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THE WATER-ENERGY NEXUS: LITERATURE REVIEW

Institute for Sustainable Futures

UNIVERSITY OF TECHNOLOGY SYDNEY

WATER ENERGY NEXUS

Literature Review

Final

For CSIRO

Authors

Monique Retamal, Kumi Abeysuriya, Andrea Turner and Stuart White

Institute for Sustainable Futures

Disclaimer

Revision 1 (Draft)	Preliminary Literature Review	30/06/08
Revision 2 (Final)	Literature Review	12/12/08

Please cite this document as follows:

Retamal, M., Abeysuriya, K., Turner, A., White, S., 2008, *The Water-Energy Nexus: Literature Review*, [prepared for CSIRO], Institute for Sustainable Futures, University of Technology, Sydney.

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Abbreviations

BASIX	Building Sustainability Index
CSIRO	Commonwealth Scientific and Industrial Research Organisation
CO_2-e	Carbon dioxide equivalent
GHGE	Greenhouse gas emissions
GL	gigalitres
IRP	Integrated Resource Planning
iSDP	Integrated Resource Planning Model
ISF	Institute for Sustainable Futures
IUWM	Integrated Urban Water Management
kL	kilolitres
kt	kilotonnes
kW	kilowatts
kWh	kilowatt hours
LCA	Life Cycle Analysis / Assessment
LCP	Least Cost Planning
MJ	megajoules
ML	megalitres
MW	megawatts
NEM	National Electricity Market
NSW	New South Wales
PJ	petajoules
STP	sewage treatment plant
uPVC	unplasticised Poly Vinyl Chloride
UV	ultraviolet

1 Introduction

1.1 Background

In 2008, the Commonwealth Scientific and Industrial Research Organisation (CSIRO) commissioned the Institute for Sustainable Futures (ISF) to undertake a study on the energy implications of emerging distributed water service infrastructure in Australia. The study, termed the Water Energy Nexus, was commissioned after ISF and CSIRO identified a gap in knowledge regarding the energy aspects of water service infrastructure and specifically the growing need to understand the energy implications of new water infrastructure currently being planned and built in Australia.

1.2 The Study

The objectives of this study are to:

- Determine the water and energy saving and use linkages associated with water efficiency and source substitution initiatives from a lot to estate scale and identify issues of concern.
- Determine issues and potential solutions to the shortcomings of the current approaches being implemented at a lot to estate scale. In particular the issues that are being affected by specific policies, such as the mandatory installation of rainwater tanks, which are being rapidly adopted nationwide.
- Provide useful guidance to inform policy and decision makers at local, state and federal levels about these issues and potential solutions. This guidance will aim to ensure well-intentioned policy decisions are not made which achieve poor water savings and increase energy usage and more broadly have poor social, environmental and economic outcomes.

This preliminary literature review is intended to provide an overview of studies carried out both nationally and internationally on the interaction between water and energy systems. Numerous studies have identified the links between water and energy systems and the need for integrated water and energy policies to ensure sustainability in these sectors. Several studies have endeavoured to quantify the interdependencies of water and energy systems at scales ranging from household appliances to cities and states. This literature review attempts to categorise these studies into broad system-wide assessments (macro scale) and detailed studies on specific technologies or end uses (micro scale).

As some time has elapsed between the conception of this study (late 2006) and the commencement of research (mid 2008), it has been considered essential to first identify and document the work that has been carried out elsewhere in this rapidly growing field and identify current knowledge gaps. The accompanying scoping paper is intended to highlight these knowledge gaps and propose the scope of the next phase of research to be undertaken in 2008/09.

The preliminary literature review and associated annotated bibliography will form working documents for the study that will be added to as the study progresses. In addition all data/information will be collated to enable it to be used in future.

1.3 This document

This document is structured with the following sections:

- Section 1 – *The Introduction* provides background to the study, an overview of the study and associated documents.
- *Section 2 - The Connections between Water and Energy Systems* describes the nature of links between water and energy systems seen through different lenses, such as an energy, water or systems perspective.
- *Section 3 - The Macro-Level Water Energy Nexus* provides an overview of studies that have been carried out in Australia and internationally on the energy impacts of water infrastructure at a broad system scale (i.e. across a city, state or residential scale).
- *Section 4 - The Micro-Level Water Energy Nexus* provides an overview of a selection of detailed water energy nexus studies, which tend to focus on a specific technology or a specific end use.
- *Section 5 - Emerging Water Infrastructure* describes the changes that are occurring in the water industry, including the changing approach to the design of water systems and the use of alternative water sources. This section sets out a series of case studies where emerging water infrastructure is planned or has been built and the details of those initiatives.
- *Section 6 - Evaluation of Water and Energy Use for Emerging Water Infrastructure* discusses the overall deficiency in evaluation of new water infrastructure that has been built, in terms of actual water savings and the energy implications of these systems. Research undertaken in this area is described here.
- *Section 7 – Potential Solutions to Water Energy Nexus Issues* puts forward some of the potential solutions to problems within the water energy nexus that have been discussed within the literature.
- *Section 8 – Summary - Research Areas* highlights the areas of the water energy nexus field which have been studied and those which require further research.

2 The Connections between Water and Energy Systems – The Water Energy Nexus

Water and energy systems are both essential to modern life, and inextricably linked. If a city's energy system fails, for example, the reliability of water services quickly plummets, posing a threat to public health and safety (California Energy Commission 2005). Energy used to deliver water around the world uses an estimated 7% of the world's energy (James et al. 2002), which highlights the importance and impact of water consumption on energy use. From the energy perspective, water is integral to electricity generation in the industrialised world. In Australia, water-based thermal processes form a significant proportion of the energy mix and water scarcity is increasingly leading generators to turn to recycled water as an alternative reliable source (Orchison 2008).

Current concerns about population driven increases in demand for water and energy and the associated environmental impacts of excessive water withdrawals, wastewater discharges and greenhouse gas emissions are catalysing research towards better integration for water and energy services. Improved integration of water and energy systems will enable these concerns to be addressed in more cost effective ways with more sustainable outcomes. Understanding the connections between water and energy services is a necessary first step to better integration in planning. While some studies adopt a systems perspective to explore the interactions of all urban infrastructure services, others adopt particular sector perspectives which can lead to increased integration within current institutional structures.

This chapter maps the different perspectives and scales adopted in the literature on the water and energy nexus.

2.1 Perspectives on the Water Energy Nexus

There are different perspectives from which the water energy nexus is considered, which illuminate different opportunities for increasing efficiency and reducing environmental impacts. The relationship can be viewed through the following key perspectives or 'lenses':

- The energy use of water infrastructure – focus on water service provision
- The water use of energy infrastructure – focus on power generation
- Energy and water as part of an urban system – analysis of overall system impacts or changes to energy or water consumption and provision.

The relationship can also be viewed from the perspective of scale, as some studies focus on the water and energy use of a specific technology or end use, while others have estimated the water and energy use across a whole state or country.

The perspectives outlined here consider the links between direct energy and water consumption. They do not include the energy and water embodied in material infrastructures which are considered in lifecycle analyses, as these are already covered extensively in literature.

Energy Use of Water Infrastructure

The urban water-supply-use-disposal chain consumes energy at each of its different stages: extraction, conveyance, treatment, distribution, end-use, wastewater collection and treatment (Cohen et al. 2004). Water - energy links identified by Marsh and Sharma (2007) include energy used for bulk water supply such as seawater desalination, pumping associated with groundwater extraction and water conveyance, electricity required for retail water treatment, pumping for water distribution, end use electricity demands for hot water and water appliances, electricity used for wastewater treatment and finally, the energy (biogas) recovered from wastewater processes using anaerobic digesters. The amount of energy used for urban water services depends on contextual factors such as local topography and distance to water abstraction and discharge location, quality of raw water, treatment technology and environmental and health requirements (Kenway 2007).

While all uses of water require energy, it is primarily the urban water sector perspective that is considered in nexus studies as its energy requirements are greater than that of the agricultural sector (California Energy Commission 2005). This is despite the fact that the agricultural sector consumes more water by volume – about 65% of all water used in Australia, compared to 11% used by households (National Water Comission 2005). Urban water requires energy for water and wastewater treatment unlike agricultural water and has a more energy intensive reticulation system (California Energy Commission 2005). Across the USA, 4% of electricity generated nationally is used by the urban water utilities sector (US DoE 2006). In Australia, Kenway et al (2007) estimate that the energy use by the major water service providers amounts to just "0.1-0.2 percent of the total energy consumption" nationally. However, hot water heating in Australia used 92 PJ in 2002, which is roughly a quarter of all residential energy consumption – approximately 402 PJ (Energy Efficient Strategies 2008).

The energy use of water infrastructure has been examined by a number of authors from the perspective of climate change. Aside from water systems being vulnerable to climate change, water systems contribute to climate change issues through the use of energy derived from carbon based fuels, the generation of fugitive emissions through biochemical treatment processes and through the consumption of materials which involved energy consumption or fugitive emissions at some upstream point (Flower et al. 2007b).

Water Use of Energy Infrastructure

Water is used during the process of electricity generation as cooling water in thermal power stations and as a source of energy for hydropower. As power stations are often located in rural areas, the water used by these power stations is usually shared and or reused by irrigators and for aquatic ecosystems (Marsh & Sharma 2007). In the USA, water used by thermoelectric power plants is similar in volume to water used in agriculture, a demand that is often not recognised because much of this water, around 97%, is returned to source and therefore available for other uses (US DoE 2006). Nevertheless these power plants rely on this water being available.

Decreasing the availability of fresh water can have serious implications for many parts of the energy sector that depend on water. The US Department of Energy (US DoE 2006) describe some of these dependencies in the USA, additional to the obvious need for water in hydroelectric power generation:

- A large proportion of electricity is generated using thermoelectric power plants using evaporative cooling that rely on fresh water: if new generation plants continue to use these technologies, the available water for electricity production would need to double 1995 levels by 2030.

- Extraction and production of transport fuels in the US use water, for drilling related to oil and gas exploration, for refining oil and gas, for growing and refining biofuels, and for synthesising synfuels. This demand has potential to grow substantially.
- Water also has a role in the transportation of some forms of energy such as coal slurry transport in pipelines and slurry mining.
- Surface and ground water quality can be affected by large volumes of water that are a by-product of mining coal and uranium.

Studies by Marsh and Sharma (2008) regarding the water intensities of different power generation technologies in New South Wales showed that aside from hydropower, coal fired power generation has the highest water intensity. Gas turbine and cogeneration systems were found to use the least water during electricity generation. These results are shown in the following table. Marsh and Sharma (2008) also noted that nuclear power (though not used in NSW) would consume 30-50% more water than coal fired power.

Table 2-1 Water intensities of power generation technologies in New South Wales

Power generation technologies	kL/MWh generated
Coal	1.70
Combined cycle gas turbine	0.99
Gas turbine (oil)	0.01
Cogeneration	0.01
Hydro	*2217.07
Renewables	0.30

Source: (Marsh & Sharma 2008)

** Amount used but the majority returned to the system*

Water and Energy as part of a System

Both water and energy represent complex systems within an urban environment and unsurprisingly, their interconnections are complex. Changes to one part of the energy or water system can create feedbacks to both the water and energy systems, as illustrated by the following examples.

- During multi-year drought periods, water supply may draw on the highest energy consuming options (such as deeper or more distant sources needing more pumping), while at the same time, the most aggressive water conservation measures might be put in place that would reduce overall water use and reduce related energy demand, however, the “net effects of this dynamic are not fully understood” (California Energy Commission 2005).
- When energy efficiency initiatives reduce the air conditioning load in large buildings using cooling towers, every unit of heat that does not need to be removed means that less water is used in the cooling towers for evaporation. The cooling water saved in the buildings means less energy consumption by the water supply system; this energy saving also means less cooling water needed at thermal power plants – the action of multiple feedback loops. (California Energy Commission 2005)

A number of studies have considered water systems and energy system as parts of a larger system. These include:

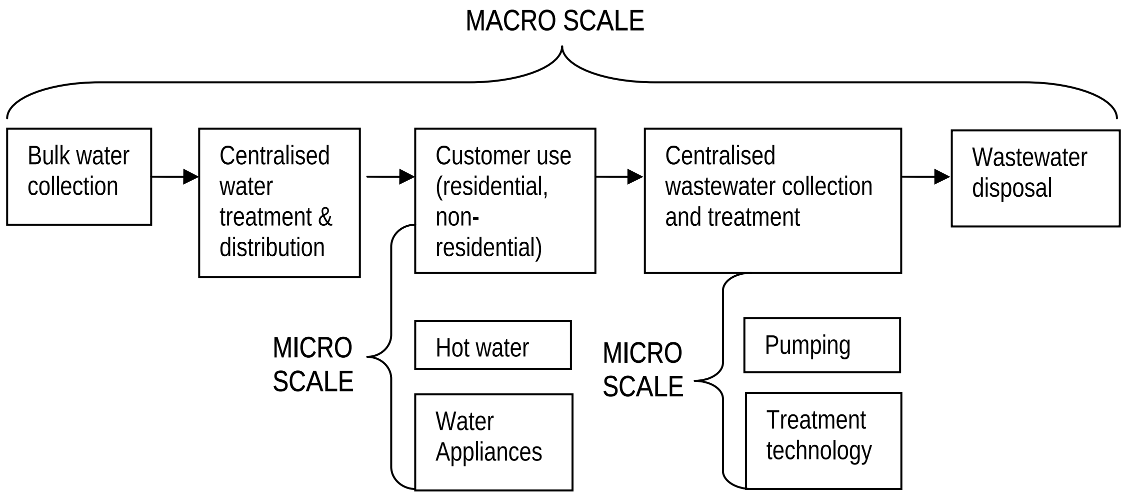
- An economy-wide perspective that considers the “water-energy-economy”, by using an input output model as a potential means for policy makers to make integrated decisions (see Marsh & Sharma 2007)
- Energy and water systems as part of an urban system also including transport, waste and materials, urban form and building design (see Rickwood et al. 2007).
- The cooling effect of vegetation and water features in the urban environment, to mitigate the ‘Urban Heat Island Effect’ (Konopacki et al. 1998) .

The Macro and Micro Level Approaches

The perspectives outlined above demonstrate the range of approaches that can be taken to examine the interactions between water and energy systems. This particular study assumes the perspective of water service provision and hence this literature review focuses on the energy use of water infrastructure. In reading the literature on the water energy nexus, the authors noted a general difference between studies that considered the broader water system and other studies that focused on a particular component of the water system. Therefore the terms ‘Macro’ and ‘Micro’ have been used to loosely categorise the literature. Macro studies included water and energy investigations that consider the water system of a development, utility, city, region, state or country. Micro studies included life cycle analyses of particular treatment technologies or the energy use of a specific household end use.

The figure below illustrates the categorisation of broader system-wide studies as ‘Macro’ and detailed studies as ‘Micro’.

Figure 2-1 – Macro and Micro Perspectives on the Water - Energy Nexus



3 Macro Level Water and Energy Nexus

The water energy nexus studies covered in this section have considered the energy implications of water systems across a development, city or region. Some studies are both broad and detailed, while others have simply aggregated the energy use of a whole system. This section is divided into 'International' and 'Australian' studies to highlight the focus of nexus work undertaken in Australia and overseas.

3.1 International – U.S. Studies

Large scale state and city wide water and energy studies have been carried out in the United States, particularly in California. The Pacific Institute's 2004 report "Energy Down the Drain: The Hidden Costs of California's Water Supply", investigated the connection between water and energy consumption in the state by developing a model to calculate the average energy intensity of each step in the water cycle including: source and conveyance, treatment, distribution, end use and wastewater treatment. This model was then applied to a number of case studies in California. The results of the Pacific Institute's study into the energy intensity associated with water and wastewater treatment and end uses are summarised below.

The average energy intensity for water treatment in California was found to be 450 kWh/acre-feet (555 kWh/ML), with the majority due to pumping treated water. The energy intensity for water in local distribution systems was 170 kWh/ acre-feet (210 kWh/ML), however, this varied enormously depending on the local topography and was as high as 940 kWh/acre-feet (1,159 kWh/ML) in north San Diego. In the United States it has been estimated that the country's water supply and wastewater systems use about 75 x 10^9 kWh/year, which is approximately 3% of the country's energy use (Cohen et al. 2004).

Residential hot water use was found to be a significant contributor to energy use within the water cycle. Estimates of energy used by different showerheads ranged from 2,855 kWh/year for older style showerheads to 1,128 kWh/year for the newer more efficient showerheads. Older style clothes washers were estimated to use 1,540 kWh/year, while newer more efficient clothes washers were estimated to use 632 kWh/year. These findings demonstrate the strong link between water and energy conservation, particularly at the point of use, as for example, hot water conservation not only greatly reduces the energy used for heating water, but also reduces the energy used both upstream and downstream of that point (Cohen et al. 2004).

The energy intensity of wastewater treatment plants varied depending on the technology used and the size of the facility. Treatment plants processing greater volumes of wastewater had lower energy intensity. Larger treatment plants were also able to reduce their overall energy intensity through recovery and use of biogas. The range of energy intensities for each wastewater treatment technology studied were:

- Trickling Filter 277-715 kWh/ML
- Activated sludge treatment 419-925 kWh/ML
- Advanced treatment 493-1067 kWh/ML
- Advanced treatment with nitrification 641-1208 kWh/ML (Cohen et al. 2004)

One case study focused on residential water use in San Diego and found that end uses of water such as showers and clothes washers used more energy than any other part of the water cycle – which highlights the importance of energy use at the point of water consumption and the potential for water conservation to provide significant energy conservation benefits. Cohen et al. estimated that if the city of San Diego relied on water conservation instead of additional water transfers to provide the next 100,000 acre-feet (123 GL) of water, then enough energy would be saved to provide 25% of all residential electricity demand in San Diego. This is due to the fact that southern California's water supply is highly energy intensive. The largest single energy consumer in California is the California State Water Project, which transports water from the San Francisco area down to southern California at 2433 kWh/ML, using 2-3% of the total energy consumed within the state. The energy intensity of water imported to southern California from the Colorado River has an energy intensity of 1622 kWh/ML (Cohen et al. 2004).

It is also worth noting that despite the high energy intensity of water supply in southern California, Cohen, Nelson & Wolff (2004) found in their case study of San Diego that "end use energy dominates the water use cycle … a rather striking result given that San Diego County imports most of its water from long distances, requiring large amounts of energy for conveyance." Hence, this would imply that the energy implications of urban water end-use elsewhere would also be quite large.

The energy used by water utilities, the basis of the studies referred to above, is generally accessible through records kept by water service providers - the energy used for water extraction and conveyance, treatment, distribution, and collection and treatment of wastewater. In contrast, energy measurements from the water end-use stage of the supply-use-disposal cycle are not directly accessible, since metering at the consumer level does not disaggregate energy further to identify water-related energy consumption (California Energy Commission 2005; Cohen et al. 2004). Available information is limited to the level of domestic fixtures and appliances (ibid) which can be utilised for bottom-up modelling (such as by Gleick et al. 2003).

> "The literature on water use contains little information on energy use integral to water end use beyond domestic fixtures and appliances. … This is an area of great significance for future research and energy and water policy." (Cohen et al. 2004, p. 18)

After the detailed water energy nexus studies that were carried out in California, the Energy-Water Research Roadmap was launched. This research project is being led by the US National laboratories (Sandia, Lawrence Berkeley) to understand emerging challenges related to the energy water nexus based on the energy sector perspective. Six technology areas were identified in the roadmap in 2006 as the key areas of the water energy nexus requiring research. These were:

- **Water efficiency in thermoelectric power generation** – As water consumption in the thermoelectric power sector may double by 2030, more research is needed to improve the performance of advanced cooling technologies and develop cooling systems that can use alternative cooling water sources.
- **Renewable and emerging energy resources –** to include investigations into new non-impoundment kinetic hydropower technologies instead of new hydropower dams.
- **Water efficiency in biofuels and biomass production** – as the demand for biofuels increases, more efficient means of biomass production are required, including the development of biomass sources that do not require fresh water or arable land to produce e.g. algae.

- **Non-traditional water utilisation and treatment –** research into water treatment technologies that can treat and reuse water produced as a by-product of mining (oil and gas)
- **Water supply characterisation –** new research into available fresh and brackish water availability in the U.S.
- **Integrated resources planning, decision support tools and policy issues –** improvements in data management and collaboration between federal, regional and state agencies involved with water and energy in the U.S (Ho et al. 2006).

3.2 Australian Studies

Australian water energy nexus studies have identified water and energy links and have included investigations into the energy use of water utilities and different water treatment technologies. Marsh and Sharma (2007) have developed a broad water, energy and economic input-output model to examine the interdependencies between the water and energy industries in New South Wales. Lundie et al. (2004) carried out a life cycle inventory analysis of Sydney Water's operations and compared this to a range of alternative scenarios. Others, including Grant, Opray et al. (2006) and Flower, Mitchell et al. (2007b, 2008) have examined the water energy nexus from a residential perspective, by examining the energy implications of: new water infrastructure in residential areas, household end uses and water efficiency measures. Most recently, Kenway et al. (2008) from CSIRO compiled energy consumption data for each major city in Australia and New Zealand. An overview of this work is provided in the following sections.

Energy Use of Water Infrastructure at the City and State Scale

In their characterisation of the nexus, Marsh and Sharma identified three major categories of water and energy links: upstream, downstream and transportation. Upstream is defined as those water and energy functions that occur closer to the source, such as bulk water supply, primary fuel sources and electricity generation. The downstream category is characterised by those functions that occur closer to end users, such as retail water and energy supply, end use and wastewater treatment. The transportation category includes transmission and distribution of energy and all of the extraction and conveyance associated with water and wastewater (Marsh & Sharma 2007).

The energy use of water supply and wastewater treatment components in Australia's cities has been examined by Kenway et al.(2008). The graph in Figure 3-1 illustrates the breakdown of energy use by each part of the water system in Sydney, Melbourne, Perth, Brisbane, Gold Coast, Adelaide and Auckland. The graph clearly illustrates the variation in energy consumed for water servicing in each city. Adelaide uses by far the most energy in water servicing (over 1200 MJ/cap/a), followed by Perth using 800 MJ/cap/a. This can be contrasted with energy use in Auckland and Melbourne, which both use less than 400 MJ/cap/a to provide water services. These differences reflect the ease of water extraction (surface water and gravity delivery in Melbourne versus pumping from the Murray River in Adelaide) and the sensitivity of receiving waters in some cities which require a high level of wastewater treatment (such as Port Philip Bay in Melbourne).

Figure 3-1 – Energy used by water and wastewater services (megajoules per capita) to service major Australian and New Zealand cities

Source: (Kenway et al. 2008)

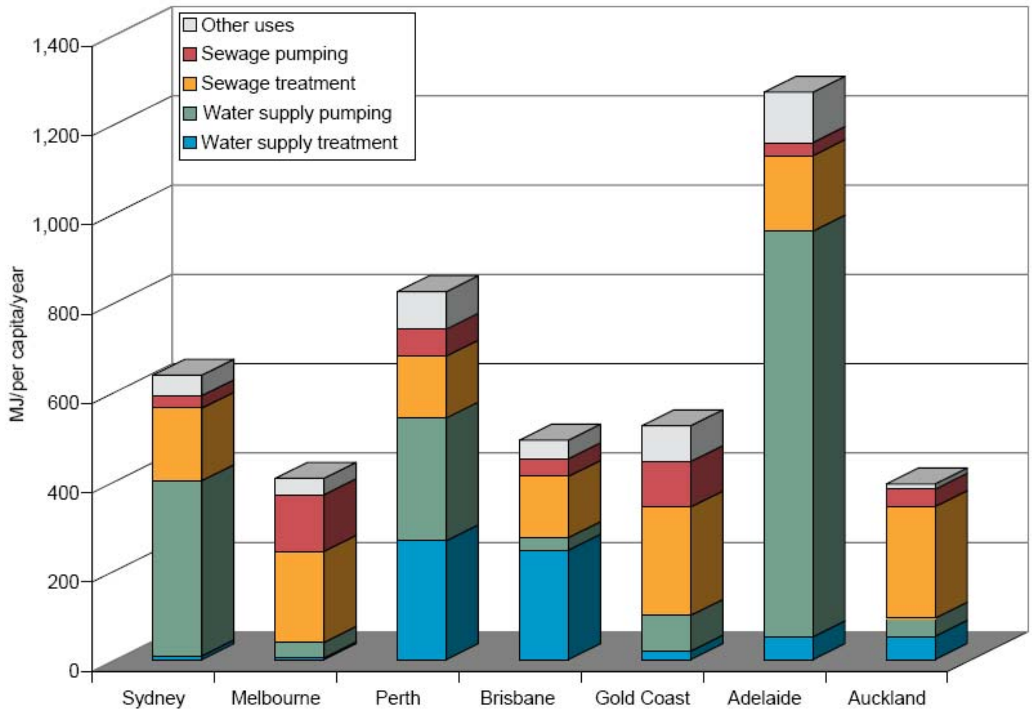
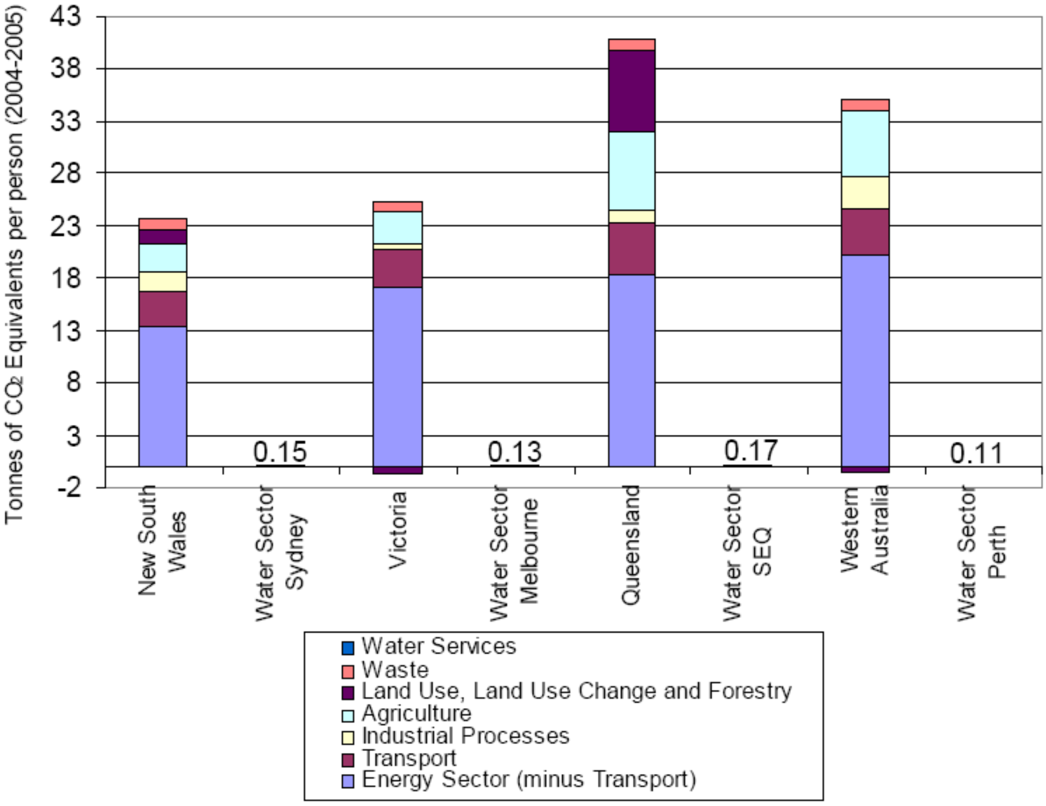


Figure 3-2 sets out the greenhouse gas emissions (GHGE) that are attributed to each sector / industry in New South Wales, Victoria, Queensland and Western Australia, as collated by Kenway et al. (2007). This graph shows that the GHGE attributable to the water supply and wastewater sector is small relative to the energy, transport and agriculture sectors. In the Kenway et al. 2008 study, the total energy used for urban water services in Sydney, Melbourne, Perth, Brisbane, Gold Coast and Adelaide during 2006/07 was calculated as 7.1 PJ, which represents only 0.2% of total urban energy use. The total energy used for water servicing in urban areas (7.1 PJ), is small compared to the energy used for water heating, which was estimated to be 46 PJ in 2006/07 (Kenway et al. 2008). This highlights that while water efficiency will save energy, saving hot water will save significantly more energy.

Figure 3-2 - Greenhouse gas emissions associated with each sector in NSW, VIC, QLD and WA. Source: (Kenway 2007)



Changes to Institutional Arrangements

Reforms in the Australian water and energy industries in the past two decades have resulted in the restructuring of these industries and changes to ownership and regulatory arrangements. For the energy industry, this has meant the separation of electricity generation and retail distribution, the corporatisation of utilities and the development of the National Electricity Market (NEM) (Marsh & Sharma 2007). For the water industry changes have also included the separation of bulk and retail water suppliers and the privatisation of many utilities. New policies were also introduced to allocate water for environmental flows and to establish water markets to allow trading of water entitlements in rural areas (Marsh & Sharma 2006). These reforms have further segregated the water and energy sectors, with implications for the water and energy nexus. Marsh and Sharma (2007) found that these reforms had been implemented with very little consideration to the interaction between water and energy.

Other key plans that impacted the water industry included the National Water Initiative and the NSW Metropolitan Water Plan. The Metropolitan Water Plan put forward a series of supply side options to alleviate Sydney's drought, such as deep water pumping from Warragamba dam, transferring water from the Shoalhaven River south of Sydney and construction of a desalination plant (Marsh & Sharma 2006; Marsh & Sharma 2007); all of which impact heavily on energy demand.

Energy Use by Technology Type

Research undertaken by Dimitriadis (2005) into the *Issues encountered in advancing Australia's water recycling schemes* for the Australian Parliament investigated the average energy intensities for a range of water recycling treatment technologies. The results are shown in the table below. These results emphasise the high energy use associated with desalination, which is 3 to 5 times greater than for wastewater recycling.

Table 3-1: Energy per megalitre of potable water produced by treatment technology and raw water source (Dimitriadis 2005)

Treatment technology	Energy intensity kWh/ML
Conventional water treatment	400 - 600
Wastewater reclamation	800 – 1000
Reverse osmosis of brackish water	700 - 1200
Reverse osmosis of seawater	3000 – 5000

A comprehensive life cycle assessment of Sydney Water's operations and future systems scenarios was conducted by Lundie et al. in 2004 as part of a review of Sydney Water's strategic vision for 2021, "WaterPlan 21". The study set out to determine the relative contribution of different parts of Sydney Water's proposed system in 2021 on a range of environmental impact categories. The total energy use of the system projected for 2021 was 8110 TJ/year resulting in GHGE of 721 kt CO_2/year. The biggest contributors to this total were water distribution systems (28% of energy use) and coastal sewage treatment plants (STPs) (29% of energy use). This base case was then used to compare the impact of a range of alternative scenarios including:

- desalination (to provide 6% of water supply),
- demand management (to reduce consumption by 6%),
- various population changes,
- energy efficiency (including installation of high efficiency pumps in all of Sydney Water's water and sewer infrastructure and other efficient appliances,
- energy recovery from biosolids (co-combustion of 50% of captured biosolids to be used in power generation)
- upgrades to coastal sewage treatment plants
- greenfield decentralised systems (including efficient appliances, rainwater tanks, local water recycling and regional biosolids treatment).

Comparison of the alternative scenarios showed that the desalination option increased total energy use by 27% and upgrades to coastal STPs would use an extra 23-26% of the total energy use by the system. The demand management option or the biosolids recovery option would decrease system energy use by 4% and the energy efficiency option would decrease system energy use by 13%. The greenfield scenario – where all new greenfield sites are serviced by local water systems, showed a reduction in fresh water use of 73% relative to a base case where traditional infrastructure is used. This scenario would also reduce energy usage by 17% and greenhouse gas emissions by 18% (Lundie et al. 2004).

Future Water and Energy Demands

Future demand for electricity and water in New South Wales, including 2000 MW of base load electricity by 2013 and an estimated 200 GL of water each year (Marsh & Sharma 2007) will place greater pressure on natural resources. An integrated approach to meeting these demands will be required so that increasing the supply of either water or energy does not place further strain on the other sector. The input-output model developed by Marsh and Sharma (2007) is expected to help determine the impact of water shortages on electricity generation output and the water savings arising from reductions in electricity consumption.

Marsh and Sharma (2007) identified a general lack of understanding of the nature of the links between water and energy and a lack of policy tools to inform decision makers in the process of developing more integrated water and energy policies. Consequently their work has focussed on developing an integrated energy-water-economic model for New South Wales to demonstrate the important economic links between water and energy systems.

Energy and Greenhouse Impacts of Distributed Water Infrastructure

Very few studies have investigated the collective energy and greenhouse impacts of distributed water infrastructure systems. Previous studies have investigated the energy use of specific technologies that are used at the household or estate scale, but few studies have considered the overall energy use of an urban water cycle consisting of a range of different technologies. One study from Melbourne, Australia by Grant et al. (2006) has investigated the overall energy consumption of a suite of distributed water cycle options for a greenfield development site and for an urban renewal site in Melbourne.

> Life cycle analysis studies show that "… capital infrastructure, while not insignificant, is much less important than operational impacts for most environmental indicators." (Grant et al. 2006)

For each site, several possible scenarios were considered for alternative water saving supply options, including different levels of demand management, and non-potable recycling of wastewater or non-potable recycling of stormwater, or on-site systems (rain tanks, onsite greywater reuse) with or without on-site wastewater treatment. The options were evaluated against input water and energy related greenhouse gas emissions and a separate paper considered nutrient emissions.

They found that the water saving scenarios for the greenfield site had greater greenhouse gas emissions relative to conventional supply. For conventional supply, the emissions were proportional to the volume supplied, demonstrating that demand management is an important emissions reduction measure. For the infill site, unlike the greenfield site the water saving options had lower greenhouse gas emissions.

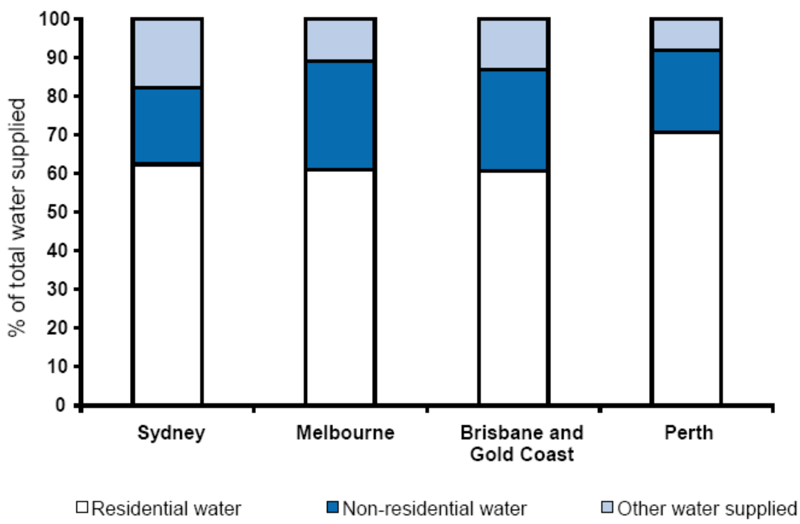
This was an artefact of the particular site chosen for the study which had an energy intensive sewerage system.

They observed that the operational energy (used to distribute water and collect wastewater through the system) is greater than the embodied energy associated with manufacture and installation, consistent with others' findings (for example, Mithraratne & Vale 2006).

Water Use in the Residential Sector

The residential sector uses a very significant proportion of urban water relative to commercial, institutional and industrial sectors, of the order of 60% in Australia as shown in Figure 3-3 (Diaper et al. 2007); a proportion representative of many cities of the industrialised world (Cohen et al. 2004). It is therefore appropriate to examine water related energy use in the residential sector in greater detail.

Figure 3-3: Breakdown of water use in major Australian cities 2004-2005. Source: (Diaper et al. 2007)



Life Cycle Analysis of Residential Water End Uses

Flower et al. (2007) used a life cycle analysis approach to assess the relative impact of components within the urban water system in Melbourne. A single residential house in eastern Melbourne with conventional water infrastructure was used as a case study to examine the overall system impacts of specific water end uses. Residential water end uses that consume energy include those that require hot water, such as showers, washing machines and taps and appliances that require energy to operate such as washing machines and dishwashers (Flower et al. 2007ba).

The energy consumed due to hot water use was estimated based on residential end uses of water and water consumption patterns determined by Roberts in 2004 and 2005. The greenhouse gas emissions associated with heating water in a residential house were determined for each of the two most common water heating systems in Australia, namely: continuously energized gas storage and off-peak energised electric storage hot water. The hot water temperature was assumed to be $40^{O}C$ (Flower et al. 2007ba).

The greenhouse gas emissions associated with residential water use for a house in Melbourne with gas hot water heating was found to be 2320 kg CO_2 equivalent over a year. This estimate includes the operational energy use of water supply and wastewater systems and found that these components of the water cycle accounted for less than 10% of the energy use associated with residential water supply. Consequently, the energy used in heating water and operating appliances within a house contributes by far the largest proportion of greenhouse gas emissions associated with the urban water cycle. In the case of an electric hot water system, greenhouse gas emissions for the same house were found to be 7146 kg CO_2 equivalent, with water supply and wastewater systems contributing only 4% of this total. This result emphasises the reduced impact of lower carbon energy sources such as natural gas and the relative importance of energy consumption associated with household water end uses, as these results clearly show that hot water systems and appliances within houses use far more energy than the water supply and wastewater systems upstream and downstream of a house (Flower et al. 2007ba).

Impact of Water Demand Management on Energy Use and GHGE

Flower et al (2007b) examined the greenhouse gas emissions related to domestic water end use in different appliances (such as showers, toilet, dishwasher etc.), and the impact of water demand management. Their Melbourne-based theoretical case study used a base case with the lowest efficiency appliances currently available in Australia. A second scenario with the most efficient available appliances and fittings was introduced to test the impact of structural demand management. Two more scenarios where behavioural changes (such as reduced shower duration and a reduction in outdoor water use) were added to the previous scenarios, so the combinations of structural and non-structural demand management on GHGE could be analysed. A Life Cycle Analysis approach was used to determine water savings and greenhouse gas emissions for each appliance in each scenario, assuming a gas hot water system.

The results showed that the scenario using the most efficient appliances reduced greenhouse gas emissions by 53% (1618 kg CO_2-e/year) when compared to the least efficient scenario. The scenario that combined structural and behavioural change with the most efficient appliances and reduced water use saved 63% (1927 kg CO_2-e/year) of GHGE produced in the least efficient scenario. Even the scenario with behavioural change in using inefficient appliances was estimated to reduce greenhouse gas by 26%. The shower was the most responsive to demand management: they estimated that structural DM could save around 60 kL/year per 2.6-person household, and when combined with non-structural DM could result in savings of 89 kL/year[1] with corresponding GHGE savings of 1170 kg CO_2-e/year (Flower et al. 2007ab).

These are significant findings as Flower et al. (2007) and others (see Cohen et al. 2004) have previously established that household end uses represent a very significant contribution to greenhouse gas emissions within the urban water cycle, since residential use is the largest component of urban water use (Cohen et al. 2004; WSAA 2006). Targeting household end use efficiency in demand management programs will thus have significant benefits from an energy perspective. Turner et al. (2007a) note the availability of a broad range of mechanisms and instruments for reducing household demand as part of a broader urban demand management program, with energy implications through the entire water supply-use-dispose cycle.

While theoretical estimates such as Flower et al.'s above show that demand management at the household level has great potential to reduce the overall energy use and GHGE of urban water systems, post-implementation evaluations are needed to verify the magnitude of the savings. Turner et al.'s (2005) evaluation of Sydney Water Corporation's residential retrofit program, for example, showed average savings of 21 kL/household/annum.

3.3 Tools / Models

Marsh and Sharma also reviewed water and energy nexus models and found that most models were for one industry or for one function within an industry – many were focused on an individual building or wastewater treatment plant. This may be due to the industry being "compartmentalised" and data not being readily available from the private sector (Marsh & Sharma 2006).

The macro level models reviewed by Marsh & Sharma were from/for:

[1] These savings appear high, as evaluations of actual savings for showerhead programs in NSW were found to be approximately 15 kL/hh/a (see Turner et al. 2006).

- San Diego (U.S.A) bulk water supply – a spreadsheet model to determine the energy use of different stages of the urban water cycle
- Columbian River Basin (U.S.A) – a spreadsheet model to determine energy impacts of diverting irrigation water upstream of a hydropower plant
- Westlands Water District (U.S.A) – a spreadsheet model to determine the energy implications of a range of options for retiring agricultural lands
- Western India – calculations to test water use with a range of electricity pricing models (electricity subsidies had resulted in excessive use of groundwater)
- Central Valley Project (U.S.A) – a supply based pricing function designed to examine how water prices for irrigation districts can be used to encourage surface or groundwater use depending on availability
- Energy & Water Conservation Model (U.S.A) – a spreadsheet model to estimate energy use for a range of water conservation options
- Copenhagen, Denmark – a model to examine water and energy price elasticities based on changes in residential demand (Marsh & Sharma 2006)

The model developed by Marsh and Sharma (2007) is an economic input-output model which has been designed to examine the interdependency of the water and energy industries and their impact on the wider economy in New South Wales.

Several urban water models (such as the Water Services Association of Australia Integrated Resource Planning Model, iSDP) have been developed for various water utilties across Australia to compare water efficiency and source substitution options against supply options using the principles of integrated resource planning. In such models a litre saved is equivalent to a litre provided by a new source but the costs, energy and greenhouse gas implications can be significantly different for each option and thus these models assist in analysing these costs and benefits. A recent example of this form of modelling and analysis has been documented for Alice Springs (Turner et al 2007a). Many of these models rely on theoretical energy savings due to the scarcity of measured data.

4 Micro Level Water and Energy Nexus

Studies on the water energy nexus at a micro scale are focused on the energy (and other environmental) impacts associated with a specific treatment technology or specific water end use, so that energy use is disaggregated. Life cycle analysis has been used to determine the energy and greenhouse impact of a number of water cycle elements including hot water heating, rainwater tanks and small scale treatment facilities. The following review summarises the findings from a selection of these studies.

4.1 Energy Use of Household End Uses

Domestic Hot Water Systems

Heating water accounts for approximately 16% of total residential energy consumption in the United States (Koomey 1994). Consequently, the conservation of hot water has a direct impact on energy use. In a U.S. study carried out by Koomey et al. (1994) the expected impact of water efficiency standards on water use and water-heating energy use were projected for the year 2010. The study was designed to determine the impact of water efficiency standards introduced in 1994. Data on end uses was based on the existing stock of toilets, taps, showerheads and dishwashers. For example, the average shower flow rate prior to the introduction of standards was 12.9 L/min. Standards introduced in 1994 meant that new showerhead flow rates were 9.5 L/min.

Estimates of the energy used by hot water heaters were carried out based on the energy content of the hot water used as well as the energy lost during hot water storage (standby losses). Energy saved due to water heater standards and water efficiency with hot water end uses such as taps, baths, showers, clothes washers and dishwashers were determined for the United States as a whole.

This study projected that hot water use in the United States in 2010 would be approximately 9 billion m^3/year (9,000 GL) and that the efficiency standards would be likely to save 1.2 billion m^3 of this total (1,200 GL). The energy expected to be saved from electrical water heating was approximately 470 x 10^{15} J/year, while an additional 400 x 10^{15} J/year would be saved from gas and oil water heaters (Koomey 1994).

4.2 Energy and Greenhouse Impacts of Water Cycle Components

Rainwater Tanks

Mithraratne and Vale (2006) compared the life cycle impacts of reticulated water supply, and concrete and plastic rain tanks (25 m^3 volume) as alternative supply for households in the Auckland region. The analysis considered life cycle energy and carbon dioxide emissions over a 100 year period, the assumed useful lifetime of New Zealand houses.

The system boundary enclosed infrastructure from the water source to the household tap, and included energy embodied in all major capital infrastructure items including dams, pipes, and pumps, and roof collection systems (but not energy associated with construction, trenching etc). An annual replacement rate of 1% of reticulation-system pipes and replacement of the plastic rain tank after 75 years was assumed. The study concluded that the concrete rain tank system had the lowest life cycle energy intensity (MJ/ML) and emissions intensity (kg CO_2/ML), followed by the conventional reticulation system, and lastly the plastic rain tank (refer to table below). It was noted, however, that the quality of water delivered by the reticulated system and rain tanks were not equal. Mithraratne and Vale highlighted the fact that rainwater tanks are beneficial primarily if they are the sole source of supply, rather than supplementary to the reticulation system, and require simultaneous implementation of water efficiency measures.

Table 4-1: Energy intensity of water supplied to average household in Auckland

	Auckland reticulated water supply	Water supply from Plastic rain tank	Water supply from concrete rain tank
Total lifecycle energy	3.1 MJ/m^3	4.9 MJ/m^3	2.8 MJ/m^3
Operating energy as % of total	65%	12%	20%
LC operational energy	0.56 kWh/kL	0.16 kWh/kL	0.16 kWh/kL

Source: (Mithraratne & Vale 2006)

Their modelling shows that for the reticulated system, with its long-lived components, the lifecycle operating energy is a high proportion of the total life cycle energy (65%). The table above also shows that operating energy intensity for the two rain tanks is much lower than for the reticulated supply in Auckland. The overall lifecycle energy (operating and embodied) is much higher for the plastic tank as it has to be replaced within the timeframe of the study.

Activated Sludge, Constructed Wetlands and Slow Rate Infiltration

A life cycle assessment (LCA) carried out by Machado et al. (2006), compared the impacts of an activated sludge treatment system with a constructed wetland and a slow rate infiltration system.

In the slow rate infiltration system, wastewater passes through a pre-treatment screening unit from where it is discharged through irrigation tubes to a large field planted with trees. The constructed wetlands system consists of pre-treatment, followed by an Imhoff tank for clarifying, followed by two wetlands in series – the first with vertical flow and the second with horizontal flow. The activated sludge system consists of pre-treatment screening and a sludge tank made of steel which has two aerators.

The resource use and emissions from each wastewater treatment system over a 20 year lifespan were estimated based on three phases: the production of components and construction, operation and maintenance and dismantling and final disposal. Each treatment system was sized and modelled based on a population equivalent of 100. Overall, the slow rate infiltration system had the most beneficial impact on global warming with a negative normalised impact score of -4.25×10^{-9} which indicates the system has an effect of diminishing global warming. The constructed wetland and activated sludge treatment systems had scores of 6.76×10^{-10} and 9.11×10^{-10} respectively. The slow rate infiltration and constructed wetlands systems were found to save energy relative to the activated sludge system due to a number of factors, including: less energy intensive materials being used during construction, less energy used during operation and maintenance and due to the absorption of carbon dioxide by the trees and wetland plants (Machado 2006).

Reed bed and Biological Filter

In a study carried out by (Dixon 2003) the life cycle impacts of two on-site wastewater treatment systems were analysed - a reed bed and septic tank system was compared with an aerated biological filter for a potential site in the UK. The reed bed system incorporates a septic system connected to a reed bed by uPVC pipes and a pump. The aerated filter consists of a two tank system with a central aeration chamber and a surrounding clarifier chamber. The two theoretical systems were compared at three scales – at 12, 60 and 200 person equivalents. The carbon uptake of the reed bed was estimated at 3.3 kg/m^2/year.

At the smaller scale, carbon emissions from the aerated filter system were due largely to pump operations (71%); pump use represented a far smaller proportion of emissions for the reed bed system (13%). Overall the carbon emissions from the aerated filter system increased with the scale of the system. At the smallest scale (12 person equivalents), the reed bed system produced roughly half the carbon produced by the aerated filter system, however, at the two larger scales the reed bed system became a more effective carbon sink as the results showed negative overall carbon emissions. Vehicles used for maintenance during the operational phase of the reed bed systems were the primary source of carbon emissions (Dixon 2003).

Embodied energy in the reed bed systems due to material and their transportation exceeded that for the aerated filter system, however, the aerated filter systems used far more energy during operation for the aeration and pumping components (Dixon 2003).

5 Emerging Water Service Infrastructure

Recent decades have seen the emergence of new approaches to water service provision, in response to challenges faced by conventional approaches. Incremental costs of water supply have increased significantly as cheaper options have already been utilised, and conventional water supply infrastructures are faced with higher costs for the operation, maintenance and replacement as they age (Tisdell et al. 2002). This has led to a re-thinking of the supply-driven logic that underpins the large scale infrastructures of conventional centralised approaches (Guy et al. 2001).

The emerging concepts are aligned with sustainability, with the aim of providing customers with the water related services they require rather than water itself, at least cost to society whilst also minimising environmental and social impacts (White 2003). Water supply and demand are balanced using Integrated Resource Planning (IRP) or Least Cost Planning (LCP) where reducing demand is seen as equivalent to increasing supplies, and a range of options and scales are considered where the marginal cost of saving water is less than the marginal cost of increasing supplies, taking all costs including externalities into account (White & Fane 2002; Wolff & Gleick 2002).

Demand management is thus a centrepiece of the emerging water service philosophy, consisting of several key elements (White & Fane 2002):

- Increasing system efficiency and conservation
- Increasing end-use efficiency and conservation
- Using distributed sources and infrastructures for supplying water-related services
- Providing the necessary services without using water

Integrated urban water management (IUWM), which is similar in concept to IRP/LCP, is a key tool for capturing synergies for increasing the efficiency and conservation potential of the system as a whole. It brings the traditionally separate planning of water supply, drainage and sanitation together as components of an integrated physical system that sits within the natural landscape and an organisational framework (Mitchell 2006).

The next level of integration to capture further synergies is through planning for water and energy in an integrated way as highlighted in the water energy nexus literature discussed earlier (California Energy Commission 2005; Cohen et al. 2004; DOE 2008; Gleick et al. 2003). The aim of this study is to make a contribution towards making this possible, by improving understanding of the energy implications of emerging approaches and distributed technologies in water related service provision.

Potential sources for studying the energy implications of the relevant technologies are the numerous Australian case studies that have implemented the emerging concepts and approaches of integrated urban water management (for example, in Diaper et al. 2006; Ghosh & Gabe 2007; Mitchell 2006; Naiad 2008).

Turner and White (2006) emphasise the importance of evaluation, to enable verification of whether the predicted benefits and water savings are actually achieved in practice, and seek to explain and learn from gaps so that future implementation of emerging approaches can be improved (Turner & White 2006; Turner et al. 2007b). This is particularly important in the current context where emerging concepts are promoted through rebate schemes and regulatory instruments (such as BASIX in

NSW and the Queensland Development Code) which in principle can be cost effective but when implemented can be costly and not achieve the original savings intended (Turner and White, 2006).

As the first step towards developing this understanding, this section briefly reviews resources and case studies that may be promising in terms of their ability to provide interesting and useful information about energy use in emerging water service infrastructures. While emphasising the critical importance of behaviour and policy, the focus here is on technologies and applications that form part of the emerging practice, to enable this study to stay within its time and budget constraints.

Key features of the emerging concepts and their application are first outlined:

- Water efficiency – decreasing demand through end-use water efficiency
- Source substitution – alternatives to reduce demand for reticulated potable water supply
- Emerging sanitation systems – alternatives to conventional centralised piped sewerage

A section on small pumps is also included (section 5.4) as these are an integral but often overlooked element of distributed technologies which can have significant energy implications (Gardner 2001).

In the final section, a small selection of case studies representative of particular scales and technologies are summarised in a table, as a preliminary set of potential case studies that could be explored further to capture energy-use measurements of emerging water service infrastructures.

5.1 Water Efficiency

End use water efficiency involves a water related service being provided with less water. This is based on improvements in fittings and appliances, such as low flow showerheads, dual flush toilets, tap flow regulators and more efficient washing machines and dishwashers, which go hand in hand with policy and economic instruments to promote their adoption, such as minimum performance standards on new appliances, rebates and retrofit programs (White & Fane 2002).

Water efficiency retrofit programs implemented in Sydney and the Gold Coast have been effective in delivering demand reductions (Turner et al. 2005; Turner et al. 2007b). Positive results of program evaluations such as Sydney's have resulted in continuation, modification and expansion of programs, as well as encouragement for other regions to implement similar programs (Turner et al. 2007b).

Water end use efficiency leads to lower energy consumption across the water supply-use-disposal chain. Less water needs to be treated and transported, and less wastewater needs to be collected and released, resulting in energy savings for water service utilities (California Energy Commission 2005; Cohen et al. 2004). In addition hot water savings result in energy savings for the end user (ibid). A number of studies in Australia have looked at the benefits of reducing water and wastewater through water efficiency programs. Such studies have encompassed in the boundary of analysis the additional benefits that can be obtained such as water and wastewater operational benefits and customer hot water energy bills (Turner et al. 2007a; Turner et al. 2007a). Many of these studies have had to rely on theoretical benefits for various end uses as the evaluation of actual benefits in implemented programs is still limited.

5.2 Source Substitution

Source substitution is the application of the “fit for purpose” or “water quality cascade” principle which matches the quality of the water supplied to the purpose it is used for (Mitchell 2006; White 2003). The cascade is a hierarchy of end uses which span from potable drinking water to non-potable end uses such as toilet flushing and irrigation. The cascade also refers to the reuse of wastewater from higher quality end uses for end uses lower down in the hierarchy. The Clovelly House (Veale 2006) summarised in the case studies section (section 5.5) demonstrates an example at the frontier of cascade application. Here, rainwater is supplied to showers and hand basins, with the resultant grey water, which is relatively ‘light’ in nutrients and organic matter (Holt & James 2006), treated by a simple technology and supplied to toilets and laundry before discharge to sewer.

Potable supply substitutes include water from rainwater tanks, stormwater harvesting, recycled greywater and recycled wastewater and groundwater/aquifer supply. The nature of these alternative water sources are briefly described in this section. For simplicity, these source substitution options have been disaggregated here, however, it should be noted that their application in emergent water service provision models frequently integrate several of them as well as alternative sanitation systems and water efficiency. In the following section, a table has been set up to outline the use of these different water system elements in case studies.

Rainwater tanks

The use of rain tanks in urban areas as a non-potable supply is encouraged by many councils and water utilities in Australia as a means of reducing demand for potable water, through the offer of rebates[2]. Turner et al. (2007b) note that the anticipated water savings may not be realised unless tanks are connected to indoor end uses.

Rain tanks have associated energy use due to the pumps that are used to circulate the water. In addition, rainwater may be treated before use, using filtration or UV disinfection, or thermal treatment (Diaper et al. 2006). Thermal treatment may not require additional energy when rainwater is used for domestic hot water supply to laundry and showers, such as is planned for the Pimpama Coomera subdivision (Apostolidis 2003; Diaper et al. 2006).

Gardner et al. (2002) noted from the Healthy Home case study that the energy consumption related to rainwater tanks can be relatively high, due to pumping and UV disinfection. While several rainwater tank case studies identify trickle feed potable mains water to top up rainwater tanks (e.g. designs of Payne Road, Pimpama Coomera), this is now discouraged as energy is unnecessarily used to pump this water out of the rainwater tank instead of using the original mains pressure (Diaper et al. 2006).

If the potable supply being substituted has high energy intensity, the rainwater tank water could result in net energy saved despite the pumps and disinfection. Mithraratne and Vale’s (2006) lifecycle analysis found that the use of concrete raintanks had a lower energy intensity than potable supply in Auckland.

Stormwater Harvesting

Stormwater harvesting refers to runoff from areas other than roofs, that is usually diverted to the stormwater system. Stormwater treatment using natural and soil-based structures such as bioswales that are integrated in the landscape and other

[2] For example see http://barinya.com/australia/environment/Rainwater_Tanks_Australia.htm (accessed 30/06/08).

low impact treatment systems (Ghosh & Gabe 2007) and re-use for irrigation can require little energy beyond pumping. When used for non-potable indoor use, however, the use of complex or energy intensive treatment such as used in the Inkerman D'Lux development (see case studies) can increase the energy intensity of this potable water substitute.

Recycled greywater

Greywater is wastewater from non-toilet plumbing fixtures such as showers, basins and taps. Although this technically includes wastewater from kitchens and dishwashers, guidelines for recycled greywater usually exclude these latter sources excluded because of the potential for contamination by pathogens (for example, EPA Victoria 2006).

While greywater recycling can be implemented on various scales, lifecycle cost considerations suggest that collection and treatment systems serving 1200 to 12,000 households may be the most economical (Pinkham et al. 2004, based on Booker 1999).

A range of treatment technologies are available for treating greywater of different qualities (Diaper et al. 2006).

Recycled wastewater

Wastewater including the used water from toilets contains pathogens, and wastewater treatment technologies need to protect public health and minimise the potential for the spread of associated disease, as well as take care of biosolids (Diaper et al. 2006).

Pinkham et al. (2004) argue that the optimal scale for wastewater treatment, based on lifecycle costs, is between 1000 and 10,000 households, as a tradeoff between the economies of scale in treatment costs and the diseconomies of scale in pipe networks. It is arguable that the optimal scale for wastewater recycling is in a similar range, based on this and their analysis of optimal scale for greywater recycling (1200 to 12,000).

The California Energy Commission (2005) argue that recycled wastewater may be seen as the lowest energy water source if used locally to recharge aquifers. "Wastewater treatment is in any case required, and the incremental energy for making re-use possible makes it the lowest intensity source" enabling displacement of more energy intensive sources such as desalination and interbasin transfers. Recharging local aquifers as a means of recycling water avoids the energy needed for reticulation in a third pipe, with the water withdrawn from the aquifer where and when it is needed.

A range of technologies for distributed wastewater treatment exist (Diaper et al. 2006; Holt & James 2006), with different energy implications, effluent water qualities and land take. Some of these are discussed later.

Groundwater/Aquifer

Groundwater can be used in some places in private wells or communal systems, as a non-potable supply. The Mawson Lakes development in South Australia (Naiad 2007a) uses aquifer storage and recovery for seasonal balancing of non-potable water supplies sourced from treated wastewater and stormwater.

The depth of the groundwater source/aquifer determines the amount of pumping energy needed (California Energy Commission 2005). Therefore again the energy intensity can vary significantly across different locations and contexts. In Alice Springs in the Northern Territory for example, the main potable water source is extracted from a confined aquifer 150m below ground. The energy intensity of the water supply system is 1100 kWh/ML and is amongst one of the highest energy intensity water sources in Australia (excluding more recently developed sources such as desalination). A more shallow alternative aquifer is used for non potable water uses as part of a dual reticulated system managed by PowerWater. Individual major non-residential users can access this resource independently. The non-potable system has a far lower energy intensity than the main potable system (Turner et al 2007).

5.3 Emerging Sanitation Systems

Emerging approaches to sanitation present many new opportunities for different infrastructure systems. A small selection of examples implemented in Australia and elsewhere are outlined to demonstrate some of the range rather than to make a comprehensive study. These are categorised below as alternative sewerage systems and waterless technologies.

Alternative sewerage systems

The systems in this category rely on water as the transport medium for toilet waste, however, the collection and treatment of wastewater differs from large scale conventional sewers.

Reduced inflow gravity sewers (RIGS) have been installed in Pimpama Coomera, which involve raised maintenance shafts instead of manholes, which reduce infiltration of stormwater (Diaper et al. 2006). As a result, smaller diameter sewers can be used. Infiltration is further reduced by the use of impervious PVC pipes. RIGS do not require additional energy relative to conventional sewerage, but reduce overall system energy by reducing the volumes of wastewater to be treated.

Septic tank effluent disposal systems (STED) have been in use for several decades in South Australia (Palmer et al. 1999), which involve primary wastewater treatment in onsite septic tanks, and transport of effluent via water tight small diameter sewers for ‘central’ or collective secondary treatment. The primary-treated effluent can be treated using simple low-energy technologies such as sandfilters and oxidation lagoons (ibid) provided sufficient land is available.

Innoflow interceptor tank-Orenco sewer-AdvanTex treatment pod system advances the concept in the previous paragraph to produce a high quality treated effluent in a relatively compact space. Filtered primary treated effluent may be pumped or gravity fed in water-tight small diameter sewers, for reticulating treatment in the passive textile treatment pod, and finally UV disinfection (Holt & James 2006). The energy consumption of the pumps and lamp are claimed by the supplier to be low for the quality of treated water produced, relative to treatment systems such as aerated wastewater treatment systems[3]. Currumbin ecovillage has installed this system to recycle water for non-potable use in toilets, laundry and irrigation (Diaper et al. 2006).

Pressurised sewer systems transport macerated sewage in small diameter pipes designed for reduced infiltration (Holt & James 2006). An onsite holding tank includes the macerating pump that grinds toilet waste to a slurry, reducing the risk of

[3] Refer to http://www.innoflow.co.nz (accessed 30/06/08).

blockages.

Vacuum sewers, like pressurised sewers, use differential pressure to force wastewater through sewers (Holt & James 2006). Household wastewater drains to a holding tank using conventional toilet fixtures. Accumulation of a set volume triggers a valve to open so wastewater is forced through the small bore sewer system to the collection tank at the vacuum station. Further transport from the vacuum station to a sewage treatment station may use gravity sewers.

Pressure sewers and vacuum sewers are suitable for use in steep terrain or in environmentally sensitive areas (ibid). Both have been installed in different developments within Pimpama Coomera where gravity systems were unsuitable (Diaper et al. 2006). Volumes of wastewater reaching a treatment plant are reduced due to the design of these sewers minimising stormwater infiltration, and thereby reducing energy for treatment. The mechanical parts mean these systems require more maintenance and periodic replacement (Pinkham et al. 2004).

An innovative water cycle termed the “Hamburg Water Cycle” designed for a new urban residential area in Hamburg-Jenfed, Germany, includes a system that collects blackwater from toilets by gravity into a storage tank. The biomass that settles at the bottom of this storage tank is then pumped under vacuum to an anaerobic digester, where it is converted to biogas (Augustin 2008). This system is an example of systems with potential to be net energy producers, if the energy from biogas is more than the energy used by the system.

Waterless Technologies

In some contexts, it is feasible to provide sanitation services without using water at all. There are numerous examples globally in the ecosan literature (for example, in Winblad & Simpson-Hébert 2004). The treatment processes for sanitising waste may be based on composting or on dehydration (ibid).

Composting toilets use processes that are usually passive and require no energy input, although some designs may use fans for aeration (ibid) or motors to move bins (such as Rotaloo[4]). Waterless toilets that use dehydration may involve the addition of materials such as lime or sawdust, or use energy for dehydration (Winblad & Simpson-Hébert 2004).

Waterless urinals have been installed in many buildings in Sydney including the Institute for Sustainable Futures. These use no additional energy, and conserve large volumes of water.

Vacuum toilets are included in this section as they use negligible volumes of water, and collect wastewater with a very high solids content. While vacuum systems consume energy, the concentrated organic composition of the wastewater is suitable for biogas generation, enabling these systems to be net energy producers. Vacuum toilets have been coupled with biogas generation in a small number of demonstration German ecovillages (Otterpohl 2002; Panesar & Lange 2003).

[4] Refer to http://www.rotaloo.com.au/ (accessed 30/06/08).

5.4 Small Pumps

A range of small pumps are associated with emergent approaches to water services, including rain tank pumps, submersible septic tank effluent pumps, macerator pumps with pressure sewers, and so on.

There is significant variation in estimates of energy intensity of water pumping by small pumps used in various applications. Mithraratne and Vale (2006) estimated 'typical' rain tank pumps (installed with 25kL tanks) to use around 0.16 kWh/kL as a lifecycle average. CHOICE (2007) conducted a product evaluation of a number of rain tank pumps available in Australia, and published data including measured flowrates (litres per minute) and measured power (Watts). A very simple combination of this data yields pumping energy intensities for these pumps that ranged between 0.55 and 1.03 kWh/kL.

Cheng (2002) considered another class of house pumps, used for lifting water to higher floors in highrise buildings. He derived a formula for the necessary power (kW rating) of a pump as a function of its pumping capacity (kL/minute) and the height the water is to be lifted, and the pump's efficiency coefficients. A pump lifting water to the top of a six-floor building would use 0.14 kWh/kL under this formula.

5.5 Case Studies

Mitchell (2006) identified the lack of ongoing monitoring and evaluation of the Australian case studies she reviewed as a research gap. While these case studies were designed with water resource management objectives, there is little information from which to evaluate whether project objectives and theoretical estimates of water savings have been realised.

The paucity of post implementation monitoring of energy is even greater. Many of the case studies of emergent water service provision (as in Diaper et al. 2006; Mitchell 2006) do not have any specific energy objectives or interest.

For the purpose of this study, we have reviewed the literature of Australian case studies of emergent water service models and made a preliminary identification of potentially useful case studies. These are where energy saving is an explicit design objective of the project, or there is evidence of water services -related energy being monitored.

The preliminary selection of case studies is presented in Table 5-1 below. These case studies will be reviewed in more detail to determine the most appropriate sites for further investigation of theoretical versus actual water and energy savings and usage. The sites chosen for further investigation will in part be dependent on the assistance researchers involved in the implementation and monitoring of those sites can provide to this study.

Table 5-1: Potential case studies for evaluating energy related to emergent water service infrastructure

Emergent water service concept	Case study	Scale	Characteristics	Technology	Energy implications	Energy data potential
Co-treated grey water and stormwater	Inkerman D'Lux, Melbourne VIC (Clearwater 2005; Melbourne Water undated)	Mixed greenfield development – 245 dwellings (medium-high density apartments) and retail Communal scale greywater system	Treats greywater from 50% of the dwellings, along with rainwater and stormwater. Reuse in toilet flushing and garden irrigation	Membrane Bioreactor (MBR) tanks, an aeration balance tank and a sand/soil/gravel wetland, UV disinfecting unit	For water utility: Anticipated potable water savings of 20% and 40% in winter and summer respectively. Reduced discharge to sewer. For strata manager: Energy associated with treatment and pumping	Dwellings designed for energy efficiency. Non-potable water system design aim to keep low maintenance and energy costs.
Rainwater for potable supply	599 Payne Road Brisbane QLD (Diaper et al. 2006; Naiad 2007c)	Greenfield residential development, low density – 22 allotments, not complete Lot scale rain tanks and greywater system Communal raintanks for backup supply to household tanks. Trickle feed backup from mains water.	Treated rainwater for all indoor uses	carbon filtration and UV disinfection	For water utility: No supply or sewage services - Development is designed to be self sufficient for water services. For strata manager: Energy associated with treatment and pumping	Extensive monitoring of water and water-related energy has been designed into the project.
Onsite greywater treatment			On-site greywater treatment with kitchen waste Re-use in subsurface irrigation	Biolytix aerobic vermiculture system Soil moisture sensor to control flows, overflow to sewer.		
Rainwater, onsite greywater treatment in cascade	Clovelly House Sydney NSW (Veale 2006)	Single residence, infill	Rainwater to showers and handbasins Treatment of grey water from showers and handbasins, re-use in laundry and toilet.	First known use of "green wall" treatment system – a set of plant boxes with filtrate that treat and polish grey water to high quality. UV disinfection	For water utility: 80% reduction in potable water, and reduction in sewer discharge. For homeowner: Small pumps for circulating rainwater, untreated and treated greywater from holding tanks, and UV disinfection systems add energy consumed by household. Net energy impact not known.	Sustainability including water and energy efficiency wer design objectives for the renovation.

Emergent water service concept	Case study	Scale	Characteristics	Technology	Energy implications	Energy data potential
Alternative sewerage system	**Pimpama Coomera** Gold Coast QLD (Apostolidis 2003; Diaper et al. 2006; Mitchell 2006; Naiad 2007b)	Greenfield subdivision with ultimate population of 150,000 by 2056. Low density housing, with some commercial and industrial sites.	"Smart sewers" transport wastewater for centralised wastewater treatment (and third pipe reticulation for irrigation) Coupled with rain tanks for indoor non-potable use, providing water cascade.	reduced infiltration gravity sewer network Some pressure sewers and vacuum sewers where more suitable.	For water utility: Anticipated potable water savings up to 84%. Reduced volumes of sewage from low infiltration. Costs related to third pipe. For homeowners: small pumps for rainwater add to energy consumption. Pressure/vacuum sewers energy – allocated to utility? Strata? Homeowner?	System monitoring is designed into the project
Wastewater treatment including alternative sewerage	**Currumbin Eco-village** Gold Coast (Diaper et al. 2006)	Greenfield low density development for 144 houses, commercial and communal facilities.	Innoflo system for communal wastewater treatment and non-potable reuse Coupled with rain tanks and high level effiency,	Water-tight onsite interceptor tanks with effluent filter, water tight small bore sewers, treatment pod with engineered textile media bioreactor, UV disinfection	For water utility: no water supply or sewerage service. The village is designed for total self sufficiency in water services (water and wastewater) Energy related to alternative technologies	Ongoing monitoring post implementation is built into project design

6 Evaluation of Water and Energy Use for Emerging Water Infrastructure

Millions of dollars are currently being spent across Australia on voluntary programs that encourage the installation of water efficient fixtures and fittings (i.e. efficient showerheads and front loading washing machines) and devices that will substitute potable water (i.e. rain tanks and greywater systems). There are also numerous regulations in various states making it mandatory to install such devices. Even though millions of dollars have been spent over the last decade across Australia on these programs and regulations there has been very little evaluation of the actual water savings achieved (Turner & White 2006; Turner et al. 2007b). Hence knowledge on the consequences of these programs both in terms of water savings and the impact on energy usage compared to theoretical and/or designed savings is very limited.

Turner et al (2007) have undertaken some of the few studies that have measured the actual water savings achieved using best practice statistical methods to assess customer meter readings. Key studies include:

- the average savings for the Sydney Water Every Drop Counts Residential Retrofit Program, 21 kL/household/annum (Turner et al. 2005),
- the results of several showerhead programs, approximately 15 kL/household/annum (Turner & White 2006),
- the savings for several products associated with the Gold Coast Home Water Saver Rebate Scheme such as front loading washing machines and rainwater tanks, 17 and 21 kL/household/annum respectively (Turner et al. 2007b).

A key evaluation has also been undertaken by Sydney Water, using an alternative statistical method. In this evaluation the water savings of 4A front loading washing machines were investigated and savings of 23 kL/household/annum were observed. Households using reticulated recycled water also showed significant potable water savings (Kidson et al. 2006).

These limited studies show that actual savings can in some cases be significantly different from designed or modelled savings. For example, as above, the actual savings resulting from the rain tank rebate program in the Gold Coast were 21 kL/household/annum (Turner et al. 2007b), in the case where the vast majority of these tanks were not plumbed into indoor end uses. However, modelled savings of rain tanks for Brisbane assuming a 5 kL tank, a roof area of $100m^2$ and serving 3 people, should be closer to 70 kL/household/annum (Coombes & Kuczera 2003) if the houses are connected to several indoor end uses. A major difference between designed/modelled water savings and actual savings for rain tanks is associated with assumptions around connecting to indoor end uses. Connecting to indoor end uses has the potential to optimise the rain tank water savings but in reality such tanks are rarely connected.

None of the published evaluation studies report on measured energy implications of the programs implemented.

Energy and greenhouse gas implications regularly form a part of the Environmental Impact Statement process for distributed infrastructure in estate-scale developments. However, Australian case studies of emergent water practices generally show actual performance monitoring and assessment post-implementation to be poor (Mitchell 2006).

Gardner et al. (2006) have undertaken monitoring of actual water and energy consumption at five allotments within the Payne Road residential development, near Brisbane. Payne Road consists of 22 detached dwellings with individual rainwater tanks (22 kL capacity) for all household use, greywater systems for subsurface irrigation and a conventional gravity sewerage system. The rainwater supply for all houses is backed up by two communal 75 kL tanks that capture overflow from the individual tanks and are also topped up by mains water when required. When the level in the individual rainwater tanks falls below a certain level, they are in turn topped up by water reticulated from the communal tanks. This top-up is regulated by pressure, so that whenever the reticulation pressure drops below 350 kPa the pump automatically starts. Each household raintank has a 0.45 or 0.75 kW submersible pump and a 40 W UV disinfection unit. Greywater is treated on-site by a “Biolytix” aerobic vermiculture composting system before being applied to soil for irrigation. Greywater diverts to the sewer if the soil moisture detects that the soil is saturated (Gardner et al. 2006).

Their findings showed that in the only house that was occupied during the monitoring period of four months, water use was 80 kL. Rainwater contributed 56% of this total water use, which represents a saving of approximately 190 kL / household/ year. This was compared with the Healthy Home which is an energy and water efficient house on the Gold Coast. The Healthy Home uses 69 kL over a four month period, 37% of which is supplied by rainwater from a roof catchment of 120 m^2. This translates to a 77 kL household potable water saving over a year. The rainwater yield from the Payne Road development was higher due to the larger roof catchment area (300 m^2) (Gardner et al. 2006).

Energy intensity due to rainwater tank pumping at both Payne Rd and the Healthy Home was found to be 2,600 kWh/ML, which is half that required to desalinate seawater and considerably higher than the energy intensity of reticulated water in Brisbane. This alarming result highlights a potential problem with individual household rainwater tanks as their energy use can be very high. The high energy use is attributed to the number of pump start ups (approximately 2,800 in one house over four months). The greywater pump used 630 kWh/ML, which is also high compared to average sewage pumping energy intensity in Brisbane (393 kWh/ML).

7 Potential Responses to Emerging Water Energy Nexus Issues

A number of recommendations are made in the literature for potential responses to emerging water energy nexus issues. These are focused on increased investment in demand management and efficiency measures, recognition of the economic benefits of co-ordinated water and energy savings and the use of alternative energy sources and synergistic water and energy systems.

Demand Management and Efficiency

A number of water energy nexus studies have highlighted the importance of water efficiency measures and demand management programs as a cost effective means of saving both water and energy simultaneously (California Energy Commission 2005; Cohen et al. 2004; Flower et al. 2007ab; Gleick et al. 2003).

Gleick et al. (2003) estimate that one-third of California's current urban water use can be saved cost effectively[5] with existing technology, where including the 'co-benefit' of energy saving improves the cost effectiveness of conservation measures. Lawrence Berkeley National Laboratory research identify measures that can reduce residential water consumption by 44% of current average use, and estimate that similar reductions can be made in the electricity and natural gas consumption associated with this water reduction (WETT undated).

Taking account of the total value of a unit of water through the complete water supply-use-disposal cycle, including energy intensity and externalities, can enable water and energy saving programs that would otherwise not be considered cost effective (California Energy Commission 2005). The California Energy Commission's (2005) analysis shows that California could achieve "nearly all of its energy and demand reduction goals for the 2006-2008 program period by simply allowing energy utilities to realize the value of energy saved for each unit of water saved. In that manner, energy utilities can co-invest in water use reduction programs, supplementing water utilities' efforts to meet as much load growth as possible through water efficiency." Their assessment suggests that this benefit is achievable at "less than half the cost to electric ratepayers for traditional energy efficiency measures."

Deferral of expansions of water, wastewater and energy infrastructure can lead to improved cost effectiveness for efficiency improvements in both sectors. As Gleick et al. (2003) observe:

> "Reductions in water use will lead to lower average peak water system loads – the most expensive kind of water to provide.
>
> Reductions in water use will lead to lower average peak energy demands – the most expensive kind of energy to provide.
>
> Reductions in water use and subsequently in wastewater generation will lead to reductions in environmental damages from water withdrawals or wastewater discharges in sensitive regions."

There is also recognition in the literature of the energy savings that can be achieved through cold water savings. The California Energy Commission (2005) noted that most studies on end use water-related energy primarily consider the energy used for

[5] A water conserving measure is cost effective when its unit cost is less than the marginal cost of expanding water supplies.

heating water. Saving cold water also saves energy upstream and downstream of the end use, and could be quite significant in some locations.

The energy implications of water saving initiatives therefore appear to be an important question, particularly in relation to emergent approaches to water services including distributed infrastructure promoted as aiding sustainability (Newman 2001). For example, Dimitriadis (2005) argues that communal greywater recycling systems clustered between 1200 and 12,000 households are the most economic compared to systems that require transport for treatment across long distances. The cost dynamics between distributed and centralised systems could change when energy is taken into account: there could be tradeoffs between having a large number of treatment systems using energy, and energy used to transport and treat more centrally (Pinkham et al. 2004).

Alternative Energy Sources

In addition to energy savings through saving hot and cold water, the California Energy Commission identified further opportunities for the water sector's support by using water sector assets and by-products for energy production. These opportunities include:

- utilising catchment land reservations (where visual impacts are low) for wind farms and solar farms
- using access reservations for solar generation
- producing biogas from sewage treatment
- placing small scale hydroelectric turbines as a means of water pressure reduction where needed

They suggest that, with the appropriate policies, programs and resources, water supply and wastewater systems could potentially change from being net energy users to becoming net renewable energy producers (California Energy Commission 2005). Another opportunity for synergistic energy and water production is for thermoelectric power plants to use brackish water for cooling and then discharge the warm wastewater to desalination plants for reuse, which also then reduces the energy intensity of the desalination system (US DoE 2006).

8 Summary – Research Areas

This literature review has highlighted a number of areas of the water energy nexus that have been well studied and other areas where there is potential to fill knowledge gaps. In summary, **the areas of this field that are sufficiently covered by the literature include:**

- The energy use of water utilities in major cities in Australia and the United States
- The energy intensity of centralised wastewater recycling plants and desalination plants
- A variety of life cycle analyses relating to specific components of the water cycle
- The relative contribution of different components of a conventional water system (water treatment, distribution, end use and disposal systems) to the overall energy use and greenhouse gas emissions associated with urban water systems

Key findings pertinent to this study:

- Residential water end use is the most significant energy using component in the conventional water cycle
- Demand management and efficiency in the residential sector has a significant role to play in reducing water and energy consumption
- The operating energy consumption of water cycle components is far greater than the embodied energy of water cycle infrastructure

Research areas that require further investigation:

- Few studies have evaluated the actual water and energy consumption of emerging water infrastructure – including efficiency and source substitution
  - The theoretical and actual energy consumption of rainwater tank pumps in different locations around Australia
  - The actual energy consumption of on-site greywater diversion, greywater / wastewater treatment and pumping systems
- Few studies have determined the overall energy intensity of water provided at a decentralised scale such as in greenfield residential developments, multi-unit residential and commercial infill developments
- Few studies have addressed the overall city-wide energy implications of the combination of on-site, decentralised and centralised water systems operating simultaneously

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