cold water needs to be considered, along with energy demand from internal heating compared with energy demand from HWS heating. Using information provided from the water audits and water diaries, each home was given a heating rating of cold, warm or hot depending on the typical load setting nominated by the householder (Table 2). The reported water demand (L/wash) available from the Australian Government Water Efficiency Labelling Scheme website [25] was compared against calculated water demand from disaggregated end use data files. There was a good correlation between the two, with a regression analysis showing an adjusted $R^2$ value of 0.91. The measured water demand of each washing machine was then used rather than published values. The equations used to calculate the energy demand from clothes washers is shown in Table 1.

**Table 2**
Number of washing machines for each HWS, water connection and wash cycle category

| Wash cycle temperature typical setting | Hot water system type | | | | | |
|---|---|---|---|---|---|---|
| | Electric cylinder | | Gas storage | | Solar (EB) | |
| | Single | Dual | Single | Dual | Single | Dual |
| Cold | 23 | 86 | 2 | 8 | 8 | 22 |
| Warm/Hot | 8 | 23 | 0 | 2 | 0 | 7 |

Note: 'Single' refers to a single cold water tap connection to washing machine, in this configuration, hot water is sourced from internal heating within the machine. 'Dual' refers to both a cold and hot water tap connection to washing machine, where the hot water is sourced from the external hot water service and not from internal heating.

### 2.2.2 Dishwasher

Unlike clothes washing machines, dishwashers (DW) are usually always a single connection to a cold water tap, with an internal element used to heat water. Therefore the energy consumption relating to dishwashers is relatively straightforward as it relates solely to appliance operation with no component of hot water system requirement. Energy consumption of dishwashers is also highly variable across machine models [29]. The energy demand for dishwasher use was calculated from the machine energy information supplied by the Australian Government energy rating website [24] (Table 1).

### 2.2.3 Taps and shower use

Energy consumption for tap end use is driven by the hot water component of tap usage. Hence, knowledge of the percentage of the hot water per use was necessary. As there is dearth of measured data relating to proportions of hot and cold water usage from taps, particularly the single lever models, data was based on information from water dairies and from published values in the literature. Almost 83% of the SEQREUS sample completed a self-reported water usage diary which provided a one week snap shot of each home's water use, including the frequency and duration of hot and /or cold tap usage. Although this is a subjective and informal dataset, and thus potentially unreliable, it nevertheless provided a valuable contribution to assist in obtaining typical hot to cold water ratios. A second method to obtain such data was to conduct a literature search of published values [23,29,30]. From this exercise, an average value of 42% was used for the proportion of hot water usage from every tap event. Using the percentage of hot water values derived from methods described above, energy consumption was calculated from the equations provided in Table 1.

Similar to tap use, shower consumption comprises a proportion of hot and cold water, with the hot water component generating energy demand only. Also like tap use, actual measured volumes of hot water used during the shower events is poorly documented in the literature, however a number of estimated values are suggested [27,29,30 ].

### *2.3 Hot water system energy requirements*

Although there was some variation in system types for heating water, the vast majority (65%) were electric HWS (sourced from coal-fired power stations) with the remainder comprising solar (21%), gas (12%), and heat pumps (2%) (Table 3). There are several important factors that need to be considered when calculating energy demand from HWS due to the inherent thermal losses and efficiency of such systems. These factors are influenced by age of system, type and thickness of material and ambient air temperatures amongst others. While it was not possible to account for all factors due to the absence of specific information, thermal losses due to air temperature differentials are embedded in the calculations for shower and tap hot water energy demand (Table 1). Refining the model input parameters and including energy demand beyond the operational stage of the appliances/fixtures (e.g. embedded energy and life cycle stages prior to and subsequent to operational stage) will be the subject of future investigations.

The energy consumption varies with the type of HWS as shown in Table 3, with the highest demand typically associated with the electric cylinder and gas cylinder. The carbon emission conversion factors for the various energy sources to heat water are also shown in Table 3. An emission factor of 0.138 was used for to determine carbon emissions from an electric boosted solar HWS based on the assumption of 10% requirement of electricity boosted heating during period of insolation. This was calculated based on historical climate data from the Australian Bureau of Meteorology website (Brisbane airport weather station) and using the value of 8.1 for average hours of sunshine [31].

**Table 3**

Energy intensity values and GHG emission conversion factors used for calculating GHG emission savings for hot water systems

| HWS type | Number in sample (% total) | Energy intensity (kWh/kL)[A] | GHG emission factor ($kgCO_2e/kWh$) |
|---|---|---|---|
| Electric | 177 (65) | 126.80 | 1.000[B] |
| Gas Cylinder | 22 (8) | 171.23 | 0.197[C] |
| Gas Instant | 11 (4) | 85.60 | 0.197[C] |
| Solar (electric boosted) | 56 (21) | 59.19 | 0.138[D] |
| Heat pump | 5 (2) | 22.09[E] | 0.500[F] |

[A]Kenway et al. [27] except heat pump values; [B]Australian Government [26] assuming 100% supply from coal-fired power station; [C]Australian Government [26] (2011) for natural gas; [D]assumes insufficient insolation for 10% of the year due to cloud cover (i.e. 0.038 [6] + 0.1×1.00), [E]heat pump energy intensity based on coefficient of performance, [F]assumed a 50% reduction in coal-fired electricity generation [32,33].

There was less information available in the literature on the energy requirements of heat pumps. These devices differ considerably from other HWS as they extract the heat in the air outside of the unit to the water stored inside the heater via an evaporator and pump device. The efficiency of a heat pump is expressed through the COP (or coefficient of performance), which for these calculations was fixed at 2.9 which is the common value of efficiency [34].

*2.4 Determining carbon emissions from water end uses*

It is possible to relate each kWh of energy used in the household to heat water with an amount of carbon emitted to produce that energy. The amount of emitted carbon is substantially influenced by the source of energy (e.g. coal-fired power station versus solar panels) used in the hot water service (Table 3). The average household in Australia is supplied by grid electricity generated from coal-fired power stations. Using published GHG emission factors and methods presented in the Australian National Greenhouse Accounts report [26] the energy use values were converted into GHG emissions. The GHG emission values are reported as kilograms of equivalent carbon dioxide ($CO_2$-e), a measure that incorporates the global warming potentials of a range of GHGs (e.g. methane and nitrous oxide).

*2.5 Resource-efficient stock intervention scenarios*

A number of scenarios were devised to determine the impact on carbon emission reductions from various water and energy-efficient technologies (Table 4). The data from each scenario was based on the average consumption calculated from SEQREUS homes that met existing sets of classification conditions.

**Table 4**

Resource-efficient intervention scenarios

| Scenario number | Intervention scenario | Rationale snapshot |
|---|---|---|
| S1 | Conversion to energy-efficient solar HWS | An increasingly popular choice for homeowners in Australia with government rebates offered. |
| S2 | Water-efficient shower heads | A very popular, cheap and effective technology [15,16]. |
| S3 | S2 + Water-efficient clothes washer | An increased penetration in Australian households with government rebates offered. |
| S4 | S3 + Tap aerators | Cheap and common solution to reducing volume but maintaining flow rate. Recommended in Queensland building codes. |
| S5 | S4 + Shower temperature reduced to average of 37 C˚ | Strategy to reduce hot water demand and heat losses [10,29] |
| S6 | S5 + Energy-efficient dishwashers (DW) | Increasing penetration in market place based on energy efficiency rather than water efficiency [ |

**Table 5**

Key assumptions for each intervention scenario (shown in Table 4)

| Scenario number | Assumptions |
|---|---|
| S1 | a) Solar panels with electric-boosted storage system; b) direct replacement of electric HWS; c) long term average solar radiation data taken from Brisbane airport and assuming same characteristics across SEQ d) 38 days or 10% of year with insufficient insolation. |
| S2 | a) Substitute high flow shower head with low flow shower head of flow rate at 0.09 L/s; b) co-efficient of 1.2 applied to compensate for increased duration due to lower flows. |
| S3 | a) CW internally heats cold water; b) front load only; c) cold water connection only; d) directly substituting dual connected front or top load CW. |
| S4 | a) Tap flow rate fixed value of 0.08 L/s [25] |
| S5 | a) Original shower temperature set at 40˚C [29]; b) existing shower head efficiencies (e.g. low or high flow roses) remain. |
| S6 | a) > 3 star rated machines considered ‘energy-efficient’; b) two efficiency clusters generated from SEQREUS data: ≤ 3 star and >3 star rated. |

For example, if determining the savings from replacing an electric HWS with a solar (electric boosted) HWS the average percentage difference between a cluster of homes with solar HWS and with electric only would then be applied to the base case. Percentage savings from the base case scenario (worst case scenario of no efficient strategies and electric HWS) were calculated when comparing to a range of sequentially applied water and energy efficiency intervention strategies.

Therefore a cumulative reduction in energy consumption can be determined as each new scenario is applied. The savings from each individual scenario was also calculated.  Some key assumptions were made during the development of these scenarios and are outlined in Table 5.

## 3. Results and discussion

### *3.1 Water and energy consumption for residential end uses*

Average annual water consumption breakdowns across residential end uses for the SEQREUS sample is shown in Fig. 1. Shower, clothes washer and tap usage comprised the bulk of the water consumption (69% combined) (Fig. 1). This represents a total of 33 kilolitres per person per year (kL/p/y) for shower, taps and clothes washer (CW).

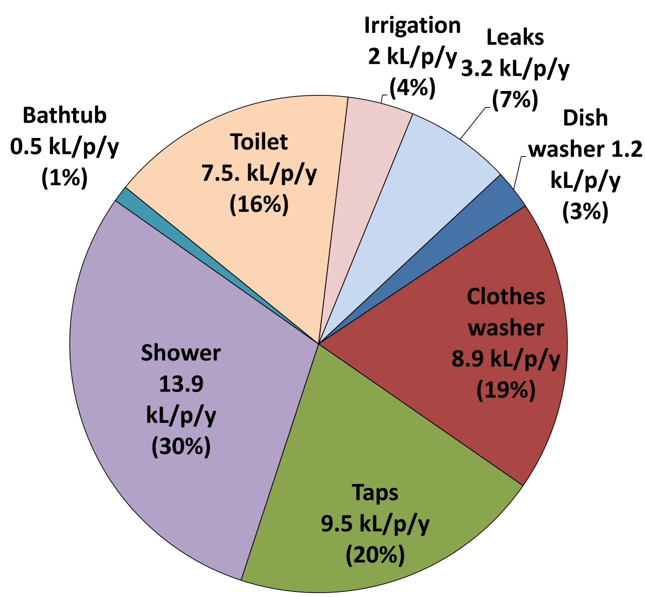
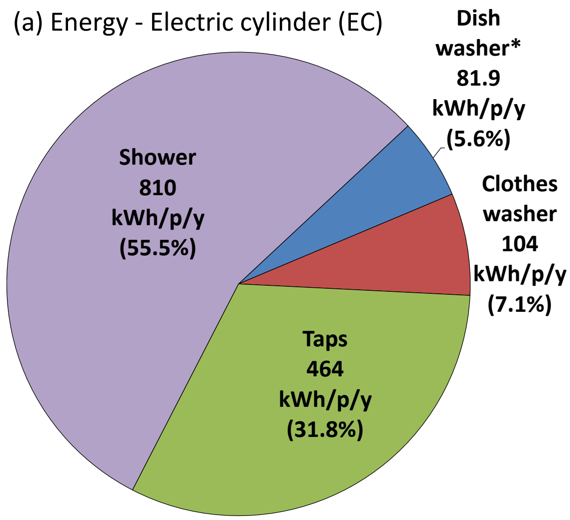
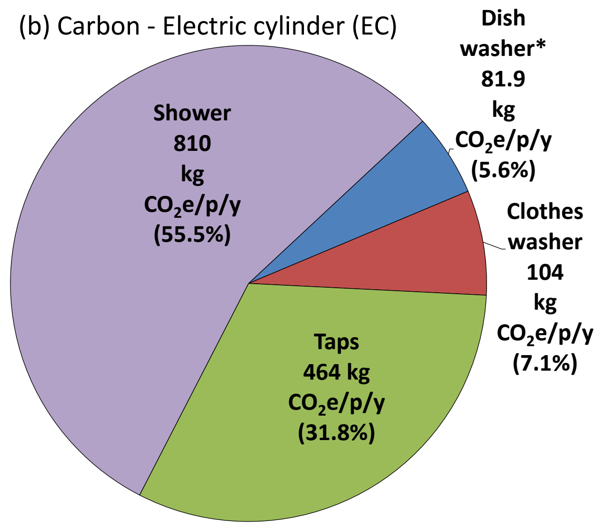


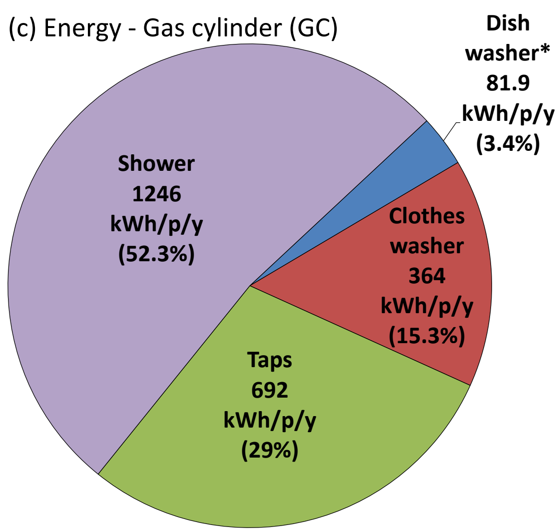

**Fig. 1**. Average annual end use breakdown for water consumption (kL/p/y.



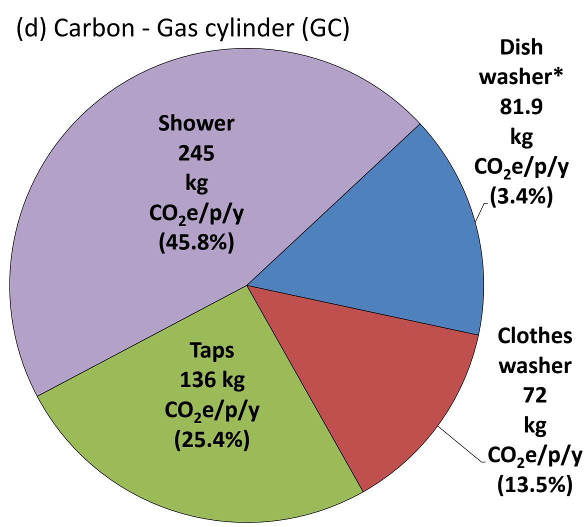

(a) average energy demand from EC



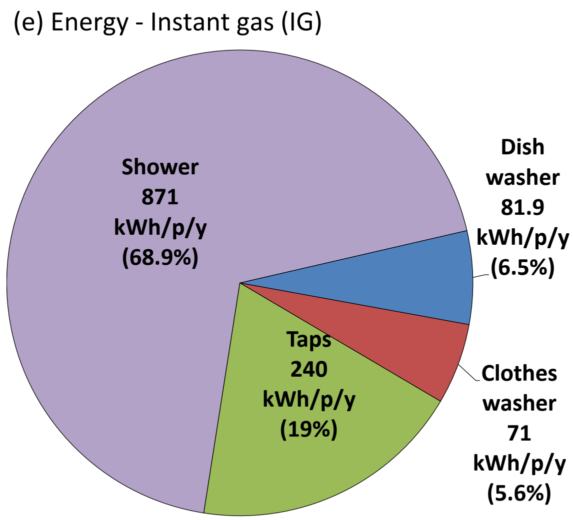

(b) average carbon emissions from EC



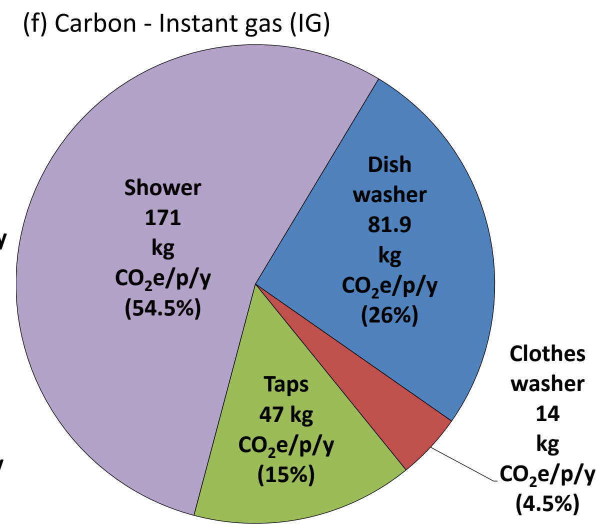

(c) average energy demand from GC



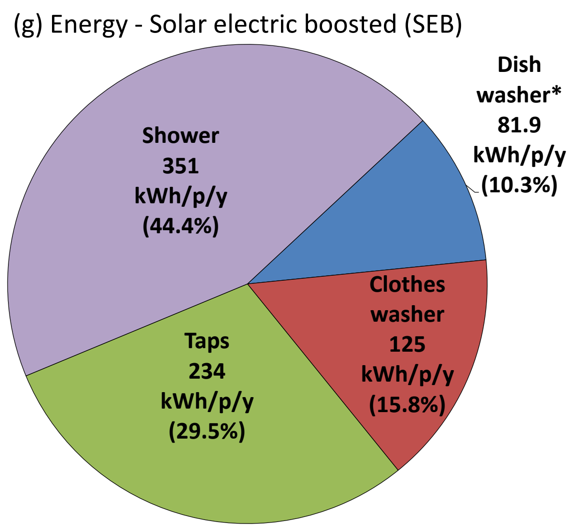

(d) average carbon emissions from GC



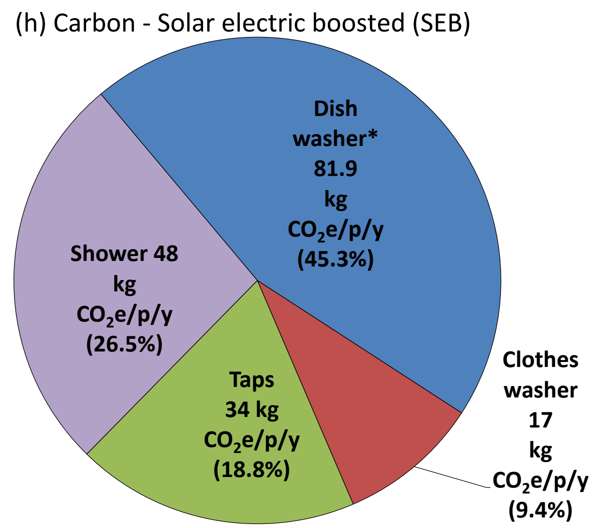

(e) average energy demand from IG




(f) average carbon emissions from IG




(g) average energy demand from SEB




(h) average carbon emissions from SEB

Note: *Dishwasher energy sourced solely from electricity grid using coal-fired power therefore energy demand and carbon emissions are constant for the four HWS scenarios.

**Fig. 2**. Average annual energy and carbon emissions end use breakdown for water-related energy based on hot water system

The proportions of annual energy demand and carbon emissions vary quite considerably across the four main HWS as shown in Fig. 2. Note that dishwasher energy demand and carbon emissions remain constant irrespective of HWS as 100% of energy requirements are drawn from the electricity grid generated from coal-fired power stations. However, the proportion of total energy and carbon emissions for dishwasher operation increases as coal-fired electric HWS sources are replaced with gas and solar HWS. Descriptive statistics for energy consumption for dishwasher and the hot water components of the shower and tap usage for the four main HWS types of electric cylinder (EC), gas cylinder (GC), instant gas (IG) and electric-boosted solar (SEB) is presented in Table 6. The energy associated with heating water is typically the major influence on household energy use [8,10] and thus hot water system type must be accounted for when comparing energy demand across end uses and households. Results demonstrate that SEB HWS require substantially less grid energy than conventional electric systems.

Specifically, energy demand can be reduced by an average of 460 kWh/p (or 56%) for shower use and 220 kWh/p (or 57%) for tap use annually if an EC was replaced with an SEB system (Table 6). This degree of energy demand reduction from solar HWS is consistent with other findings [36-38]. Even greater energy savings is indicated using a GC system due to its lower energy intensity than a EC (Table 3).

**Table 6**

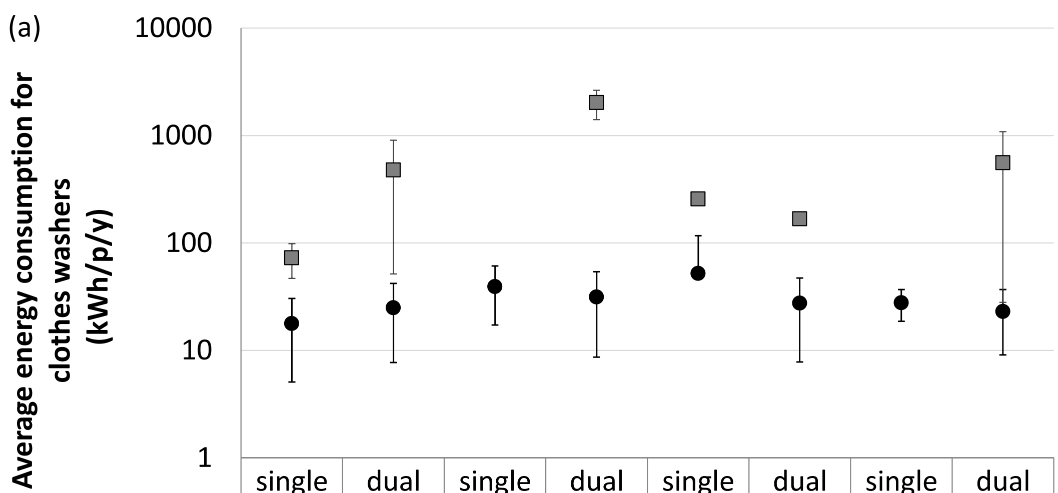
Descriptive statistics for energy consumption and carbon emissions from energy-related residential water end uses in average household.

| Hot water system | Statistic | Shower (hot water component) | | Tap (hot water component) | | Dishwasher[A] (machine operation + internal heating) | |
|---|---|---|---|---|---|---|---|
| | | Energy demand kWh/p/y | Carbon emissions kg $CO_2$.e/p/y | Energy demand kWh/p/y | Carbon emissions kg $CO_2$.e/p/y | Energy demand kWh/p/y | Carbon emissions kg $CO_2$.e/p/y |
| Electric cylinder (EC) (coal-fired power) | Mean | 810.3 | 810.3 | 463.8 | 463.8 | 81.9 | 81.9 |
| | Median | 714.8 | 714.8 | 422.5 | 422.5 | 73.7 | 73.7 |
| | SD | 521.7 | 521.7 | 317.6 | 317.6 | 71.6 | 71.6 |
| | 95% CI | 85.2 | 85.2 | 51.9 | 51.9 | 19.5 | 19.5 |
| Gas cylinder (GC) | Mean | 1246.4 | 245.4 | 691.8 | 136.3 | - | |
| | Median | 1080.7 | 212.9 | 492.8 | 97.1 | | |
| | SD | 624.0 | 184.7 | 591.7 | 116.6 | | |
| | 95% CI | 353.1 | 109.1 | 334.8 | 66 | | |
| Instant gas (IG) | Mean | 871.5 | 171.7 | 239.6 | 47.2 | - | |
| | Median | 630.6 | 124.4 | 190.8 | 37.6 | | |
| | SD | 937.5 | 187.4 | 214.2 | 42.2 | | |
| | 95% CI | 554.0 | 109.1 | 126.6 | 24.9 | | |
| Solar [B] (Electric boosted) (SEB) | Mean | 350.8 | 48.4 | 244 | 33.7 | - | |
| | Median | 324.7 | 44.8 | 215.6 | 29.8 | | |
| | SD | 184.3 | 25.4 | 179.5 | 24.8 | | |
| | 95% CI | 57.1 | 7.9 | 56.3 | 7.8 | | |

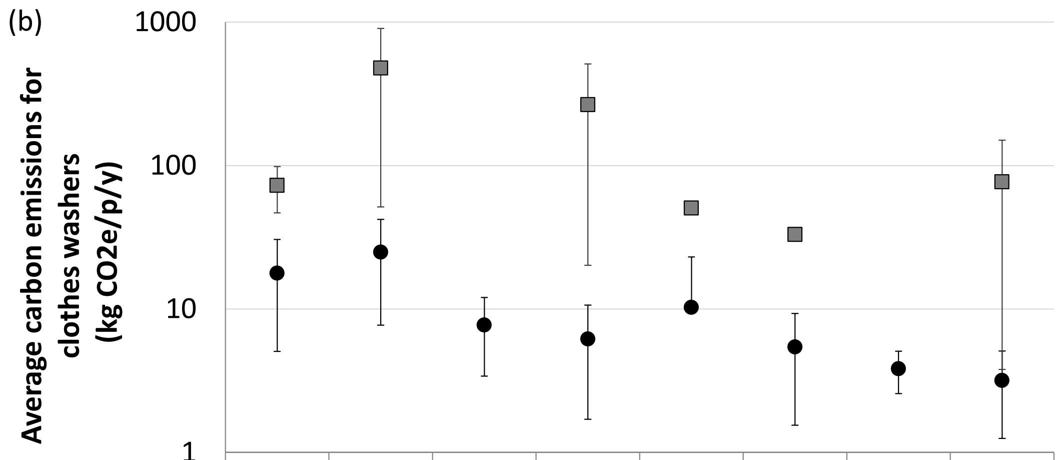
[A] assuming all dishwashers are operated from energy sourced from coal-fired power stations, where carbon emissions factor = 1.0 [26], B assuming electric booster used 10% of the year i.e. carbon emissions factor = 0.138 (0.1 [coal-fired power station] + 0.038 [solar panels]).

As all dishwashers for the sample internally heated water, energy consumption is solely from the mains electricity grid and is comparatively low at an average of 82 kWh/p/y, compared to the fixtures reliant on the HWS. Average energy demand from showering ranges from 1246 kWh/p/y (GC) to 351 kWh/p/y (SEB). A sensitivity analysis indicated that % hot water consumption determined energy demand more so than HWS type. As shower usage is consistently the greatest proportion of total indoor water consumption in homes, this is an ongoing area for demand managers to target both from a water and energy perspective. For tap usage, energy demand was lower than showers as expected due to the reduced total water consumption (4.4 kL/p/y less than showers), including a 2% reduction in average hot water consumption.

Estimating the energy demand from clothes washers is more complex and requires consideration of the various configurations of tap connections, HWS types and temperature wash cycles. Fortunately, the data registry available from the SEQREUS allowed a high level of precision in clustering each of the configurations, although sample size was quite low for some categories (see Table 2). Average and standard deviations of energy consumption for each of these configurations is displayed in Fig. 3a.




| | Electric | | Gas cylinder | | Instant gas | | Solar (EB) | |
|---|---|---|---|---|---|---|---|---|
| | single | dual | single | dual | single | dual | single | dual |
| ● Cold | 17.8 | 24.9 | 39.2 | 31.4 | 52 | 27.5 | 27.7 | 23.0 |
| ■ Warm/Hot | 72.7 | 478.5 | | 2024.5 | 256.3 | 167.8 | | 558.0 |




| | Electric | | Gas cylinder | | Instant gas | | Solar (EB) | |
|---|---|---|---|---|---|---|---|---|
| | single | dual | single | dual | single | dual | single | dual |
| ● Cold | 17.8 | 24.9 | 7.7 | 6.2 | 10.25 | 5.43 | 3.8 | 3.2 |
| ■ Warm/Hot | 72.7 | 478.5 | | 265.9 | 50.5 | 33.0 | | 77.0 |

**Fig. 3**. Average (a) energy consumption and (b) carbon emissions from clothes washing machines. Error bars represent standard deviation.

The lowest energy demand was from machines using a cold cycle exclusively where no warm/hot wash is used and therefore there is no requirements for hot water (externally or internally heated). The energy demand from these machines are based on the published values for each machine and are irrespective of HWS. Once a warm or hot cycle is chosen with a single (internally heated) or dual (external hot water from HWS) connected machine, then energy demand rises. For a single, cold tap only connection warm or hot wash cycle, energy demand is solely from the machine (operation plus internal heating) thus is again irrespective of HWS. However, for a dual connection warm/hot wash the hot water is sourced from the HWS and energy demand sharply increased, particularly so for an EC, 478.5 kWh/p/y, and a GC, 2024.5 kWh/p/y (Fig.3 ).

*3.2 Carbon emissions from energy-related water end uses*

Water-related carbon emissions are also presented for the dishwasher, tap and shower (Table 3) and clothes washers (Fig 3b). The carbon emissions from end uses relaying non a solar HWS with electric booster are based on the assumption that the electric booster would only be required 10% of the year based on average sunny days in the sub-tropical climate for Brisbane, Queensland. Any extrapolation of these values to regions of lower insolation need to consider greater reliance on the electric booster and thus would potentially increase the carbon emissions associated with a SEB HWS.  Notwithstanding this, the reduction in carbon emissions associated with an alternative HWS to electric is clear; whether it be a gas or solar based HWS.

In terms of end uses, results demonstrate that appliances that internally heat water are substantially more economical in terms of operational energy demand and carbon emissions than those that source hot water externally from an electric or gas cylinder. This is exemplified by the results for dishwashers and single connected clothes washers where carbon emissions were an average of 82 (SD± 72) kg $CO_2$-e/p/y and between 3.8 (SD± 1.3) to 73 (SD± 26) kg $CO_2$-e/p/y, respectively. In comparison, carbon emissions from sourcing hot water from either gas or electric storage (cylinders) ranged from 245 (SD± 185) to 810 (SD± 523) kg $CO_2$-e/p/y for respectively, for showers and 136 (SD± 116) to 464 (SD± 318) kg $CO_2$-e/p/y respectively, for taps (Table 3). The large standard deviation observed for energy use and subsequent carbon emissions, is a reflection of the inherent variability in water and energy demand from appliances and fixtures within a household [21,29].

*3.3 Energy intensity comparisons between end use appliances and fixture*s

Energy intensity (EI), sometimes referred to as specific energy, is a quantum of the kilowatt per unit of water used, and in this case is expressed in kilowatts per kilolitre (KWh/kL). A comparison of EIs is useful as it provides gauge of the relative energy efficiency for each water end use (Fig. 4). Again, end uses which rely on externally heating water clearly have higher EIs than those that internally heat water, with the exception of dishwashers which had an EI of 55 (SD± 11) kWh/kL. This suggest that the typical dishwasher is not overly energy-efficient in relation to the amount of water it requires, however due to the low water demand, around 2-3% total average household water consumption (Fig. 1), its overall energy demand is reduced.

Clothes washer with dual connection on a warm/hot wash cycle requires energy for both heating water and appliance operation. In this study the EI for these activities were 55.1 (SD± 16) and 3.3 (SD± 1) for external heating and operation, respectively. Conversely, for the same warm/hot wash cycle, the single connected clothes washers had an average EI of 4.2 (SD± 3) kWh/kL. That is, the additional energy required to heat the water internally is lower than the energy required to heat the water via the HWS which heats larger volumes of water to a great temperature. The majority of these single connected systems were front loading (or horizontal axis) machines. The results emphasise the importance of knowing details on clothes washer configurations in order to produce a representative dataset.

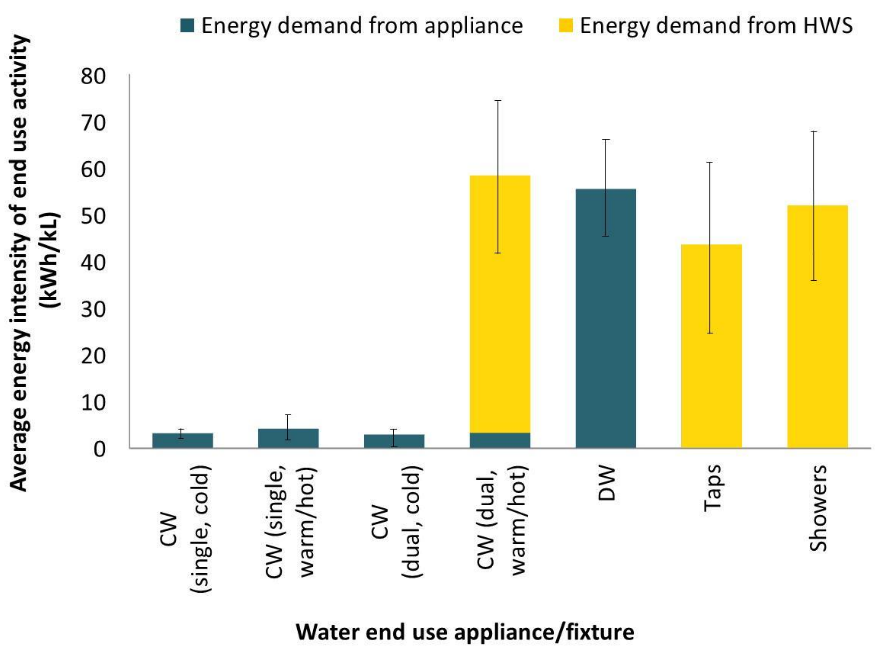
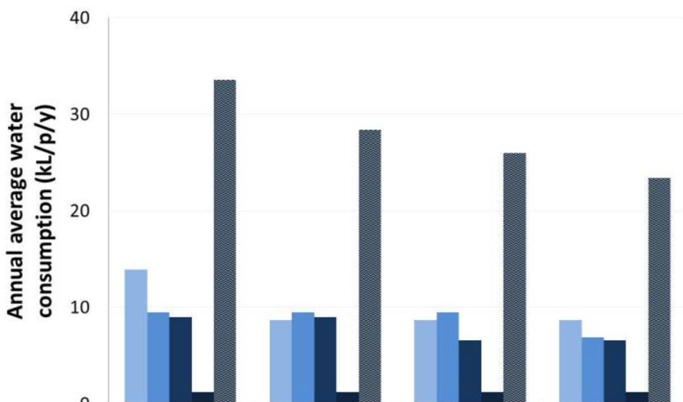



**Fig 4.** Average energy intensities for water-related energy in households.

*3.2 Impact of intervention scenarios on water, energy and carbon emissions*

3.2.1 Total household savings

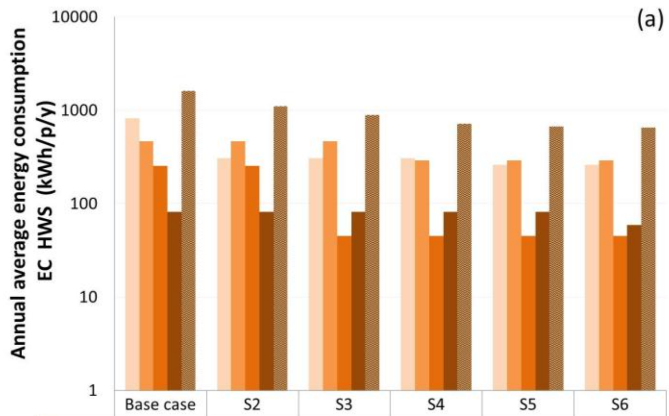
A number of energy-efficient intervention scenarios were modelled to quantify reductions in carbon emissions compared with base (worst) case scenario for a household with no water-efficient appliances/fixtures and an electric cylinder HWS. The scenarios described in Tables 4 and 5 were modeled for shower, tap, clothes washer and dishwasher. Results shown in Fig. 5 relate to annual water consumption starting with the base case using SEQREUS data from homes without any of the water-efficient technologies. Cumulative reductions are then shown as each scenario is applied (i.e. the final row in Fig 5. assumes all the previous scenarios are applied as well as installing a 4 star shower head). Results show that a savings of 10.2 kL/p/y can be achieved by installing a combination of water-efficient shower, tap and clothes washer stock. The water savings from efficient clothes washers are a little lower than reported elsewhere [e.g. 28], and may be a function of a small number of elevated water usage for a small number of homes with high star-rated machines. Beal et al. [39] discuss the phenomenon where people with a high level of water-efficient stock do not necessarily exhibit water conserving behaviours (such as reducing washing loads) and this may also have been a factor in the observed lower water savings from homes with water-efficient clothes washers.




| | Base case | S2 | S3 | S4 |
|---|---|---|---|---|
| Shower | 13.9 | 8.7 | 8.7 | 8.7 |
| DW | 9.5 | 9.5 | 9.5 | 6.9 |
| CW | 9.0 | 9.0 | 6.6 | 6.6 |
| Taps | 1.2 | 1.2 | 1.2 | 1.2 |
| Total | 33.6 | 28.4 | 26.0 | 23.4 |

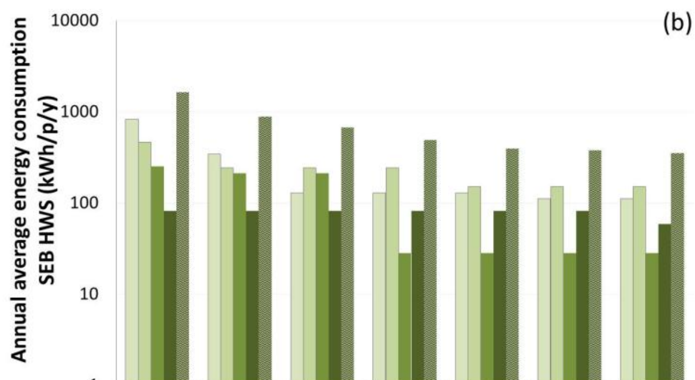
**Fig. 5.** Cumulative impact of various water-efficient intervention scenarios on water consumption savings. Savings are cumulative as each scenario is applied – see Table 4.

The annual household energy consumption and carbon emission savings was also predicted for various resource-efficient stock for two groups: (i) no change to an existing electric HWS (Fig. 6a); and (ii) replacement of an electric HWs with a solar HWS (SEB) (Fig. 6b and Fig 7). Both these scenarios have been presented to represent older/existing homes with retrofitted resource-efficient indoor stock but an existing EC HWS, and newer homes built under current building code sustainability requirements which would include both an efficient HWS (in this case a SEB) and resource-efficient stock. Knowledge of the savings from both scenarios can assist in the decision making for developing future building development codes.




| | Base case | S2 | S3 | S4 | S5 | S6 |
|---|---|---|---|---|---|---|
| Shower | 821 | 305 | 305 | 305 | 259 | 259 |
| Taps | 464 | 464 | 464 | 291 | 291 | 291 |
| CW | 252 | 252 | 45 | 45 | 45 | 45 |
| DW | 82 | 82 | 82 | 82 | 82 | 59 |
| Total | 1619 | 1103 | 896 | 723 | 677 | 654 |

(a) Energy savings from an existing EC HWS + efficient stock.

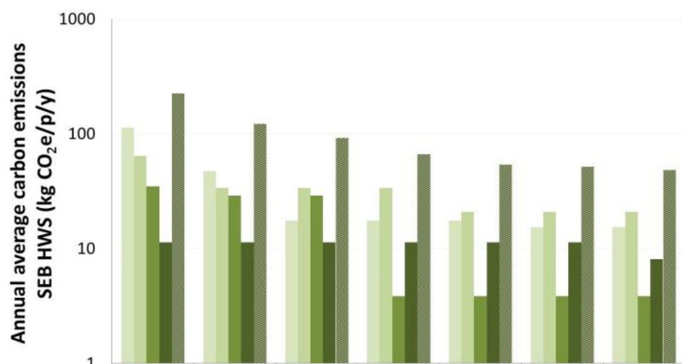



| | Base case | S1 | S1 + S2 | S1 + S3 | S1 + S4 | S1 + S5 | S1 + S6 |
|---|---|---|---|---|---|---|---|
| Shower | 821 | 345 | 128 | 128 | 128 | 112 | 112 |
| Taps | 464 | 244 | 244 | 244 | 151 | 151 | 151 |
| CW | 252 | 211 | 211 | 28 | 28 | 28 | 28 |
| DW | 82 | 82 | 82 | 82 | 82 | 82 | 59 |
| Total | 1619 | 882 | 665 | 482 | 389 | 373 | 350 |

(b) Energy savings by replacing an existing EC HWS with a SEB HWS + efficient stock.

**Fig. 6.** Cumulative impact of various water and energy-efficient intervention scenarios on annual household energy consumption. Savings are cumulative as each scenario is applied – see Table 4.

Results demonstrate that substantial savings to energy and carbon emissions can be achieved by retrofitting without replacing an existing EC HWS (Fig 6a). If all intervention scenarios were adopted, an energy savings of about 965 kWh/p/y (or 60%) may be achieved. This equates to the same volume of carbon emissions savings due to the emissions factor of 1 for Queensland [26]. In contrast, average energy and carbon emissions savings from applying the same scenarios to households who also installed a SEB HWS were estimated at 1,269 kWh/p/y (or 78%) (Fig. 6b) and 175 kg/$CO_2$-e/p/y (Fig. 7), respectively.




| | Base case | S1 | S1 + S2 | S1 + S3 | S1 + S4 | S1 + S5 | S1 + S6 |
|---|---|---|---|---|---|---|---|
| Shower | 113 | 48 | 18 | 18 | 18 | 15 | 15 |
| Taps | 64 | 34 | 34 | 34 | 21 | 21 | 21 |
| CW | 35 | 29 | 29 | 4 | 4 | 4 | 4 |
| DW | 11 | 11 | 11 | 11 | 11 | 11 | 8 |
| Total | 223 | 122 | 92 | 67 | 54 | 51 | 48 |

**Fig. 7.** Cumulative carbon emission savings by replacing an existing EC HWS with a SEB HWS + efficient stock. Savings are cumulative as each scenario is applied – see Table 4.

*3.3 Savings from individual resource-efficient stock*

Individual volumetric and percentage savings for each resource-efficient scenario were also determined (Table 7). Installing a solar HWS (electric boosted) was the most energy-efficient scenario reducing total household energy savings of around 46% at an equivalent volumetric savings of 737 kWh/p/y and 102 kg $CO_2$-e/p/y. Results from other studies suggest that this may be a conservative estimation with reductions of up to 60% [27] and 75% [40], however there are many factors that influence the efficacy of solar HWS which must be considered when comparing energy reductions and subsequent carbon emissions savings. These include climate, type and location of solar cells and storage systems, and method of booster (gas or electric).

In terms of the most optimal solution for reducing both water *and* energy saving is the installation of a low flow shower rose. This resulted in a potential total savings of 37% of annual total household water consumption and 63% energy savings (Table 7). This is the best water/energy saving combination of all scenarios tested, and also one of the cheapest. Other studies have shown the substantial reductions to total household water and energy use from low flow shower heads [11,41]. Locally however, the margin for savings may not be as great than for other resource-efficient strategies, such as water-efficient clothes washers, due to the already high penetration of low flow shower heads in Australian homes. Savings of around 183 kWh/p/y and 25 kg $CO_2$-e/p/y (or 27%) were found by installing a water-efficient single connected clothes washers. Reducing the temperature of the hot water from 40 to 37° C also resulted in notable energy savings of about 13% (Table 7). Replacement of standard dishwashers to low energy use dishwashers reduced energy demand by 23 kWh/p/y, which is an annual savings of about 28 % of carbon emissions per person.

**Table 7**

Individual savings from various resource-efficient scenarios

| Resource-efficient scenario | Individual Savings – volumetric | | | Individual Savings – percentage | |
|---|---|---|---|---|---|
| | Water consumption (kL/p/y) | Energy consumption (kWh/p/y) | Carbon emissions[A] ($kgCO_2$-e/p/y) | Water consumption (%) | Energy consumption[B] (%) |
| Solar HWS (EB) | - | 737 | 102 | - | 46 |
| Water-efficient shower head | 5.2 | 217 | 30 | 37 | 63 |
| Water-efficient clothes washer | 2.4 | 183 | 25 | 27 | 87 |
| Tap aerators | 2.6 | 93 | 13 | 27 | 38 |
| Shower reduced to 37°C | - | 16 | 6 | - | 13 |
| Energy-efficient dish washer | - | 23 | 3 | - | 28 |

Notes: [A] applicable for conversion to solar HWS (electric-boosted) only as current carbon emissions factor for electricity generated from coal-fired power stations in Queensland is 1 [26], therefore carbon emission savings if no conversion from EB HWS to SEB HWS will equal the values in the energy consumption volumetric savings column; [B] carbon emission percentage savings is equivalent to energy consumption percentage savings.

Calculations show that replacing a conventional electric HWS with SEB HWS, the annual carbon emissions can potentially decrease from an average of 1,618 to 882 kg $CO_2$e/kWh/p/y. However, this is a slightly simplistic argument, particularly in regard to economic savings – replacing an old electric with a new solar HWS can be expensive. Calculated payback periods for solar HWS and low flow shower heads were estimated at 9.6 years and 1.1 years, respectively. This aligns well with other reported values by where a payback period for water-efficient shower devices is between 1 to 1.5 years [16] compared to installing a solar HWS which may be around 10 years [38]. Retrofitting old shower heads with low flow roses is regarded as a cheap and relatively easy to install solution to reducing both energy and water consumption.

## 4. Conclusions

There is considerable variation and uncertainty in estimating water and energy consumption and greenhouse gas emissions from water end uses. A major driver of water-related energy is the type of hot water system and percentage of hot water demanded from each end use. Such knowledge was available from over 200 homes for this study and highlighted the reductions in energy demand and carbon emissions achievable from replacing an electric hot water system with a solar system (with electrical booster). Further, the energy intensities (or specific energy) from clothes washers vary widely depending on number of tap connections and temperature of wash cycle. Unsurprisingly, end uses that relied on an externally heated water source, such as showers and hot water tap usage, consumed the most energy and generated the highest carbon emissions annually per capita. In terms of the most optimal solution for reducing both water *and* energy saving technology is installing a low flow shower rose. This resulted in a potential total savings of 37% of annual total household water consumption and 63% energy savings. Cold tap only connected washing machines were also very effective in reducing energy demand, even if the warm/hot wash temperature cycle was used.

Mandating resource-efficient technologies in building codes such as tap aerators, low flow shower heads and solar or instant gas hot water systems will significantly reduce residential energy demand in new developments. Understanding the linkages between residential water and energy consumption can inform design optimisation and improve the sustainability of future urban planning. For example, knowledge of the savings achievable from retrofitting homes with resource-efficient technology with existing electric storage water heaters or mandating new homes with both heating system and internal resource-efficient technologies can assist decision makers on the optimal solution for future sustainable urban planning. In this study, it was shown that retrofitting with simple and cheap water-efficient technologies can markedly reduce energy savings due to the reduction in water consumption.

Limitations of the study relate to the energy consumption values used for generating carbon emission estimates; only a small pilot sample of HWS was instrumented (water and electricity use). Moreover, theoretical and not empirical appliance energy use data was used (although this is presently common practice). Accounting for thermal losses from the HWS would also reduce uncertainties in the data. Ideally, all water appliance or fixture energy consumption and HWS end uses would be based on a representative sample of field collected empirical data. This is a primary aim of a forthcoming research project using 150 homes which will be monitored for energy and water end use consumption.

## 5. Acknowledgments

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