Unpacking the energy implications of distributed water infrastructure: how are rainwater systems performing?

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ABSTRACT

Drought and concern over climate change has led to the increased use of distributed water systems in Australia to supplement centralised supply systems. A literature review carried out by the Institute for Sustainable Futures (ISF) into the energy consumption of water infrastructure found that very little data on energy consumption exists, particularly for distributed systems. This paper reviews the findings of the literature review and presents results from a preliminary monitoring study on the energy implications of household rainwater systems. Typical household systems that are currently being installed in ouses cross Australia use approximately 1.5 kWh/kL.

Key words | distributed water systems, evaluation, monitoring, rainwater, water-energy

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INTRODUCTION

The nature of water supply systems in Australia and other countries has been changing significantly over the past decade, due to extended droughts and concern over climate change. Existing large scale centralised supply systems drawing from dams and groundwater are being augmented with alternative supplies which are less rain dependent, such as large scale desalination and water recycling plants. Simultaneously, smaller scale water supply systems are gaining currency, such as package water recycling plants and household greywater and rainwater systems–collectively referred to as distributed systems.

While the focus to date has been on increasing water supplies and managing water demand through water efficiency programs, the energy implications of these new systems has typically been overlooked. In Australia, understanding the energy impacts of large scale systems has only recently been investigated by people such as Kenway *et al.* (2008). However, for distributed water systems, energy demand remains a significant knowledge gap. This raises two major concerns; firstly, that the energy intensity of these systems could potentially be high and that they are being rapidly installed without regard to energy efficiency; and secondly, that the energy intensity of our water supplies

as a whole is increasing unchecked. A 'whole of system' perspective is needed to ensure that our water service provision is not having a detrimental impact on energy usage and greenhouse gas production.

THE RISE IN DISTRIBUTED SYSTEMS

In Australia, distributed systems are increasing in popularity on several fronts. The rise in new 'green' buildings is being supported by sustainability rating tools such as Greenstar, run by the Green Building Council of Australia which awards points for recycling wastewater within buildings. This has led to the increased use of package wastewater treatment plants, which are usually installed in the basements of high-rise buildings so that water can be reused for non-potable end uses.

State legislation introduced in New South Wales in 2004 has mandated that all new housing be designed to reduce mains water consumption by 30–40% from a baseline, depending on location. This legislation, called BASIX (Building Sustainability Index) is focused on improving the energy and water efficiency of new residential buildings. Aside from the installation and use of water

efficient fixtures and appliances, this legislation has led to the widespread use of household rainwater tanks as an alternative water supply and to a lesser degree, greywater reuse systems. At some new housing developments, water savings are being achieved through the use of cluster or estate scale water recycling schemes. However, rainwater tanks are most commonly chosen as the means to achieve water savings, with around 96% of new households choosing to install a rainwater tank under the BASIX legislation (Department of Planning (NSW) 2008).

For those in existing homes, generous rebates are available from water utilities as well as state and federal governments for residents willing to install rainwater tanks and greywater systems. In Sydney, rainwater tank rebates of up to $1,500 AUD are available for existing households installing rainwater supply for indoor end uses and approximately 47,000 rainwater tank rebates have been given to householders in Sydney to date (Sydney Water Corporation 2008). As of 2008, the Australian federal government has set aside $250 million AUD to provide rebates to householders under the National Rainwater and Greywater Initiative (DEWHA 2009). The most recent available statistics on rainwater use state that in 2007, there were 1.66 million rainwater tanks in use in Australia, which represents 20% of all dwellings ((ABS) Australian Bureau of Statistics 2007).

THE NEED FOR EVALUATION

Distributed systems have a number of features that may cause them to use more energy than large scale centralised systems. To begin with, these systems use smaller pumps that are typically less energy efficient. These systems sometimes also include small storages and a number of small pumps operating in series, which can be inefficient if double pumping of water is necessary due to the system configuration. In addition, small scale systems use a variety of different treatment technologies and system configurations tailored for a specific location. This uniqueness makes it difficult to generalise about the energy usage of new systems being installed and means that monitoring of a range of different systems will be required.

The individual and specific nature of distributed systems provides unique opportunities to augment water supply, by using locally available resources, to suit local needs. They also provide a means of increasing water supply incrementally, as required, rather than developing large scale water infrastructure that may not be fully utilised until some time in the future. Hence they are an invaluable option within the spectrum of options available to augment water services into the future. However, due to the variability in system configuration and the water industry's lack of knowledge on their energy usage there is a need to fill this knowledge gap and ensure careful consideration is given to optimising the design of distributed systems to ensure maximum water and energy efficiency. To enable this, monitoring, evaluation and learning from existing systems is urgently needed.

LITERATURE REVIEW ON THE WATER-ENERGY NEXUS

The Institute for Sustainable Futures (ISF) in collaboration with the Commonwealth Scientific and Research Organisation (CSIRO) carried out a preliminary study investigating the energy implications of distributed water infrastructure. This study commenced with an extensive literature review[1] documenting research in the water-energy nexus, particularly from the perspective of the water industry.

Centralised large-scale infrastructure

The literature review found that a number of studies have been carried out at the city scale, where elements of an entire city's water supply system have been examined to determine the overall energy intensity of the water supplied and wastewater discharged. The Pacific Institute carried out one such study on the energy intensity of different elements in Californian water systems (Cohen et al. 2004). The results have been summarised in Table 1 and include ranges for different treatment types and inter-basin transfers, depending on the source of the water.

Water transferred from San Francisco to Southern California has an energy intensity of 2.43 kWh/kL, even before it has been treated and distributed to customers. This water transfer, 'The California State Water Project' uses 2–3% of the total energy consumed within California

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[1] (Retamal 2009a) http://www.isf.uts.edu.au/publications/retamaletal2009wenlitreview.pdf.

Table 1 | Average energy intensities of steps in the Californian water cycle (Cohen et al. 2004)

Step in water cycle	Average energy intensity (kWh/kL)
Water transfer from San Francisco to Southern California	2.43
Water transferred from the Colorado River to Southern California	1.62
Raw water treatment	0.56
Local distribution	0.21 (up to 1.16 depending on location)
Wastewater treatment	
Trickling filter	0.28–0.72
Activated sludge	0.42–0.92
Advanced treatment	0.49–1.07

(Cohen et al. 2004). If raw water treatment, local distribution and wastewater treatment and conveyance are added to this, the energy intensity of one kilolitre passing through the urban system could be as high as 5 kWh/kL, with the water transfer making up half of this. This example highlights the potential energy impacts of large scale water system augmentation. Such energy intensive water supply options leave a legacy of high energy demand for the future.

The energy consumption of water supply and wastewater treatment components in some of Australia's major cities has recently been collated by Kenway et al. (2008). The results from Kenway's study have been converted to energy intensities and are shown in Table 2.

The table shows that the energy intensity of water supplies in Adelaide, Sydney and Perth are currently considerably higher than for water supplies in Melbourne or the Gold Coast. The key difference and reason for higher energy intensities in these cities is that all three have had major system augmentation works that have been built in response to recent droughts. The energy intensities of the supply systems before and after these major works are shown in Table 3.

Pumping from the Shoalhaven River has quadrupled the energy intensity of the Sydney's water supply. While in Perth, the construction of a 45,000 ML/a desalination plant in 2006 doubled the energy intensity of water supplied. Water supply energy intensity also doubled from one year to the next in Adelaide, as drought conditions prompted large-scale water pumping from the Murray River.

Table 2 | Summary of energy intensities associated with water treatment, supply and wastewater disposal in cities around Australia during 2006/07 (adapted from Kenway et al. 2008)

City	Water supplied (kWh/kL)	Waste-water (kWh/kL)	Total excluding end use (hot water) (kWh/kL)
Sydney	1.03	0.47	1.49
Melbourne	0.09	1.13	1.22
Brisbane	0.68	0.57	1.25
Gold Coast	0.21	1	1.21
Perth	0.98	0.71	1.7
Adelaide	1.84	0.69	2.52

This upward shift in the energy intensity of water supply systems is likely to represent the start of a trend; as new, resource intensive water supply infrastructure is currently being planned and built in cities around Australia. In Sydney and Melbourne, new desalination plants are being built and a second plant is underway for Perth. On the Gold Coast, the Western Corridor Water Recycling project is nearing completion. These projects will further increase the energy intensity of water supply in these cities, beyond those observed in 2006/07.

Figure 1 illustrates this upward trend by using Sydney as an example. The average household water consumption, approximately 250 kL/annum, has been multiplied by the energy intensities of the water supply in 2001, 2006 and in 2011. This graph shows the historical increase in energy consumed through the use of mains water supplies in 2001 and 2006. For 2011, the Kurnell desalination plant (currently under construction) is assumed to be on line and contribute 10% of Sydney's water supply at an energy intensity of

Table 3 | Energy intensity of water supply before and after large-scale system augmentation in Sydney, Perth and Adelaide (adapted from Kenway et al. 2008)

City	Year	Energy intensity (kWh/kL)	Comments
Sydney	2000/01	0.25	
	2006/07	1.03	Inter-basin transfer (Shoalhaven)
Perth	2001/02	0.56	
	2006/07	0.98	Desalination
Adelaide	2005/06	0.85	
	2006/07	1.84	Inter-basin transfer (Murray)
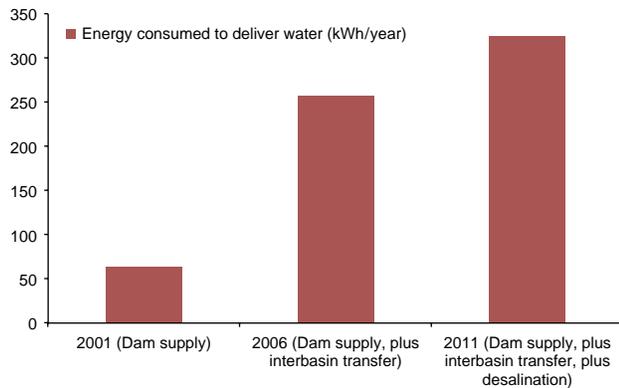
Figure 1 | Increase in energy consumed through water supplies for an average household in Sydney, Australia.

5 kWh/kL. It is also assumed to operate in addition to the Shoalhaven water transfer in 2011. Figure 1 provides an example of how energy consumption in the water sector can rapidly increase if water supplies are augmented through more energy intensive infrastructure. This example assumes that average water consumption remains the same.

Distributed infrastructure

In parallel to the centralised augmentation of water supply systems, a range of distributed water supply systems are also emerging. While there is a growing body of work with regards to the energy consumption of centralised water supply and wastewater systems (Cohen *et al.* 2004; Kenway *et al.* 2007; Kenway *et al.* 2008), there are very few studies currently available that assess the energy intensity of distributed systems, either at the cluster/estate or household scale.

One of the first studies to be conducted in Australia into the energy consumption of smaller-scale systems was carried out by Gardner *et al.* (2006). This study monitored the energy intensity of an estate-scale rainwater supply system in South East Queensland called Silva Park. The energy intensity of pumping in this rainwater system was found to be 2.6 kWh/kL (Gardner *et al.* 2006), and when the UV treatment was included, total energy intensity was calculated at 5 kWh/kL (Beal *et al.* 2008). These figures are alarmingly high, however, it should be noted that the Silva Park system is unusual as each household has an individual rainwater tank which overflows to a communal storage. The communal storage is subsequently used to top up individual rainwater tanks when supplies run low. This system of top up requires significant pumping and the energy used by this system is exacerbated by the fact that the system is located on a steep hillside with higher lifting requirements.

Gardner *et al.* (2006) also examined the energy intensity of a rainwater system at the Healthy Home (an eco home in South East Queensland) and found an energy intensity of 2.6 kWh/kL, which supports the results from Silva Park. The high energy intensities recorded at these two locations raised concern that this might be the case for other household rainwater systems. However, aside from the studies by Gardner *et al.* (2006) and Beal *et al.* (2008) in South East Queensland, no other data regarding the energy use of rainwater systems was found in the literature review.

Following the literature review, ISF carried out a search for water and energy data from distributed systems around Australia. This included estate scale greywater and water recycling systems in Melbourne, Sydney and Queensland as well as households with innovative systems. Corresponding water and energy data for these systems was not available as in most cases it had not been measured. One distributed system in Queensland, at Currumbin Ecovillage is currently being monitored, however, the first results from this study have only recently become available. Lane *et al.* (2009) have reported on a life cycle assessment of the water cycle at Currumbin and have found the rainwater pumping energy intensity to be 1.3 kWh/kL, while the cluster scale wastewater treatment facility is expected to consume approximately 1.4 kWh/kL.

While these numbers provide some fresh insights on the energy consumption of distributed systems, they represent just one ecovillage, where energy and water efficiency have been a high priority. With increasing numbers of distributed systems being installed in households, high-rise buildings and in housing developments, significant monitoring will be required to establish the true energy impacts and to investigate means of improving the efficiency of distributed systems installed at various scales.

The lack of available monitoring data demonstrates the fact that energy consumption is not currently being adequately considered in the planning of new water infrastructure. With climate change and energy and greenhouse gas impacts becoming increasingly important it is

imperative that the Australian and International water industry address the knowledge gap regarding the energy consumed by centralised and distributed water systems. Obtaining this knowledge is the first step towards developing options to reduce the energy usage associated with our water and wastewater systems.

PILOT MONITORING STUDY ON HOUSEHOLD RAINWATER SYSTEMS

Individual household rainwater systems are becoming increasingly common in urban areas in Australia. Of the 1.66 million tanks installed in Australian households, 640,000 are located in state capital cities. In Queensland alone, there were approximately 360,000 in use in 2007, which represents a 38% increase since the previous survey in March 2004, when there were 261,000 tanks (ABS 2007). The rapid uptake of rainwater tanks is expected to continue in the future, and with such large numbers in use it is becoming increasingly important to understand the actual yield from these systems and the corresponding energy and economic costs.

This knowledge gap prompted ISF to undertake primary research involving monitoring the energy and water consumption of a selection of household rainwater systems. The objective of the study was to determine the energy intensity of rainwater delivery at an individual household scale. The scoping stage of this study found that household rainwater systems differ considerably, with regard to system configuration and the types of end uses. Rather than attempting to examine each configuration and combination in detail, a range of different systems were chosen for monitoring, with the intention of capturing the spectrum of likely energy intensities. Within that spectrum, a number of houses that appear to represent 'typical' household rainwater systems were also monitored. A typical household rainwater system uses a fixed speed pump and an automatic switch to the mains water supply as a backup. Most commonly, these households use rainwater for toilet flushing, laundry and outdoors.

The monitoring results yielded energy intensities that ranged from 0.9 to 2.3 kWh/kL for the more common systems, with 0.9 kWh/kL representing a household with higher overall water use and 2.3 kWh/kL representing a

household with very efficient appliances and low overall water use. The average energy intensity was found to be 1.5 kWh/kL. For households using more unusual pumps, such as venturi jet and variable speed or with unusual configurations energy intensities were higher, ranging from 3.0 to 4.9 kWh/kL (Retamal *et al.* 2009b). These results show that system configuration can make a significant difference to energy consumption. They also highlight the need to examine both the energy intensity and overall energy consumption when assessing individual systems; as in a number of cases high energy intensity was a result of efficient rainwater use. Efficient water appliances use smaller volumes of rainwater, often at lower flow rates, however, the rainwater pump uses the same amount of power to pump water to a low flow end use, such as toilet cistern as it does to pump water to a high flow end use, such as a garden hose. Hence the energy intensity of more efficient low flow end uses is higher than less efficient high flow end uses.

It is useful to compare the results of energy intensity with rainwater and energy consumption over a year. The projected annual rainwater use and corresponding energy consumption for four of the monitored households representing 'typical' rainwater system configurations are shown in Figure 2. All of these households have very similar pumping configurations, however, their water using equipment and behaviour varies. The very low rainwater use at 'Enmore' is associated with low energy use overall, but a proportionally higher energy use compared to the other households. This can be seen in Figure 3 which charts the energy intensity of each of these household systems. Whilst the house at 'Padstow' uses much more rainwater and energy, the energy intensity or ratio between water and energy is much lower. A low energy intensity or ratio between energy used per kilolitre of water pumped, does not necessarily indicate low energy use overall. The use of water efficient appliances in households and using less water is still the key to using less energy.

These graphs also suggests that 'typical' household rainwater pumping systems are not energy efficient when used in households with low flow, water efficient appliances. This is due to the fact that rainwater pumps are designed to deliver water at high pressure, similar to mains water pressure, which uses a lot of energy. However, for
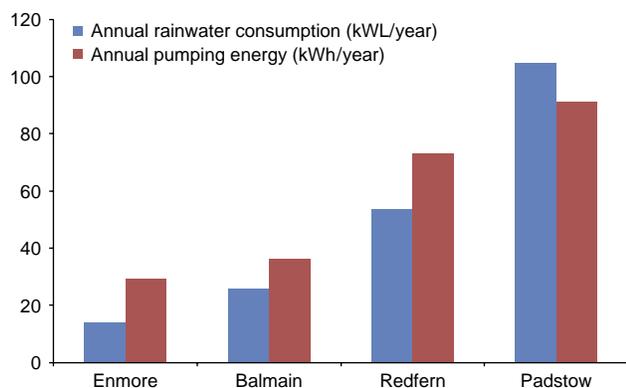
Figure 2 | Expected annual rainwater consumption and corresponding energy use for four 'typical' household systems in Sydney.

many end uses, such as toilet cisterns, efficient washing machines and sub-surface irrigation, water pressure equivalent to mains pressure is not required. This brings to light the importance of matching the pump's flow rate to the flow rate required by the end use to optimise efficient use (i.e. varying levels of service for different end uses within a house).

BROADER IMPLICATIONS

The broader implications of increasing energy intensity can be considered through different future scenarios. In the first scenario, the increase in rainwater tanks due to the BASIX legislation in Sydney, Australia, is considered.

The Shoalhaven water transfer to Sydney is intended to supply water to the city only during drought periods. If we assume that this water Sydney transfer is not permanently required and that it is used only once every 10 years in the
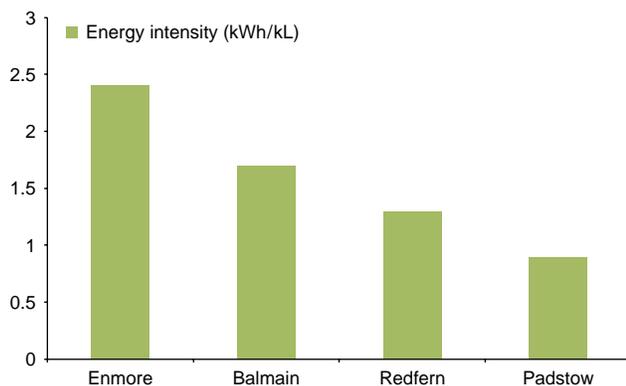
Figure 3 | Average energy intensity for four household rainwater systems in Sydney using a 'typical' system configuration.

long term, then the long term average energy intensity might be $0.33\,\text{kWh/kL}$[2]. This is $1.17\,\text{kWh/kL}$ less than the energy intensity of a 'typical' household rainwater supply system ($1.5\,\text{kWh/kL}$). Households that have installed rainwater tanks as a result of BASIX are expected to use approximately $53\,\text{kL/year}$ of rainwater. This would mean that an average household would use an additional $62\,\text{kWh}$ each year through the use of a rainwater system.

In the last 3 years, approximately 13,000 rainwater tanks have been installed annually due to BASIX (Department of Planning (NSW) 2008). Therefore, based on this rate of uptake, by 2030 there will be over 320,000 rainwater systems in New South Wales due to the BASIX program alone. This will mean that by 2030 an additional $20,000\,\text{MWh/year}$ will be required as a result of this water saving initiative. This is equivalent to approximately 20,000 tonnes/a of greenhouse gas emissions.

The projected increase in the numbers of rainwater tanks and the associated energy consumption to 2030 is shown in the graph in Figure 4.

Another possible scenario is that water transfers from the Shoalhaven become permanent as the Sydney catchment becomes water stressed. With the desalination plant operating simultaneously, this would drive the overall energy intensity up to $1.3\,\text{kWh/kL}$ as is shown in Figure 1. This figure has been modified in Figure 5 to show the impact of adding a rainwater supply system to the mix of water supply sources. This figure represents the energy consumed through water use for an average household in Sydney over a decade. This household uses $250\,\text{kL/annum}$ and is assumed to source $53\,\text{kL/annum}$ of that from rainwater. The rainwater supply is assumed to have an energy intensity of $1.5\,\text{kWh/kL}$.

In this scenario, the use of rainwater as an additional supply source increases the energy consumed by a household for their water supply from $64\,\text{kWh/year}$ in 2001 to $340\,\text{kWh/year}$ in 2011. While this represents just a fraction of annual household energy use, it remains a five-fold increase in energy use for water. In order to reduce the energy consumption associated with supplying water, water can be used more efficiently; however, new water supply sources also need to be chosen and designed with energy

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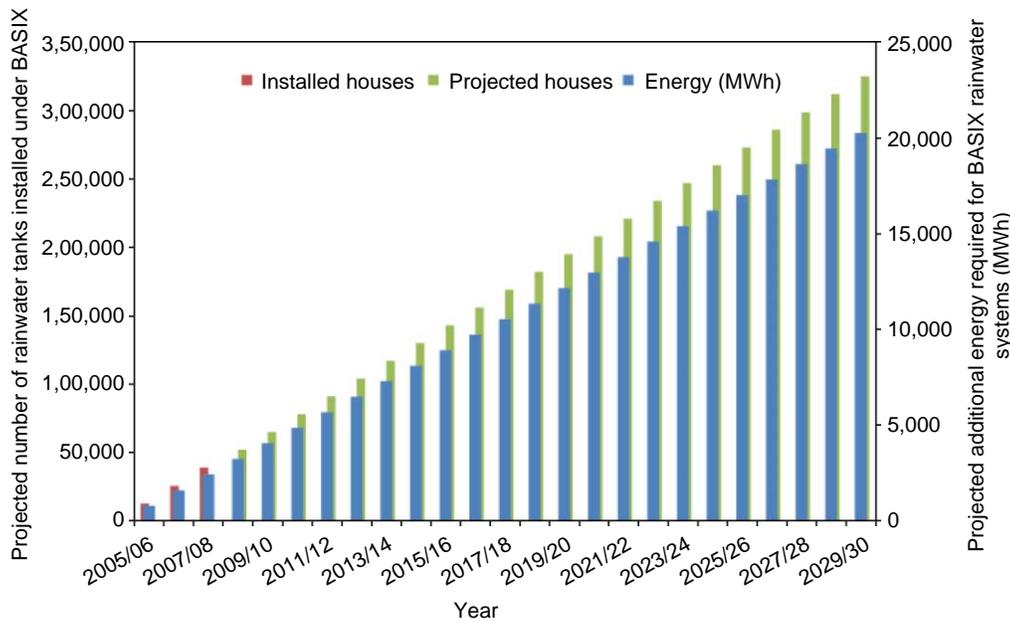[2] Derived from $1\,\text{kWh/kL}$ once every 10 years and $0.25\,\text{kWh/kL}$ for the remaining time.

Figure 4 │ Projected number of rainwater tanks and energy consumption in BASIX houses in Sydney.

efficiency in mind. Due to the strong linkage between water and energy and the ever increasing demand for both due to population rise, it is essential that both are used efficiently. There is a need to optimise the trade-off between the two, such that increases in water supply do not disproportionately increase the demand for energy.

A key finding from the monitoring study was that there is a need to improve the performance of household rainwater tank pumps. Small pumps are typically much less efficient than large pumps and actual pump efficiency tends to decrease as motor size decreases (Evans *et al.*

Figure 5 │ Energy consumed through water supplies for an average household in Sydney, Australia.

1996). This may be due to the fact that pumps for smaller applications tend to be less highly engineered than the large pumps used in industry. Aside from pump losses, another key reason why household rainwater tank pumps are less efficient than large pumps is because their design flow rate often does not match the flow rate required by the end uses in a house, which can be wide ranging. This is generally because the pump is over specified for the use to ensure householders obtain the equivalent of mains pressure for high flow end uses in the home. This issue could potentially be mitigated by the use of a variable speed pump or a lower flow rate pump for end uses that do not need a high flow rate (e.g. toilet cisterns, irrigation systems, washing machines).

Pressure vessels may also be useful devices for optimising pump use. A pressure vessel is placed after the pump and is used to store pressurised water that is drawn upon when a tap is opened. This effectively acts as a buffer between the pump and the household end uses, as while the flow rates and durations of end use events vary, the pump is only used to fill the pressure vessel. The pump is triggered to fill the pressure vessel when it reaches a specified low pressure threshold. This allows the pump to operate closer to its best efficiency point, rather than cycling on and off for small, low flow end uses.
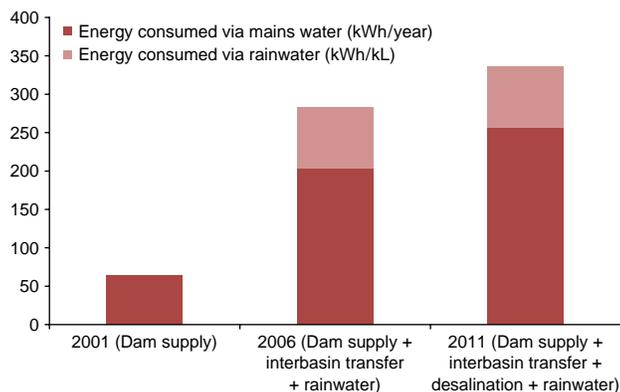
Cunio & Sproul (2009) have conducted preliminary experiments with rainwater pumping systems, with the aim of reducing energy consumption. These tests were conducted on a house in New South Wales, Australia to examine the use of header tanks and low power, low flow pumps. Cunio & Sproul (2009) also investigated the use of large diameter piping to reduce friction losses in rainwater delivery.

Two low flow pumps were used to fill a toilet cistern with rainwater using a 40 mm pipe. While these pumps would be somewhat slower to fill a cistern with flow rates of 3 and 3.5 L/min, they yielded energy intensities of 0.071 and 0.105 kWh/kL (Cunio & Sproul 2009), which is about 93% lower than the energy intensities recorded in the recent ISF study by Retamal *et al.* (2009*a,b*). The author notes however, that such systems can only be used in applications with low head requirements and may not be practical for all households. A further test using a low flow pump to fill a header tank resulted in an energy intensity of 0.04 kWh/kL (Cunio & Sproul 2009). While these are early experiments, they highlight the potential for further product development with regard to small pumps and particularly with regard to current system configurations. Larger piping, low flow pumps and header tanks may enable rainwater to be delivered at a lower or equivalent energy intensity to that delivered by the mains supply. Providing more water using less energy would deliver benefits to both the water and energy sectors.

CONCLUSIONS AND RECOMMENDATIONS

The literature review and monitoring study carried out by ISF with CSIRO, highlighted significant knowledge gaps with regard to the energy consumed by distributed systems. Early results indicate that rainwater systems are using 1.5 kWh/kL to deliver rainwater. This is almost 5 times greater than the long term average energy intensity expected for Sydney without desalination (0.33 kWh/kL) and contributes to an upward trend where the energy intensity of water supplies appears to be steadily increasing.

More monitoring and evaluation of distributed systems is required, not only to verify water savings, but also to determine their energy impacts and establish where systems can be modified to improve energy efficiency. Further research may also reveal the need for design guidelines to be developed to ensure that distributed systems are configured to reduce energy use.

Future investment should be directed towards systems that have mutual benefits to water and energy systems.

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