Australian Water Recycling
Centre of Excellence

Industry & Academic Exchange Program
An integrated approach for performance benchmarking of water recycling operations

A report of a study co-funded by the Australian Water Recycling Centre of Excellence and the University of South Australia

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September 2014

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About the Australian Water Recycling Centre of Excellence

The mission of the Australian Water Recycling Centre of Excellence is to enhance management and use of water recycling through industry partnerships, build capacity and capability within the recycled water industry, and promote water recycling as a socially, environmentally and economically sustainable option for future water security.

The Australian Government has provided $20 million to the Centre through its National Urban Water and Desalination Plan to support applied research and development projects which meet water recycling challenges for Australia's irrigation, urban development, food processing, heavy industry and water utility sectors. This funding has levered an additional $40 million investment from more than 80 private and public organisations, in Australia and overseas.

ISBN 978-1-922202-18-5

Date of publication: September 2014

Publisher:
Australian Water Recycling Centre of Excellence
Level 5, 200 Creek Street, Brisbane, Queensland 4000
www.australianwaterrecycling.com.au

This report was funded by the Australian Water Recycling Centre of Excellence through the Australian Government's National Urban Water and Desalination Plan.

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Abbreviations And Technical Nomenclature

AS	Activated sludge
ASR	Activated sludge reactor
BOD	Biochemical oxygen demand
CFU	Colony-forming units
CIP	Clean in place
COD	Chemical oxygen demand
DAF/F	Dissolved air flotation/filtration
DOC	Dissolved organic carbon
EEO	Energy efficiency opportunities
FCV	Feed control valve
GARWS	Glenelg–Adelaide Recycled Water Scheme
GL	Gigalitre
GL	Gigalitre
HVAC	Heating, ventilation and air conditioning
kL	Kilolitre
kWh	Kilowatt hour
LED	Light-emitting diode
LRV	Log_{10} reduction value
MBR	Membrane bioreactor
MF	Microfiltration
mJ/cm^2	Millijoule per centimetre squared
ML	Megalitre
MLR	Mixed liquor recycle
MLSS	Mixed liquor suspended solids
NF	Nanofiltration
NTU	Nephelometric turbidity unit
O&M	Operation and maintenance
ODS	Operational data store
PDF	Probability–density function
PE	Population equivalent
PLC	Programmable logic controller
PS	Pump station
RED	Reduction equivalent dose
RO	Reverse osmosis
r_s	Spearman's rank-order correlation coefficient
RWTP	Recycled water treatment plant
SCADA	Supervisory control and data acquisition
SEC	Specific energy consumption (kWh/kL)
SRT	Solids retention time
SURP	Aldinga Southern Urban Reuse Project
SVI	Sludge volume index
TDS	Total dissolved solids
TN	Total nitrogen
TOC	Total organic carbon
TSS	Total suspended solids
UF	Ultrafiltration
UV	Ultraviolet light
UVT	Ultraviolet light transmittance
V, P, B	Virus, protozoa, bacteria
VFD	Variable frequency drive
WAS	Waste activated sludge
WWTP	Wastewater treatment plant

Executive Summary

This report presents the outcomes of a 12 month research project (Centre Fellowship) undertaken at the South Australian Water Corporation and co-funded by the Australian Water Recycling Centre of Excellence and the University of South Australia. The primary objective of the research was to explore and develop a new integrated performance benchmarking approach (energy, health, greenhouse gas emissions criteria) suitable for optimising the energy efficiency of full-scale water recycling systems in Australia. Several South Australian case study water recycling systems were selected to 'road test' the new benchmarking method and the results of these investigations are presented. Another key objective was to make the first steps toward developing a new suite of energy benchmarks for various advanced water recycling processes, suitable for the water industry to use in future benchmarking activities.

Following an extensive literature review of specific energy data for a range of recycling-relevant processes, preliminary benchmarks for water recycling processes were developed. Probability–density functions for each technology group were used to develop new Guide (50th %ile) and Target (20th %ile) benchmark values for specific energy consumption (SEC) of recycling processes (Table i). While good alignment was generally observed between our new energy benchmarks and comparable existing benchmark standards, we recommend that they are considered indicative on the basis that further work is required to consolidate the benchmarks according to size of operations and key operating parameters.

Table i. Preliminary energy benchmarks for various water recycling technologies, processes and systems (kWh/kL) based on literature survey. Where they exist, equivalent benchmarks from the current industry standard (Haberkern *et al.*, 2008) are given alongside in italics.

Process group	**Average (mean)**	**50th %ile (Guide number)**	**20th %ile (Target number)**
UV (combined)	0.083	0.046	0.017
UV medium pressure	0.095	0.065	0.02
UV low pressure	0.084	0.031	0.012
UV (generic)[1,2]	*0.026–0.30*		*0.030*
MBR	0.95	0.95	0.613
MBR[1]		*0.7–0.9*	
Ozonation	0.163	0.055	0.026
Ozonation[1]	*0.03–1.05*		
Chlorination	0.012	0.003	0.001
Membrane filtration (combined)	0.224	0.189	0.102
Microfiltration	0.137	0.122	0.061
Ultrafiltration	0.228	0.174	0.116
Tertiary membrane filtration (generic)[1]		*0.10–0.15*	
Whole-of-plant recycling	2.112	1.104	0.58
Water distribution	0.408	0.346	0.181

[1]Benchmarks of Haberkern et al. (2008)

[2]Target UV benchmark relates to equivalent UV dose of 40–50 mJ/cm^2

Following benchmark development, three South Australian recycling schemes (Aldinga, Glenelg and Christies Beach) were energy benchmarked. The Aldinga and Glenelg recycled water treatment plants produce recycled water of a dual reticulation standard, whereas the Christies Plant consists of two different treatment trains, one of which is a membrane bioreactor (MBR). Energy use was benchmarked to unit process and equipment level via energy sub-metering data obtained from the online data and control systems. Operational energy efficiency at each site was benchmarked against the Guide and Target values and investigations made to identify potential process improvements for energy savings, with these improvement opportunities noted throughout the report.

Overall, the Glenelg recycled water treatment plant performed well relative to process energy benchmarks, with the plant-level SEC (0.31 kWh/kL) outperforming the nominal Target benchmark value (0.58 kWh/kL). Energy benchmarking of the Aldinga recycled water treatment plant revealed a SEC of 1.58 kWh/kL which was of the same order of the Guide benchmark value (1.1 kWh/kL). The lower volumetric energy efficiency of the Aldinga plant relative to the Glenelg was determined to be a likely result of scale factors in the operation of unit processes and volumetric throughput. At both the Glenelg and Aldinga sites, the SEC was found to vary significantly with seasonal demand (i.e. plant operations were relatively more efficient during high demand/flow periods). The concept of plant flow rates or 'production schedules' was also explored to highlight to Operators there potential energy implications of plant flow set-points and volumetric production bands. Benchmarking work at the Christies Beach site showed the MBR (0.96 kWh/kL) to be operating close to the industry average Guide performance benchmark (0.95 kWh/kL), indicating room for further optimisations.

Following initial energy benchmarking work, opportunities for process optimisation were identified at all three sites. Integrating public health performance criteria into energy benchmarking activities via so-called 'energy–health' benchmarking allowed for critical assessment of process optimisations identified during energy benchmarking activities. For UV disinfection processes, opportunities for optimisation were confirmed across all case study sites as a result of reviewing the operating envelope of the processes and contrasting this against validation and equipment criteria, and regulated recycling system performance requirements under the *Australian Guidelines for Water Recycling*. A preliminary assessment of benchmarking pathogen log reduction values to energy use was also carried out, with opportunities remaining to further explore the energy cost of pathogen removal barriers in the context of different recycled water schemes and end-uses. Research here has highlighted the value of the new energy–health benchmarking approach for optimising recycling operations for energy efficiency gains and should assist the water industry to better understand how to go about designing and operating true 'fit for purpose' water recycling systems.

1. Introduction to Australian water recycling

Water recycling is widely accepted as a key strategic supply source in the water resources portfolio of an increasingly 'climate-ready' water sector (Rodriguez *et al.*, 2009; WSAA, 2012). While the last 25 years has seen considerable expansion of the scope and capacity of water recycling in Australia (Radcliffe, 2004), water recycling remains largely under-developed with just 10% of Australia's urban water sources presently from recycled supplies (Spies and Dandy, 2012). Despite the recent growth, obstacles remain to the continued development and expansion of water recycling applications, with such obstacles including: public acceptance issues for potable reuse (Hurlimann and Dolnicar, 2010; Khan, 2013); inadequate pricing structures and inconsistent regulation (Productivity Commission, 2011; AWRCE, 2013b); and a rudimentary understanding of the true cost–benefits and life cycle environmental performance of water recycling operations (AWRCE, 2012; Spies and Dandy, 2012).

While water recycling provides valuable resource-recovery functions for increasingly scarce and valuable resources (water, nutrients), recycling processes are among the most energy-intensive operations conducted by water utilities today (Cook *et al.*, 2012; Spies and Dandy, 2012). In addition to the already high capital and energy costs, many schemes are perceived to 'over-treat' water without justifiable public health or local environmental benefit, resulting in unnecessary material and resource inputs, operational and maintenance (O&M) costs, electricity costs and environmental emissions (Bichai and Smeets, 2013). Internationally, there is also a growing perception that increasingly stringent and complex environmental regulations are driving unsustainable outcomes across the water sector more broadly (Black *et al.*, 2012). While recycled water supplies are largely considered 'climate-independent' (i.e. urban wastewater sources are relatively secure in supply), further optimisations of energy-intensive water recycling processes are required in order to avoid 'maladaptive' outcomes (Short *et al.*, 2012).

The recent extended drought throughout much of Australia saw many water recycling schemes commissioned as a means of securing more diverse and climate-independent water supplies, or in response to political imperatives. Many of these schemes required financial subsidisation from government and the economics of recycled water supply was often not the primary driver for these schemes at that time. The break of drought conditions and heavy rainfall from the record-breaking, consecutive 2010–2012 La Niña events (Bureau of Meteorology, 2012), combined with financial austerity directives since the Global Financial Crisis, means that the economics of water recycling is now an issue of increased focus for water utilities, governments and regulators, with important implications for water recycling initiatives (AWRCE, 2013a).

Demonstration of the importance of economics in recycled water supply can be found in recent events. For example, the City of Gold Coast recently resolved to discontinue implementation of dual reticulation recycled water in all areas of the Gold Coast on the grounds of economic non-viability, with Class A+ recycled water supply to cease by the end of 2016 (City of Gold Coast, 2014). In New South Wales, the Independent Pricing and Regulatory Tribunal recently recommended that Sydney Water's usage and efficiency targets—including those for recycled water supply—be scrapped on the basis that they are unnecessary and costly (Hasham, 2014). At the same time, dual reticulation recycled water schemes are presently being implemented in new housing developments elsewhere in Australia (e.g., Bowden and Seaford Heights, South Australia), highlighting the state-specific nature of attitudes to recycling. Internationally, water recycling operations are also being rolled out in parts of Central and South America, and East Asia (Liu *et al.*, 2012). Accordingly, there is a need for a standardised approach to measure and compare the performance and sustainability of these recycling systems.

Costs for water recycling vary considerably depending on the source water quality, location and delivery distance, and treatment level required (e.g., ≈$0.50/kL for low-cost systems up to ≈$6.00/kL for highly-treated recycled water (Whiteoak *et al.*, 2008; Spies and Dandy, 2012)). Moves toward economic regulation of the Australian water sector in recent decades now sees independent regulators set the price for water services in many states (including recycled water) and define how water utilities can allocate financial resources in set time frames, such as over four year periods (Productivity Commission, 2011). In response to the current state-based regulatory approach, the Australian Water Association (AWA) has recently called for a national framework to guide the economic regulation of the water sector (McKeown, 2013); echoing earlier calls made elsewhere (WSAA, 2009; Liggins, 2010). Accordingly, there is a need for the Australian water sector to better understand the economics of recycled water supply to enable it to make more informed and cost-effective future policy decisions.

Recent drivers for water sector focus on energy efficiency come from a number of areas, including water supply scarcity and the associated move toward advanced water recycling, the push for effective wastewater treatment and higher secondary effluent standards to reduce pollutant loads to receiving waterways, and wholesale energy tariff increases. Energy tariff increases in Australia in recent years (e.g., in response to Commonwealth Government energy and environmental policy initiatives) have already and will continue to motivate water utilities to look at ways of optimising their operations to minimise energy use (WSAA, 2008; WSAA, 2011). The energy-intensive nature of urban water service delivery translates to considerable economic risk via exposure to market electricity tariffs; at the same time, access to water is also a growing risk for the electricity sector internationally through the so-called 'water–energy nexus' (WEF, 2008). Consequently, there is now sector-wide recognition of the need to consider water–energy linkages and encourage resource efficiency in the planning and deployment of future water infrastructure (WSAA, 2012). Beyond internal economic motivations, large energy consumers like industry sectors are seen as having an equivalently large role to play in implementing responsible energy efficiency measures to help manage the ever-growing pressures on energy supply security in urban environments (Johansson *et al.*, 2012).

Recycled water systems are often complex, not only in terms of treatment configuration, but also in terms of source waters and end-uses, such that there now becomes 'inter-basin' like transfers in sewage, treated effluent or recycled water. For example, treated effluent from Adelaide's Christies Beach wastewater treatment plant (WWTP) is pumped to the Aldinga storage systems (managed aquifer recharge or lagoons) and reused for commercial food crop irrigation, or further treated for dual reticulation. Consequently, energy is used not only to treat the water, but also to transfer it to other sites for subsequent treatment and reuse. Conversely, other sites like the Altona Recycled Water Treatment Plant (RWTP) produce fit for purpose streams of recycled water with differing qualities in terms of pathogen removal for therefore different customers, but the implications of this configuration in terms of the energy required to produce the various product waters remains unclear.

Given the high associated energy demands and cost, there is a need to optimise the management and operation of water recycling systems so that they provide 'fit for purpose' recycled water at the lowest energy and environmental cost. Since one can *manage only what one measures*, water utilities must first 'benchmark' the energy use performance of their current operations in order to drive and inform future energy optimisation and efficiency initiatives. The concept of fit for purpose must take into account the balance of treatment processes to produce recycled water and on-site preventative measures which control the application and access to recycled water to protect the public in the vicinity of irrigation areas, consumers of produce or livestock (Table 1). By developing a novel benchmarking approach, this project seeks to address these issues via the integration of public health, energy and environmental considerations into the performance benchmarking of water recycling systems, using several full-scale recycling plants in South Australia as case studies.

Table 1. Summary of minimum required pathogen log reductions in recycled wastewater and stormwater (indicated in parentheses). Adapted from NRMMC *et al.* (2006).

End-use	**Log reduction targets (log_{10})**		
	Virus	**Protozoa**	**Bacteria**
Dual reticulation, toilet flushing, washing machines, garden use	6.5 (2.4)	5.0 (1.9)	5.0 (2.4)
Dual reticulation – outdoor use only or indoor use only	6.0	4.5	5.0
Municipal use – open spaces, sports grounds, golf courses, dust suppression	5.0 (1.3)	3.5 (0.8)	4.0 (1.3)
Landscape irrigation	5.0	3.5	4.0
Commercial food crops	6.0 (2.3)	5.0 (1.7)	5.0 (2.3)
Non-food crops – trees, turf, woodlots, flowers	5.0 (1.3)	3.5 (0.8)	4.0 (1.3)

1.1 The South Australian landscape

South Australia has a proud history of water recycling. As early as the 1960s, investigations were already being made into the reuse of wastewater from Adelaide's main WWTP at Bolivar, with a State Government report at the time outlining potential future uses for Adelaide's recycled water including: advanced treatment for domestic reuse; industrial reuse; irrigation; aquifer recharge; and public amenity (South Australian Government, 1966)—all of which occur today. Drivers for water recycling in Adelaide during recent decades have related to both supply security and environmental protection. The primary environmental driver has been the protection of Adelaide's coastal environment (Gulf St Vincent) where prolonged stormwater and wastewater discharges have had a detrimental impact on local marine ecology (Fox *et al.*, 2007). In response to this, metropolitan wastewater treatment processes underwent a series of Environmental Improvement Programs under direction from the state's Environment Protection Authority.

The South Australian Government recognises the importance of alternative water sources in its policy document *Water for Good*. Since 2006, priorities for water management have required an increased focus on the use of recycled water and stormwater to reduce the reliance on using traditional supplies such as from the Mt Lofty Ranges and River Murray. *South Australia's Strategic Plan* emphasises the importance of water recycling and the *Waterproofing Adelaide 2005-2025* strategy set targets for storm- and wastewater reuse in Adelaide by 2025 (Government of South Australia, 2005). In 2001–02, Adelaide recycled around 11 GL of wastewater (Radcliffe, 2004). Today, South Australia is the national leader in terms of water recycling operations, with some 32% (≈28 GL) of metropolitan Adelaide's wastewater recycled during the 2012–13 financial year. Assuming the current rate of expansion continues into the future, Adelaide will soon surpass touted water recycling targets for 2025 of 30 GL/year (Government of South Australia, 2005; Radcliffe, 2006). For comparison, recycling schemes supplied ≈40 GL of recycled water to the Sydney region for industrial, irrigation and residential use in 2010 (SWC, 2013); this is for a population some four-fold higher than Adelaide. Incidentally, initial aims of having this figure increase to 70 GL/year by 2015 now appear defunct in light of recent recommendations of the Independent Pricing and Regulatory Tribunal of NSW to scrap Sydney Water's usage and efficiency targets (Hasham, 2014).

1.2 Water recycling and the water–energy nexus

Water and energy are intrinsically and inexorably linked in urban environments, with this interrelationship known today as the so-called 'water–energy nexus'. While the recognition of and appreciation for water–energy linkages in our urban environments has improved during the last decade in particular, our understanding of the true nature and extent of these water–energy interactions remains underdeveloped (Kenway *et al.*, 2011). Energy requirements for treating water to acceptable levels vary considerably according to water source type and quality, as well as local climatic, geographic and demographic conditions. Given the tremendous scope for variability in these parameters, the specific energy consumption for water production can range from 0.03–7.0 kWh/kL (Lazarova *et al.*, 2012b); although typically these values are more constrained (Table 2). Even for water sources at the high end of this energy spectrum, they compare favourably with bottled water which can require around 50–70 kWh/kL product water depending on bottle size (Person *et al.*, 1998).

Table 2. Indicative specific energy consumption (kWh/kL) for different Australian water sources based on literature data[1].

Water source	SEC (kWh/kL)
Conventional surface water	0.3–0.6
Treated River Murray water	1.9
Rainwater	1.0–1.6
Stormwater harvesting	0.8
Wastewater recycling	1.1–1.8
Brackish water desalination	0.7–1.2
Seawater desalination	4.0–5.5

[1] Cook *et al.* (2012); Spies and Dandy (2012); Vieira *et al.* (2014).

Water recycling provides unique opportunities for energy recovery and/or offsetting. For example, where recycled water is on-sold for irrigation, some of the energy used during upstream wastewater treatment processes may be able to be effectively recovered by fractional allocation to water recycling processes. Additionally, in cases where recycled water is displacing other high energy potable supplies such as desalination, there is an effective energy 'offset' from the avoided conventional supply which may then be able to be credited to the recycled supply (Park *et al.*, 2008). While the cost of labour typically dominates the overall operating cost of water recycling operations in developed nations (≈45–50%), the cost of energy use is also significant at around 15–30% of typical operating costs (excluding capital) (Lazarova *et al.*, 2012c; Lazarova *et al.*, 2013; Walker, 2013). In less developed countries such as India where labour is cheaper, labour makes a relatively lower operating cost contribution (≈10%) such that energy costs may be around 50% of the total operating cost of a water recycling facility (Lahnsteiner *et al.*, 2013)—creating opportunities for cost savings via energy optimisation efforts. Elsewhere, industry experts have estimated that untapped energy efficiency opportunities in water and wastewater treatment are in the order of 5–30% (CEC, 2005). Prior work investigating the environmental energy use performance of urban water treatment systems concluded that the analyses of energy requirements of each system are highly dependent on local conditions and cannot be generalised (Friedrich *et al.*, 2009). For example, a process which is efficient in one system may be inefficient in another system due to factors like water quality or pumping distances/head). As concluded by Friedrich *et al.* (2009), this site specificity necessitates that investigations into the energy intensity of water treatment systems must be assessed on a case-by-case basis.

1.3 Energy benchmarking: the what, how and why?

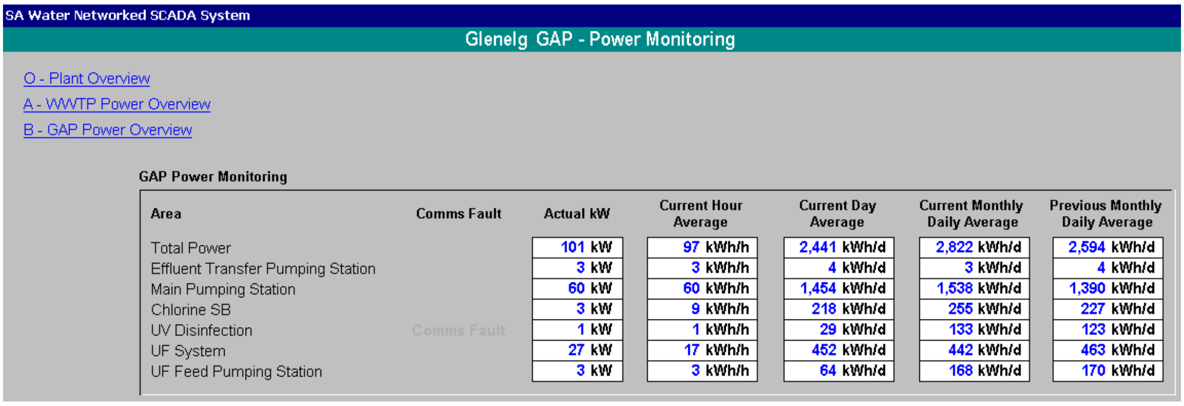
Benchmarking methodologies offer a standardised approach to measure, monitor and improve performance across a variety of water sector operations. The earliest reports of benchmarking approaches being applied to the Australian water sector are from the 1990s, with applications including urban waterway management and economic performance assessment (WSAA, 1994; WSAA, 1995a; 1995b). Various benchmarking approaches and applications exist today (Cabrera Jr. *et al.*, 2011; Rathor *et al.*, 2014), with the focus of this report being on energy. Energy benchmarking is a relatively new phenomenon and falls under the International Standard *ISO50001:2011 Energy Management Systems* (ISO, 2011). The Standard defines benchmarking as "*…the process of collecting, analysing and relating energy performance data of comparable activities with the purpose of evaluating and comparing performance between or within entities*." The basic approach is to undertake an initial energy review in order to establish an energy baseline. Future changes in energy performance are then measured and tracked against energy baseline(s). Different types of benchmarking exist, from internal to external. External benchmarking is done in order to establish the "best in industry/sector" performance of an installation, facility or a specific product or service in the same field or sector. Provided relevant and accurate data are available, energy benchmarking is a valuable input to an objective organisational energy review and serves to inform the setting of energy objectives and targets (ISO, 2011).

From a water industry perspective, the benefits of energy benchmarking to utilities can include:

- identifying opportunities for energy savings and energy production;
- providing a documented baseline for measuring and monitoring performance improvements and/or efficiency retrofits and trending of energy performance over time;
- uncovering industry 'best practices' regarding energy performance; and the fostering of an institutional energy efficiency culture (Ast *et al.*, 2008; Crawford, 2010);
- identifying operational inefficiencies and prioritising optimisation efforts to achieve 'industry best practice' operation (Lindtner *et al.*, 2008). This focuses a utilities attention on process and auxiliary equipment optimisation, not just on product quality compliance;
- highlighting the poor operation of equipment (e.g., age, installation) and or instrumentation which is monitoring the equipment performance (e.g., dissolved oxygen probes in biological treatment);
- identifying inappropriate operating set-points (e.g., start and stop set-points; validation of equipment operating envelope criteria relative to what was installed; alarming and or assist with establishing production schedules);
- allowing utilities to demonstrate to the public that they are striving for 'best practice' and are willing to learn in order to improve the efficiency of their operations (Lindtner *et al.*, 2008). This makes the benchmarking process itself, as well as the information derived from it, of significant value to water utilities.

The Australian water sector recognises that energy efficiency programs are effective means by which help utilities can better manage their exposure to future electricity prices while also minimising the flow-on effects to their customers (WSAA, 2011). While 'plant-level' energy benchmarking offers useful macro-scale performance insights, previous benchmarking of wastewater treatment operations in California (PG&E, 2003) and Australia (Krampe, 2013; GHD, 2014) has highlighted the impracticality of 'single value' energy performance criteria for plant level operations, whereby performance varies widely according to plant location, process configuration and water quality requirements. To overcome these plant-scale issues, 'process-level' benchmarking is the preferred approach as it negates many of the complications that arise from regional/operational differences and allows for more direct operational performance comparisons to determine where efficiency improvements can be made (Crawford, 2010). Accordingly, the ultimate goal of energy benchmarking and optimisation of water treatment systems should be industry best practice performance at the *process level*. To make the most of process-level benchmarking opportunities, good temporal resolution to energy data (daily/sub-daily) is also needed in order to drill down into process performance, identify inefficiencies and seek out efficiency improvements. This reemphasises the importance of process level energy sub-metering for efficient operations.

SA Water has an existing Energy Efficiency Opportunities (EEO) program which recently completed its first five year assessment cycle (SA Water, 2011). This EEO program serves to provide the institutional framework for the current research and project outcomes will feed directly into SA Water's energy management activities in this area. SA Water's initial EEO assessment highlighted several key findings: that a systematic energy reduction approach was necessary; and that extensive process energy sub-metering was required for its wastewater treatment operations (Steele *et al.*, 2013). Following these recommendations, extensive energy sub-metering was rolled out followed by an energy benchmarking study for all of SA Water's WWTPs (Krampe and Trautvetter, 2012; Krampe, 2013; Steele *et al.*, 2013). This electrical sub-metering allows for detailed process-level energy breakdowns via 'power monitor' readouts from SCADA systems (Figure 1) and the linked Operational Data Store (ODS), giving Plant Operators valuable information on process performance. While the initial capital outlay for energy sub-metering is often considerable, international case studies have demonstrated that such sub-metering (both for energy and water use) can have relatively short payback periods, with potentially significant return on investment in addition to the obvious resource savings and emissions abatements (NSTC, 2011). As a result of this pioneering work, SA Water is now considered the national industry leader in energy benchmarking.


SA Water Networked SCADA System

Glenelg GAP - Power Monitoring

O - Plant Overview
A - WWTP Power Overview
B - GAP Power Overview

GAP Power Monitoring

Area	Comms Fault	Actual kW	Current Hour Average	Current Day Average	Current Monthly Daily Average	Previous Monthly Daily Average
Total Power		101 kW	97 kWh/h	2,441 kWh/d	2,822 kWh/d	2,594 kWh/d
Effluent Transfer Pumping Station		3 kW	3 kWh/h	4 kWh/d	3 kWh/d	4 kWh/d
Main Pumping Station		60 kW	60 kWh/h	1,454 kWh/d	1,538 kWh/d	1,390 kWh/d
Chlorine SB		3 kW	9 kWh/h	218 kWh/d	255 kWh/d	227 kWh/d
UV Disinfection	Comms Fault	1 kW	1 kWh/h	29 kWh/d	133 kWh/d	123 kWh/d
UF System		27 kW	17 kWh/h	452 kWh/d	442 kWh/d	463 kWh/d
UF Feed Pumping Station		3 kW	3 kWh/h	64 kWh/d	168 kWh/d	170 kWh/d

Figure 1. Example of online SCADA power monitors for sub-metered process operations at SA Water.

While comprehensive, this prior energy benchmarking work excluded water recycling schemes due to a lack of available performance benchmarks for comparison (Krampe and Trautvetter, 2012). Internationally, and while there is a growing body of emerging research presenting energy performance data for various recycling unit processes and system configurations (Chang *et al.*, 2008; Cooley and Wilkinson, 2012; EPRI, 2013; Jacangelo, 2013; Salveson *et al.*, 2013), this research is yet to be scrutinised and synthesised in the form of technological performance benchmarks for industry energy benchmarking activities. As a leading nation in water recycling efforts internationally, Australia should be striving for world's best practice in terms of energy efficiency of its recycling operations. To achieve this, however, relevant performance benchmarks for recycling technologies must first be established.

1.4 Energy benchmarking for recycled water systems—a new approach

Internationally, standardised approaches already exist for energy benchmarking of water and wastewater treatment operations, such as those in Europe (reviewed by Crawford (2010)) and the United States (Carlson and Walburger, 2007; US EPA, 2008). For wastewater systems in particular, where most work has been done, existing benchmarking approaches and performance metrics are done within the context of a different water treatment objective (i.e. nutrient removal and environmental protection) to that which is required for recycling operations (i.e. pathogen removal and public health protection). The standard metric for wastewater treatment energy benchmarking relates energy efficiency to the organic removal performance efficiency (i.e. kWh/PE_{BOD60}/y; or kWh per population equivalent (PE) organic load per year, assuming a daily per capita 5-day biochemical oxygen demand (BOD) emission of 60 g) (Haberkern *et al.*, 2008; Crawford, 2010). While ideal for wastewater applications, this existing approach is irrelevant for assessing the performance of water recycling systems and also does not reflect the relevant regulatory framework underpinning recycled water supply in Australia—the Australian Guidelines for Water Recycling (NRMMC *et al.*, 2006).

Prior work has indicated that the European (in particular the German) approach to energy benchmarking of wastewater treatment operations is preferred (i.e. grouping according to wastewater treatment type and plant size class, and use of load-specific energy use (kWh/PE/y) rather than flow-specific (kWh/unit volume) (Crawford, 2010). In fact, the same recommendations were actually made a decade earlier by Balmér (2000) on the basis that flows to a wastewater treatment plant can vary considerably between years in line with variable precipitation rates and while this flow variation has a marginal incremental impact on the operating costs of a plant, it has a much greater impact in terms of the cost per kL wastewater treated. While this argument holds true in the wastewater context, it is less applicable to water recycling wherein Plant Operators generally have much greater control over inflows. Accordingly, we argue here that flow-specific energy use is, when used correctly, a valid benchmarking metric for recycling operations and as such have such applied it during the current study.

Similar to wastewater benchmarking, one thing that must be integrated into recycled water systems benchmarking, however, is consideration of plant size. As described by Mizuta and Shimada (2010) in a wastewater context, larger plants are afforded ‘economies of scale’ effects in terms of inherently lower volumetric energy intensities (kWh/kL) for various treatment processes. Such is the importance of plant size on process-level volumetric energy efficiency, Mizuta and Shimada (2010) conclude it is the primary determining factor for plant-level volumetric energy efficiency. Accordingly and to ensure fair performance comparisons, operational size must be taken into consideration when energy benchmarking water recycling processes. Given that the adopted wastewater approach for plant size classification is done based on a connected PE sliding scale (<1,000; 1,000–5,000; 5,001–10,000; 10,001–100,000; and >100,000 PE), equivalent plant size classes require translation to volumetric units for meaningful interpretation in a recycled water context. Based on average South Australian (Krampe and Trautvetter, 2012) and international (Henze and Comeau, 2008) per capita wastewater generation rates of 0.20 kL/person/day, the above PE-based plant size classifications translate to volumetric size class bands of:

- <0.2;
- 0.2–1;
- 1–2;
- 2–20; and
- >20 ML/d.

Until further work is done to verify the validity of these volumetric plant size classes in a recycling context, they should be viewed as indicative.

2. Research context, objectives and approach

This study was undertaken as part of a *Centre Fellowship* co-funded by the Australian Water Recycling Centre of Excellence (AWRCoE) and the Centre for Water Management and Reuse at the University of South Australia, and hosted by the industry partner SA Water. The Fellowship project sought to build upon the prior energy benchmarking work of SA Water in the area of wastewater treatment performance optimisation and extend this to water recycling systems.

The primary aim of the project was to explore and develop a new integrated 'energy–health' benchmarking approach suitable for optimising the energy efficiency of full-scale water recycling systems in Australia. Several South Australian case study water recycling systems were selected to 'road test' the new benchmarking method (i.e. Glenelg, Aldinga and Christies Beach sites all in Adelaide) and this report presents the results of these initial investigations. While the new methodology is specific to the Australian context, the general approach and much of the report's content will be relevant to water recycling operations elsewhere.

Another objective of the project was to make the first steps toward developing a new suite of energy benchmarks for various advanced water recycling processes. Earlier wastewater systems energy benchmarking work by SA Water highlighted that equivalent benchmarks for water recycling processes do not currently exist (Krampe and Trautvetter, 2012). A key outcome of the work from the industry partner's perspective was to undertake benchmarking analyses of the case study sites and demonstrate the value of the project by identifying real energy savings and making subsequent recommendations for process optimisations at full-scale. Where we have estimated such energy savings in the report, the associated dollar value of these savings is based on an assumed electricity tariff of $0.10/kWh as per Spies and Dandy (2012).

2.1 Benchmarking approach for recycling systems

Generally speaking, our energy benchmarking work followed the general framework approach of the 'Energy review' component of the ISO50001:2011 Standard and mirrored SA Water's earlier wastewater benchmarking work (Krampe and Trautvetter, 2012; Krampe, 2013; Steele *et al.*, 2013), with the key performance metric for various unit processes at each of the case study sites being specific energy consumption (SEC; kWh/kL). System boundaries for benchmarking the case study recycling operations here were adapted from the recommendations of Haberkern *et al.* (2008)—outlined in Krampe and Trautvetter (2012)—and reflect the need for case-by-case benchmarking assessments for consideration of local context (e.g., where effluent pumping makes up a considerable part of the total energy budget). Briefly, energy benchmarking analyses incorporated:

- All treatment processes at the water recycling facility;
- Energy credits from on-site energy recovery (e.g., hydraulic devices);
- All pumping stations on site, with energy use partitioned in case of effluent reuse pumping stations or where head is too high.

Not included was the energy use associated with:

- Pre-treatment steps (e.g., upstream wastewater treatment processes);
- Treatment of process backwash waste/sludge at WWTP and sludge disposal;
- Embodied energy for the construction of plant infrastructure and equipment (e.g., buildings, membranes);
- Energy consumption for the production and transport of treatment chemicals and other consumables.

With specific reference to embodied energy of materials and chemicals, these impacts are covered by other standard assessment methodologies such as environmental life cycle assessment (ISO, 2006). Additionally, utilities have much less control over the extent of embodied energy in purchased goods than they have for process energy use on site.

Beyond aspects of benchmarking according to volumetric SEC and as alluded to in Section 1.4, the requirements for performance benchmarking recycling operations are clearly divergent from those of wastewater treatment when it comes to the regulatory context. Australian water recycling operations are regulated according to a quantitative risk-based management framework in the Australian Guidelines for Water Recycling (NRMMC *et al.*, 2006)—hereafter the *Guidelines*. Australia is relatively unique internationally in having such quantitative risk-based guidelines for water recycling in terms of managing microbial risks associated with recycled water supply, with the only other country to have formally adopted quantitative microbial risk assessment-based guidelines for public health regulation of recycled water schemes being the Netherlands (Bichai and Smeets, 2013). The *Guidelines* give a range of indicative pathogen $\log_{10}$ reduction values (LRVs) for various microbial pathogen types (viruses (V), protozoa (P) and Bacteria (B)) and various engineered treatment 'barriers' (see Table 3). They also give indicative pathogen LRVs for non-engineered on-site control / preventative measures (Table 4). The *Guidelines* present a unique opportunity to tailor water recycling systems to achieve fit for purpose end use water quality while maximising the value of non-engineered on-site barriers for optimum recycling system cost and energy efficiency.

Table 3. Indicative log removals of enteric pathogens and indicator organisms by various treatment process barriers. Reproduced from Table 3.4 of NRMMC *et al*. (2006).

	Indicative log reductions[a]							
Treatment	***Escherichia coli***	**Bacterial pathogens (including *Campylobacter*)**	**Viruses (including adenoviruses, rotaviruses and enteroviruses)**	**Phage**	***Giardia***	***Cryptosporidium***	***Clostridium perfringens***	**Helminths**
Primary treatment	0–0.5	0–0.5	0–0.1	N/A	0.5–1.0	0–0.5	0–0.5	0–2.0
Secondary treatment	1.0–3.0	1.0–3.0	0.5–2.0	0.5–2.5	0.5–1.5	0.5–1.0	0.5–1.0	0–2.0
Dual media filtration with coagulation	0–1.0	0–1.0	0.5–3.0	1.0–4.0	1.0–3.0	1.5–2.5	0–1.0	2.0–3.0
Membrane filtration	3.5–>6.0	3.5–>6.0	2.5–>6.0	3–>6.0	>6.0	>6.0	>6.0	>6.0
Reverse osmosis	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0	>6.0
Lagoon storage	1.0–5.0	1.0–5.0	1.0–4.0	1.0–4.0	3.0–4.0	1.0–3.5	N/A	1.5–>3.0
Chlorination	2.0–6.0	2.0–6.0	1.0–3.0	0–2.5	0.5–1.5	0–0.5	1.0–2.0	0–1.0
Ozonation	2.0–6.0	2.0–6.0	3.0–6.0	2.0–6.0	N/A	N/A	0–0.5	N/A
UV light	2.0–>4.0	2.0–>4.0	>1.0 adenovirus >3.0 enterovirus, hepatitis A	3.0–6.0	>3.0	>3.0	N/A	N/A
Wetlands — surface flow	1.5–2.5	1.0	N/A	1.5–2.0	0.5–1.5	0.5–1.0	1.5	0–2.0
Wetlands — subsurface flow	0.5–3.0	1.0–3.0	N/A	1.5–2.0	1.5–2.0	0.5–1.0	1.0–3.0	N/A

N/A = not available; UV = ultraviolet
a Reductions depend on specific features of the process, including detention times, pore size, filter depths, disinfectant
Sources: WHO (1989), Rose et al (1996, 2001), NRC (1998), Bitton (1999), USEPA (1999, 2003, 2004), Mara and Horan (2003).

Table 4. Exposure reductions provided by on-site preventive measures. Reproduced from Table 3.5 of NRMMC *et al*. (2006).

Control measure	Reduction in exposure to pathogens
Cooking or processing of produce (eg cereal, wine grapes)	5–6 log
Removal of skins from produce before consumption	2 log
Drip irrigation of crops	2 log
Drip irrigation of crops with limited to no ground contact (eg tomatoes, capsicums)	3 log
Drip irrigation of raised crops with no ground contact (eg apples, apricots, grapes)	5 log
Subsurface irrigation of above ground crops	4 log
Withholding periods — produce (decay rate)	0.5 log/day[a]
Withholding periods for irrigation of parks/sports grounds (1–4 hours)	1 log
Spray drift control (microsprinklers, anemometer systems, inward-throwing sprinklers, etc)	1 log
Drip irrigation of plants/shrubs	4 log
Subsurface irrigation of plants/shrubs or grassed areas	5–6 logs
No public access during irrigation	2 log
No public access during irrigation and limited contact after (non-grassed areas) (eg food crop irrigation)	3 log
Buffer zones (25–30 m)	1 log

a Based on virus inactivation. Enteric bacteria are probably inactivated at a similar rate. Protozoa will be inactivated if withholding periods involve desiccation.
Source: Based on: Asano et al (1992), Tanaka et al (1998), Haas et al (1999), van Ginnekin and Oron (2000), Petterson et al (2001), Mara and Horan (2003).

Our method for recycled water systems energy benchmarking here involved a dual approach. Conventional energy benchmarking work was initially undertaken as detailed above. Following this, information on the public health performance criteria for each recycling scheme (i.e. V, P and B pathogen LRVs) was analysed in conjunction with energy benchmark output data to identify potential energy optimisation opportunities (process modifications) within the bounds of the limits of public health criteria under which the recycling scheme operates.

While it was initially proposed that recycled water systems performance benchmarking be done according to several metrics (energy, cost and greenhouse gas emissions intensity), energy was ultimately favoured as the primary performance metric for this preliminary study. Energy was considered to be the most objective metric for the ‘inter-system’ comparative nature of benchmarking work, whereas other parameters such as cost and greenhouse gas emissions intensity vary widely according to plant location. Variations in (inter)national electricity tariffs is one example of this (ESAA, 2012; Mountain, 2012), whereby recycling operations subject to high energy tariffs may perform poorly relative to those with access to cheaper energy supplies if benchmarked on an economic basis. This issue was previously raised by Balmér (2000) where it was concluded that non-monetary plant performance metrics are to be favoured over monetary ones on the basis of simpler international comparison. Likewise for a greenhouse gas emissions intensity metric, the benchmarked performance of process operations will vary widely based on the renewable energy fraction of local grid electricity supplies. For example, South Australia’s stationary energy emission factor for grid purchased electricity is 0.62 kg CO_2-e/kWh, whereas the equivalent numbers vary considerably for states such as Tasmania (0.20 kg CO_2-e/kWh) and Victoria (1.17 kg CO_2-e/kWh) (AGO, 2013)). Accordingly, we consider it more appropriate for these alternate performance metrics to be used by utilities for their own internal economic and environmental assessment purposes, such that they are not referenced in any further detail here.

Historical energy data were collected from online utility data systems for benchmarking analyses at the various case study recycling sites (refer Section 2.2). While some of these recycling schemes were operational for several years, data quality issues were problematic for benchmarking work at some sites due in part to the ongoing rollout of energy sub-meters and or final construction, commissioning and rectification activities. Accordingly and to make use of the most recent and high quality data, benchmarking work was focused on the 2013–14 financial year, with results presented in this report drawn from the same monitoring period (i.e. 01/07/2013–30/06/2014) except where indicated.

2.2 Case study sites

During the course of the project, site visits were made to several WWTP and RWTPs in the greater metropolitan Adelaide region: the Glenelg WWTP and RWTP, the Aldinga WWTP and RWTP, the Christies Beach WWTP, the Bird-in-Hand WWTP, the Bolivar WWTP and RWTP; and the Lochiel Park and Adelaide Airport stormwater recycling–aquifer storage and recovery facilities. Following initial discussions with SA Water, a number of potential case study sites were identified from these, with three sites ultimately selected for project benchmarking activities: Glenelg; Aldinga; and Christies Beach. Site visits were carried out at each of these candidate sites, initially to familiarise the project team with recycling operations at each site, with follow-up visits as required to check plant equipment and liaise with Plant Operators.

2.2.1 Aldinga Southern Urban Reuse Project

Commissioned in January–May 2010, the $62.6 million Aldinga Southern Urban Reuse Project (SURP) has the capacity to provide up to 1,600 ML of recycled water each year to about 8,000 new homes in Adelaide's southern suburbs. The quality is of a dual reticulation standard, with the treatment process achieving 6.5, 5.0 and 5.0 $\log_{10}$ virus, protozoa and bacteria removal respectively. The Aldinga SURP (Figure 2) consists of:

- a pump station at the Christies Beach WWTP and transfer pipeline to transfer treated wastewater to the Aldinga site;
- a bulk water storage lagoon at Aldinga (Lagoon 3);
- the 9.1 ML/d tertiary level Aldinga RWTP; and
- a distribution pumping station to feed dual reticulation recycled water to the nearby Seaford Meadows urban development.

The Aldinga RWTP receives secondary effluent from the Christies Beach WWTP via storage Lagoon 3 where it is conveyed to a single 5 ML membrane-lined, covered feed water basin. As required, reclaimed feed water is pumped through 200 μm screens (Amiad ABF15000) to the ultra-filtration membrane system (3× Siemens Memcor L20V units, 0.04 μm pore size, PVDF material, outside-in filtration), with filtrate receiving two-stage disinfection via UV irradiation (3×Wedeco LBX1000) and chlorination (NaClO). The finished water is stored in two 5 ML membrane-lined, covered storage basins to service daily product water demands to the dual reticulation residential network. A schematic overview of the Aldinga RWTP is given in Figure 2 and a SCADA screenshot of the RWTP provided in Appendix A.

2.2.2 Glenelg–Adelaide Recycled Water Scheme

Commissioned in December 2009, the $76 million Glenelg–Adelaide Recycled Water Scheme (GARWS) can provide more than 3,800 ML/year of recycled water to the Adelaide airport, parklands and central business district for dual reticulation and unrestricted municipal irrigation. The Scheme comprises:

- the 35 ML/d tertiary level Glenelg RWTP;
- a distribution pumping station (pump station 03);
- a trunk main, and a ring main and associated pipework to deliver recycled water to the Adelaide Park Lands and CBD area.

The Glenelg RWTP receives secondary effluent from the Glenelg WWTP where it is pumped through fine screens (Amiad ABF15000; 200 µm) and stored in two 4 ML feed water storage basins. As required, feed water is pumped through one of eight PVDF ultra-filtration membrane units (8× Siemens Memcor L20V units, 0.04 µm pore size, PVDF material, outside-in filtration), with filtrate receiving two-stage disinfection via UV irradiation (12×Wedeco LBX1000 configured in 6×2 reactor trains) and chlorination (NaClO). The finished water is stored in two 7.5 ML membrane-lined, covered storage basins to service daily product water demands. A schematic overview of the GARWS is given in Figure 3 and a SCADA screenshot of the GARWS is provided in Appendix B.

2.2.3 Christies Beach Wastewater Treatment Plant

Commissioned during October 2012–June 2014, the $272 million Christies Beach WWTP upgrade was implemented primarily to reduce pollutant loads to the adjacent Gulf St Vincent (Fox *et al.*, 2007) while also ultimately providing up to 9,000 ML of recycled water each year for reuse as part of the Aldinga SURP. The Christies Beach WWTP consists of the original ‘A/B Plant’ (conventional activated sludge, post-clarification and chlorination) and the new ‘C Plant’. The 27 ML/d (22.5 ML/d operating flow) C Plant comprises two parallel trains based on a four-stage Bardenpho process configuration with six membrane bioreactors (MBRs) each with seven membrane cassettes (GE Zenon ZeeWeedZW-500d-48E; 0.04 µm pore size, PVDF material) and UV disinfection (6×Calgon, *$C^3$500 D* low pressure, high intensity reactors configured in three channels). Schematic overviews of the Christies Beach WWTP and new C Plant MBR are given in Figure 4 and Figure 5 respectively. A SCADA screenshot of the Christies Beach C Plant membranes is also provided in Appendix C.

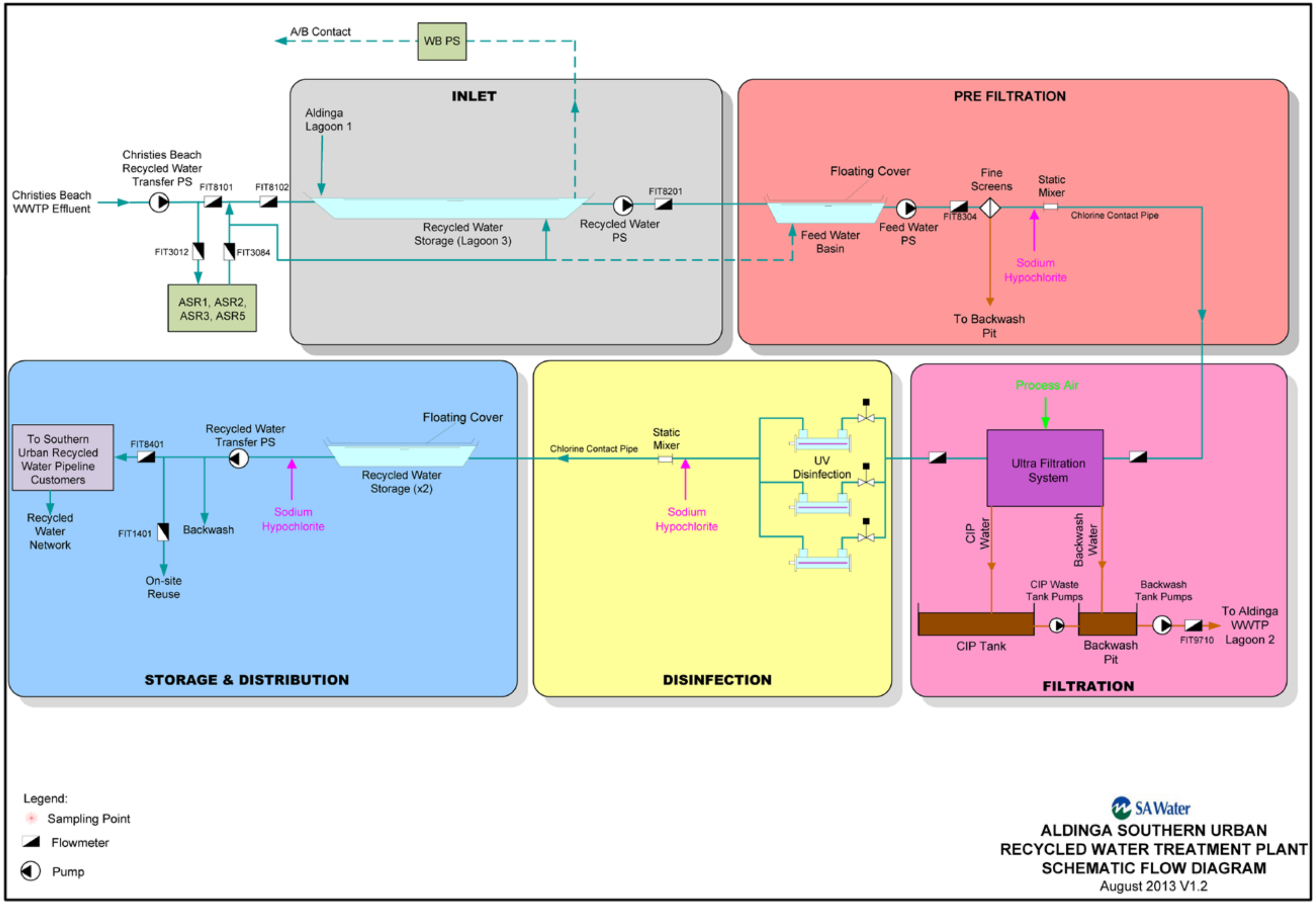


Figure 2. Schematic flow diagram of the Aldinga Southern Urban Reuse Project (SURP) recycled water treatment plant.

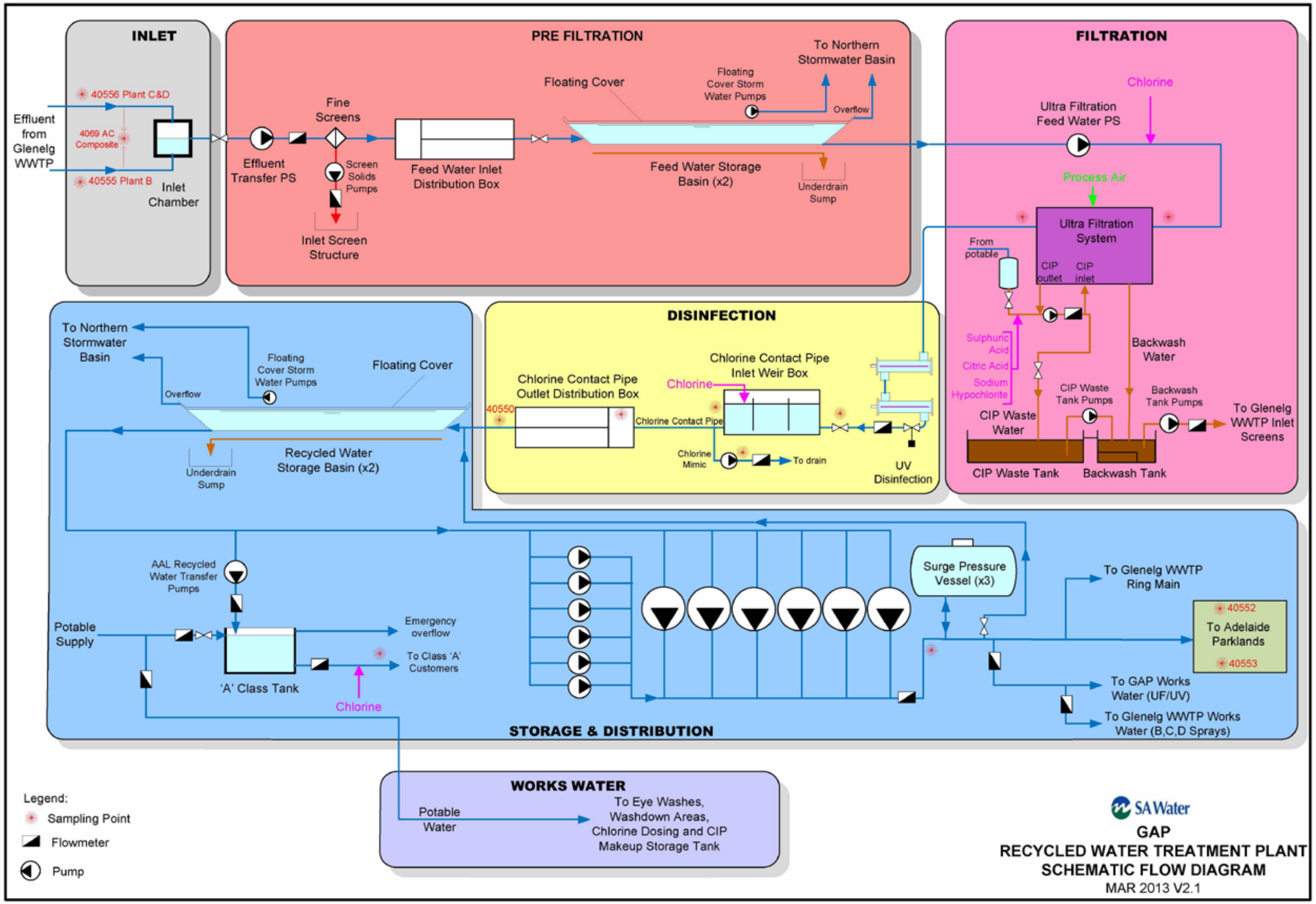


Figure 3. Schematic flow diagram of the Glenelg–Adelaide Recycled Water Scheme (GARWS) recycled water treatment plant.

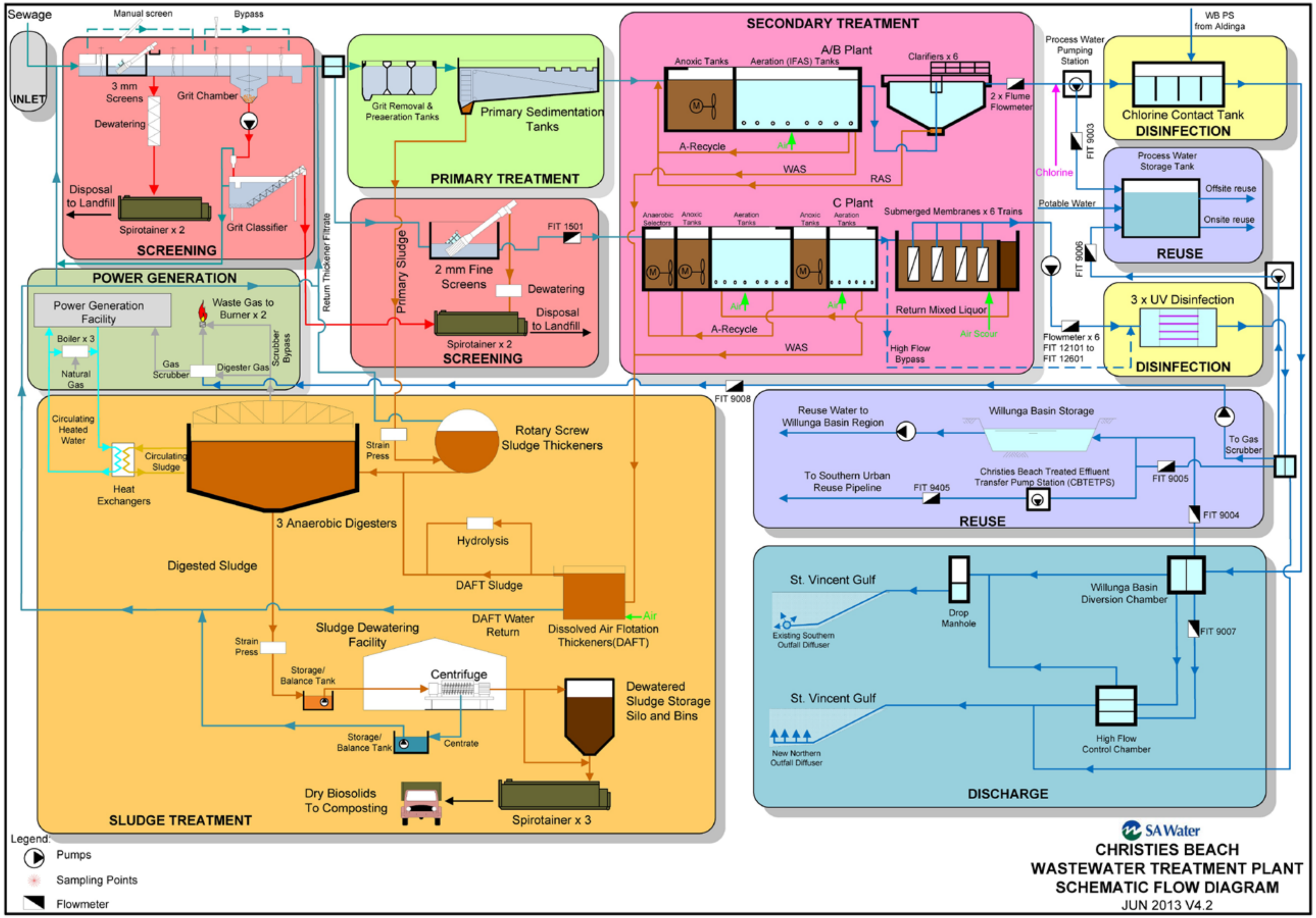


Figure 4. Schematic flow diagram of the Christies Beach WWTP.

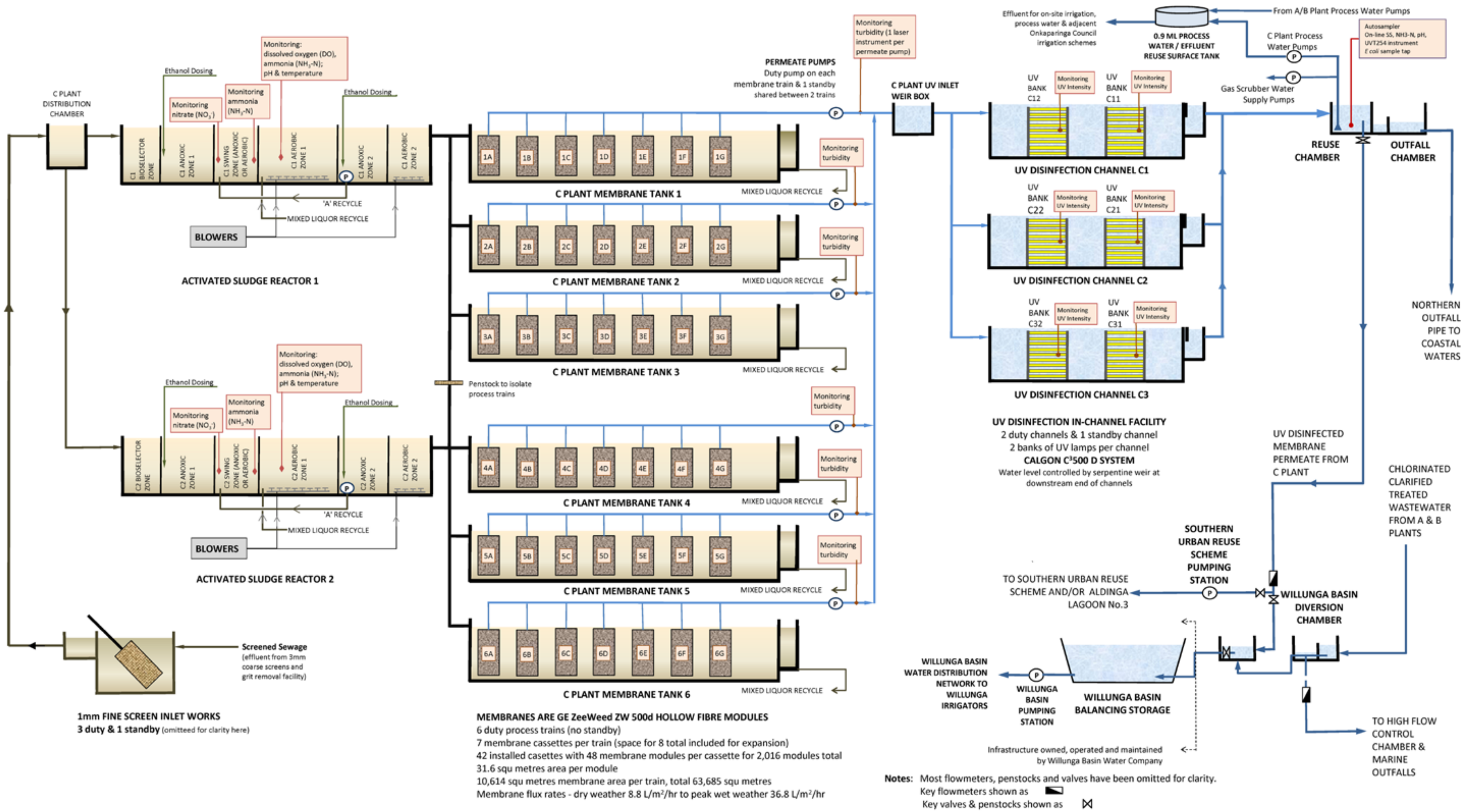


Figure 5. Schematic flow diagram of the Christies Beach 'C Plant' membrane bioreactor, UV disinfection system and Southern Urban Reuse Project infrastructure.

3. Results and discussion

3.1 New energy benchmarks for water recycling processes

During the course of the project, a comprehensive literature survey was undertaken targeting energy use data for a range of processes relevant to water recycling at SA Water and more broadly. One of the outputs of this review was a comprehensive energy benchmarking review table (Appendix D). Based on the literature review and Appendix D data, probability–density functions (PDFs) were compiled for each recycling process group and Guide (50th %ile) and Target (20th %ile) performance benchmarks ascertained (Appendix E), with these process benchmarks summarised below in Table 5.

Table 5. Preliminary energy benchmarks for various water recycling technologies, processes and systems (kWh/kL) based on literature survey (see **Appendix** D for literature). Where they exist, equivalent benchmarks from the current industry standard (Haberkern et al., 2008) are given alongside in italics.

Process group	**Average (mean)**	**50th %ile (Guide number)**	**20th %ile (Target number)**
UV (combined)	0.083	0.046	0.017
UV medium pressure	0.095	0.065	0.02
UV low pressure	0.084	0.031	0.012
UV (generic)[1,2]	*0.026–0.30*		*0.030*
MBR	0.95	0.95	0.613
MBR[1]		*0.7–0.9*	
Ozonation	0.163	0.055	0.026
Ozonation[1]	*0.03–1.05*		
Chlorination	0.012	0.003	0.001
Membrane filtration (combined)	0.224	0.189	0.102
Microfiltration	0.137	0.122	0.061
Ultrafiltration	0.228	0.174	0.116
Tertiary membrane filtration (generic)[1]		*0.10–0.15*	
Whole-of-plant recycling	2.112	1.104	0.58
Water distribution	0.408	0.346	0.181

[1]Benchmarks of Haberkern et al. (2008)
[2]Target UV benchmark relates to equivalent UV dose of 40–50 mJ/cm^2

We wish to emphasise that the benchmark values in Table 5 remain preliminary and more work is needed to broaden the input data base and further sort and refine benchmarks prior to widespread application. For example, some benchmarked technologies/processes include potable water applications (e.g., UV, membrane filtration) or are drawn from some very large operations (80–150 ML/d). Benchmarks for whole-of-plant recycling are indicative as they incorporate a wide range of operational size classes, technological configurations and sometimes also distribution pumping energy. Table 5 benchmarks for recycled water distribution are also indicative at best, since distribution energy is largely dependent on local topography (i.e. pumping head) and proximity of the RWTP to the end-user (i.e. pumping distance). The benchmarks for UV disinfection in particular incorporates energy data from potable water applications as well as a broad range of UV reduction equivalent dose rates (design set-points) (25 to >200 mJ/cm^2). Interestingly, our suggested 50th %ile 'Guide' benchmark (0.031 kWh/kL) was very similar to the 20th %ile 'Target' number of Haberkern *et al.* (2008) (0.030 kWh/kL), providing reassuring third party validation to our preliminary UV benchmarks. Likewise, our benchmarks for 'membrane filtration' processes were again of a similar order to those of Haberkern *et al.* (2008). While the literature review informing the development of these new recycling benchmarks was extensive, the values of Table 5 are preliminary and require further disaggregation (e.g., by plant size, UV/ozone dose rate, etc.) before they will be able to be applied with confidence to future benchmarking studies.

One thing that should also be mentioned in the present context of energy benchmark development is that by nature, they are not static values, but will change and require ongoing updating over time as technological advances and industry efficiency measures improve the energy efficiency of treatment operations. In particular, the use of a literature-based percentile approach to benchmark development means that ongoing efficiency improvement by industry will push the Guide (50^{th} %ile) and Target (20^{th} %ile) values towards ever more stringent performance goals (e.g., Krampe and Trautvetter, 2012); although the rate of decline in Guide and Target benchmark numbers should slow over time as efficiency improvements are progressively implemented and efficiency gains become more difficult to achieve.

Clearly there is a point at which the limits of technological efficiency are reached for individual processes, after which further net energy efficiency gains must come from outside of normal treatment operations (e.g., installation of energy recovery devices, or the pursuit of more sustainable procurement practices). Alternatively, there may also be a point at which a particular level of operational efficiency is reached (e.g., 10% above the best practice benchmark), after which the pursuit of further energy efficiency gains comes with diminishing returns and relatively longer energy payback times. Electricity prices will interplay in this dynamic also, with progressively greater incentives for operational energy efficiency under higher tariffs and *vice versa*. Additionally, and as wastewater treatment operations continue to push toward the ultimate goal of energy neutrality or net energy positive status (Lazarova *et al.*, 2012c), the goalposts for the current energy efficiency drive by utilities may shift and that this should be integrated into any long term considerations for energy benchmark development and energy benchmarking as a methodology.

3.2 Aldinga RWTP case study

Results from the detailed process-level benchmarking work for the Aldinga site are given in Table 6, Figure 6 and Figure 7 for the RWTP and the scheme level SURP which includes wastewater transfer from Christies Beach WWTP and recycled water network distribution pumping energy. Comparing the plant-level specific energy use at Aldinga (1.58 kWh/kL) to the new Guide benchmark of Table 5 (1.1 kWh/kL) indicates that the plant is operating within the same order efficiency as those in the literature. Remembering again that the Aldinga RWTP is relatively small (9.1 ML/d design flow), the plant is most likely performing somewhere around average efficiency for its size class. To investigate temporal/seasonal trends in RWTP performance, the data of Table 6 are also presented as monthly average SEC alongside mean monthly plant flows for the Aldinga RWTP (Figure 8) and scheme level SURP (Figure 9). Looking at both Figure 8 and Figure 9, there is an apparent seasonality in monthly SEC (kWh/kL) relative to average plant flow rate for the same period, suggesting likely economies of scale effects under higher plant flows (a concept introduced in Section 1.4). Statistically, this relationship was clearly evidenced by the strong anti-correlation between daily plant flow rate and SEC ($r_s = -0.85$; $p < 0.0001$).

Table 6. Aldinga RWTP and SURP benchmarked process energy data for the 2013–14 study period (annual feed water volume ≈100 ML).

Functional process group	Sub-functional group/unit process	Total energy use (kWh/yr)	Specific energy use (kWh/kL)	Comments
Major pump stations	Christies Beach effluent transfer PS	25,500	0.26	Treated effluent from Christies Beach WWTP pumped ≈20 km to Aldinga RWTP
	Influent pumping	5,314	0.053	Partial gravity feed from Lagoon 3 to feed water basin
	Backwash return pumping	2,126	0.02	Return fine screen + UF backwash water to WWTP
	Effluent distribution PS (3×15 kW + 3×150 kW)	56,962	0.64	Effluent pumping to residential SURP network; actual 2013–14 SURP flow 89 ML
	Major pumps total	**89,902**	**0.90**	Excludes UF feed water pumping energy
Filtration	UF feed water pumps (3×30 kW)	18,819	0.19	Power estimate based on yearly hours run × pump rating
	200 μm fine screens (0.18 kW)	2	0.00002	Amiad ABF15000
	UF air scour blowers (17.8 kW)	343	0.003	
	UF CIP pumps (18.5 kW)	402	0.004	
	Neutralisation pumps (4 kW)	112	0.001	
	UF air compressors (7.5 kW)	30,905	0.31	
	Sodium hypochlorite dosing pumps (0.24 kW)	75	0.0008	NaClO dosing to UF membranes for bio-fouling control
	UF total	**50,658**	**0.507**	
Disinfection	UV (3×14.5 kW LBX1000 reactors)	7,039	0.073	Benchmarked to UV process flows; UVT set-point 68.5%; actual yearly 2013-14 mean UVT 86%
	Sodium hypochlorite peristaltic dosing pumps (0.24 kW)	72	0.0007	NaClO dosing to chlorine contact pipe
	Disinfection total	**7,111**	**0.074**	
Residual/non-benchmarked power		**92,673**	**0.927**	Likely building services/lighting/HVAC, control room, auxiliary equipment (equivalent 10.6 kW constant draw)
Aldinga RWTP total		**157,882**	**1.58**	Excluding recycled water distribution
SURP total		**240,344**	**2.40**	Christies Beach effluent transfer + recycled water treatment + distribution

PS – Pump station; UF – ultrafiltration; CIP – clean-in-place; UV – ultraviolet light disinfection; UVT – ultraviolet light transmittance; HVAC – heating, ventilation and air conditioning.

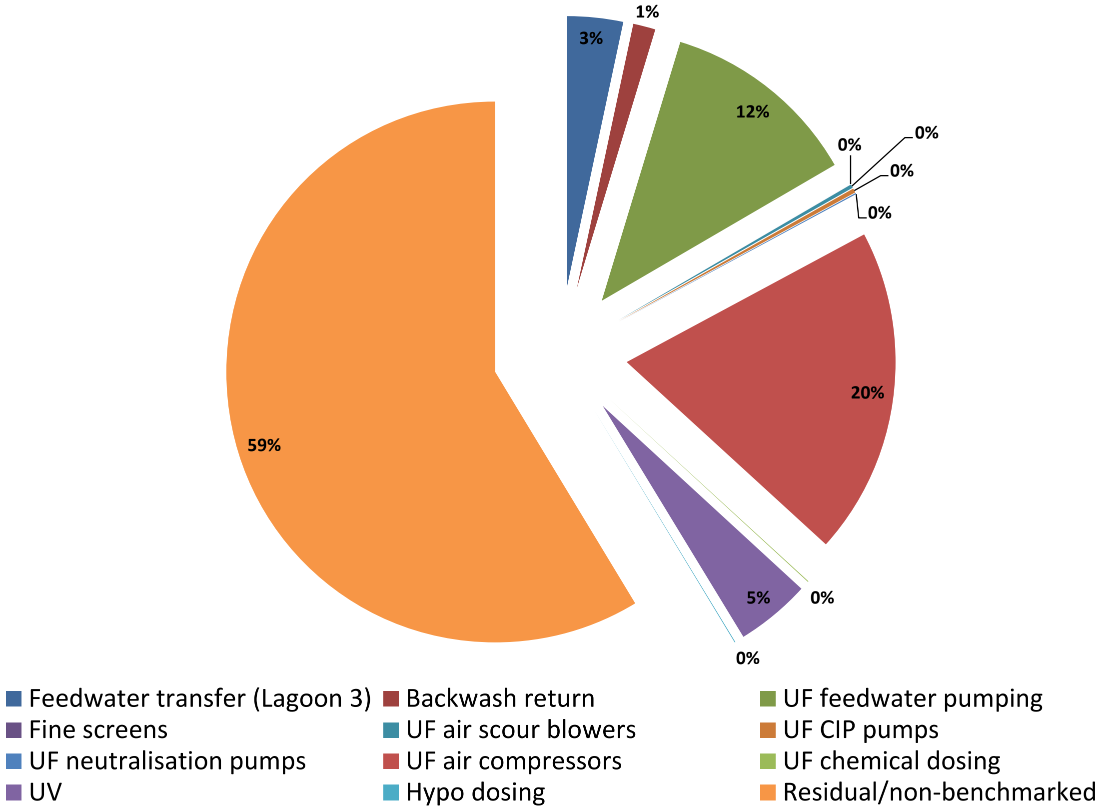


Figure 6. Breakdown of electricity use (percent total) for Aldinga RWTP during the 2013–14 period showing the relative contribution of each of the major benchmarked processes.

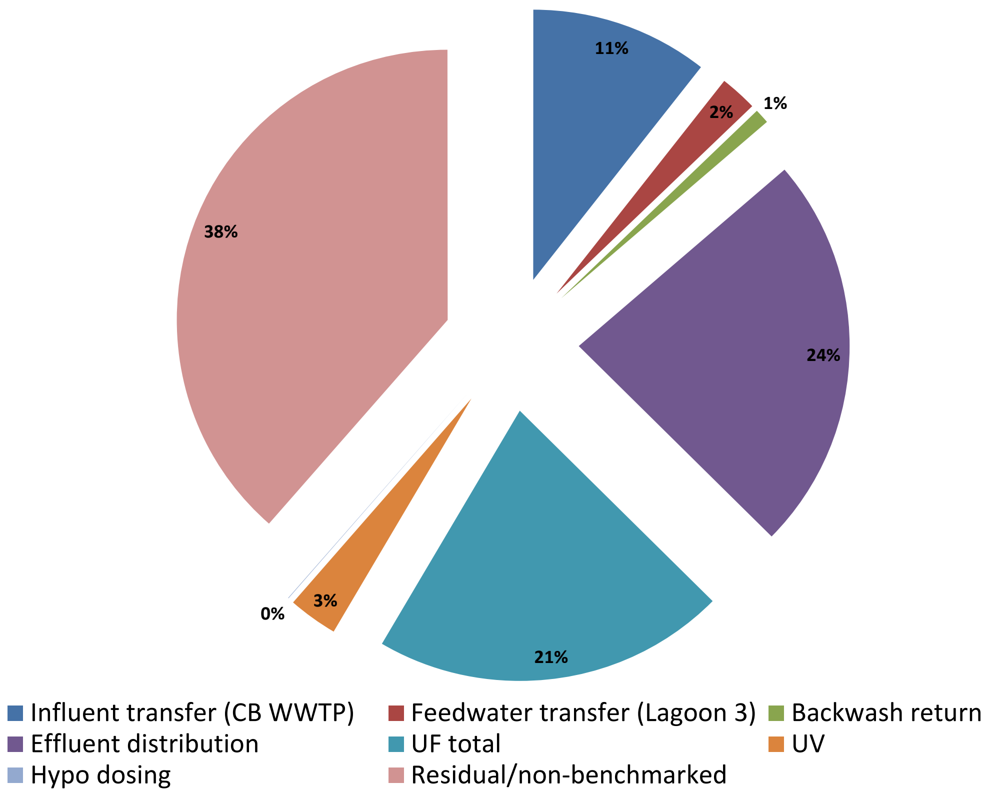


Figure 7. Breakdown of electricity use (percent total) for Aldinga Southern Urban Reuse Project (SURP) during the 2013–14 showing the relative contribution of each of the major benchmarked processes.

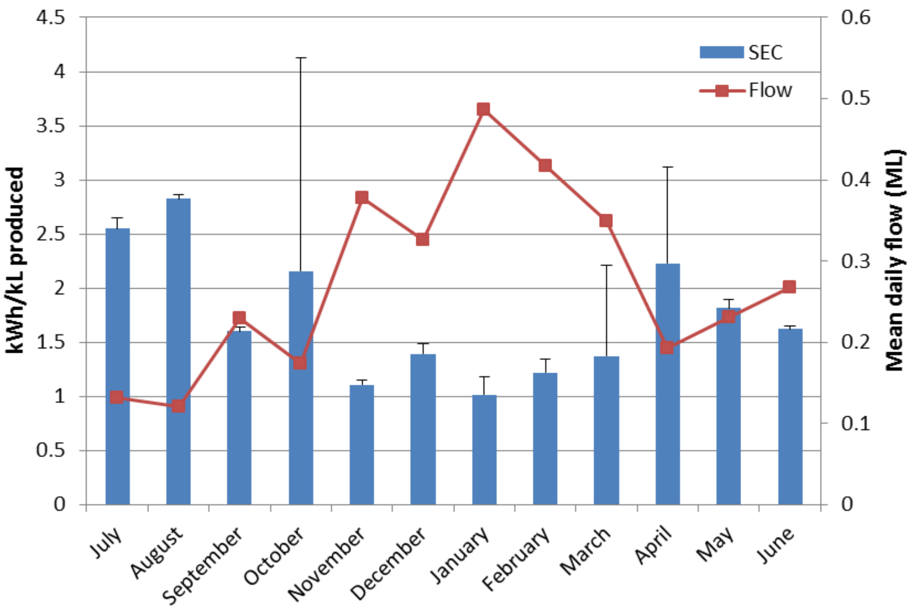


Figure 8. Mean monthly specific energy consumption (SEC; kWh/kL) of the Aldinga RWTP (excluding SURP distribution pump station energy) plotted against mean monthly RWTP flows (ML/d) for the 2013–14 period. Error bars show 1 standard deviation of the monthly mean SEC.

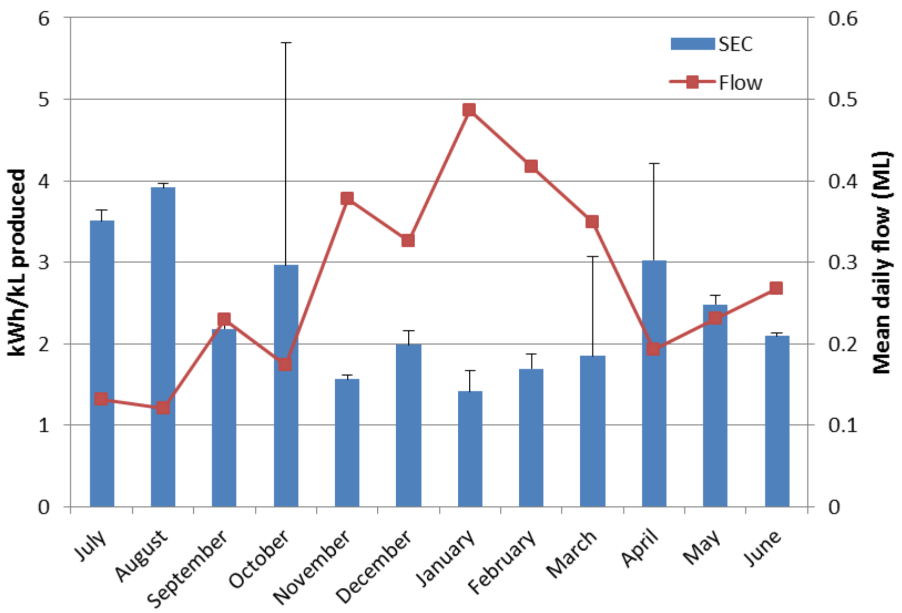


Figure 9. Mean monthly specific energy consumption (SEC; kWh/kL) of the Aldinga Southern Urban Reuse Project (SURP; including distribution pump station energy) plotted against mean monthly RWTP flows (ML/d) for the 2013–14 period. Error bars show 1 standard deviation of the monthly mean SEC.

Looking at the energy breakdowns of Table 6, Figure 6 and Figure 7, pumping energy is seen to be a major contributor to total RWTP and SURP electricity use (≈45% for the scheme-level SURP data). This is unsurprising, as pumping requirements typically dominate the energy balance for wastewater treatment and water recycling systems elsewhere. For example, Jacangelo (2013) reported figures of >50% total energy consumption for pumping in advanced water recycling plants (MF/RO + UV) followed by air compressors/blowers

(16%) and aerators (8%), complementing the data of Figure 6 where air compressors and blowers consumed ≈20% of total RWTP power. This highlights the need to carefully design distribution pipework to minimise head, consider the location of RWTPs (e.g., satellite plants) and/or establish delivery pressure set-points for recycled water customers.

The UV process was a relatively modest energy user at just 5% of total RWTP; although this was not initially the case. Following energy benchmarking of the Aldinga RWTP, initial efforts for detailed investigations were focused on the UV system due to 10-fold higher electricity use numbers (45% of total plant energy) resulting from a data scaling error in the electrical–SCADA communications (an error that the Plant Operator had rectified August 2014 based on this research). While this error inadvertently focused attention away from the actual major power users at the plant, it served as a useful reminder of the value of good process benchmarks as well as the need to exercise due diligence when interpreting SCADA data, as treating the data as absolute exposes one to the risk of interpretation errors and/or misdirection of energy optimisation activities. This data error also served to highlight the need to perform independent quality cross-checks of energy data from online systems. For example, hard copies of manual electricity meter readouts were obtained during site visits to some RWTPs in order to verify energy data from online systems.

Looking again at Figure 6, it is immediately apparent that the majority of power used at the RWTP (≈60%) was not able to be benchmarked. While this ≈93 MWh is a significant fraction of the Plant's overall energy budget, it equates to a relatively modest continuous power draw of around 10.6 kW. Although it is unclear exactly where this power is used, it seems likely that much of it is consumed by ancillary plant and building equipment (e.g., heating, ventilation and air conditioning (HVAC), staff facilities, lighting, plant control room computing and switchboard equipment, etc.). Given the incidence of energy sub-meter programming errors at Aldinga as described above, the possibility that this high residual energy use fraction is the result of a SCADA communications error should not be excluded at this point.

Assuming for now that the data are valid, this relatively high contribution of residual or 'non-benchmarked' power in the case of Aldinga may relate to the small size of the plant and perhaps more importantly, the relatively low recycled water production volume during the 2013–14 period (i.e. ≈100 ML or ≈0.3 ML/d average). It can be appreciated that with larger volumetric production rates, proportionally more electricity is used by water recycling processes while the power requirements for ancillary plant and building equipment (e.g., building HVAC, lighting and other electronics/online process control instrumentation) will remain more or less static and hence diminishes in relative terms as the plant approaches its design flow (9.1 ML/d in the case of Aldinga RWTP). Processes like membrane filtration also have certain 'fixed energy' requirements which diminish in relative terms with increasing hydraulic loading rates (Lazarova *et al.*, 2012d). Additionally, some pieces of equipment less able to tolerate intermittent 'on–off' operation (e.g., UV reactors) require warm-up periods and should remain on as long as possible to minimise start-ups and maximise asset lifespan (e.g., ballast cards, lamps). Once again, such intermittent and/or low flow operation can impart a relatively greater energy cost to low production volume water treatment processes (Steele *et al.*, 2013).

To further emphasise this point, if we assume this 93 MWh/year figure is 'flow-independent' and assuming that energy use for each of the benchmarked processes of Table 6 is 'flow-proportional' (i.e. increases linearly with volume), this residual/non-benchmarked power fraction drops to around 5% of total RWTP energy use when the plant operates at its peak design flow of 9.1 ML/d (Figure 10). Looking at the hypothetical design flow operational situation of Figure 10, the UF is clearly the primary energy user on site (≈75%), with UV disinfection the second largest user at 10%. While this simple assumption of linearity in flow-weighted scaling of process energy use doesn't factor in economies of scale concessions and is likely to overestimate actual treatment process power use, it may offer a useful means of 'horizon scanning' to benchmark plants that are operating well below design flows. In the interim, there may also be opportunities for optimising plant and/or building auxiliary power use, such as lighting control in the main plant building; site visits indicated that flood lighting may remain on regardless of personnel requirements.

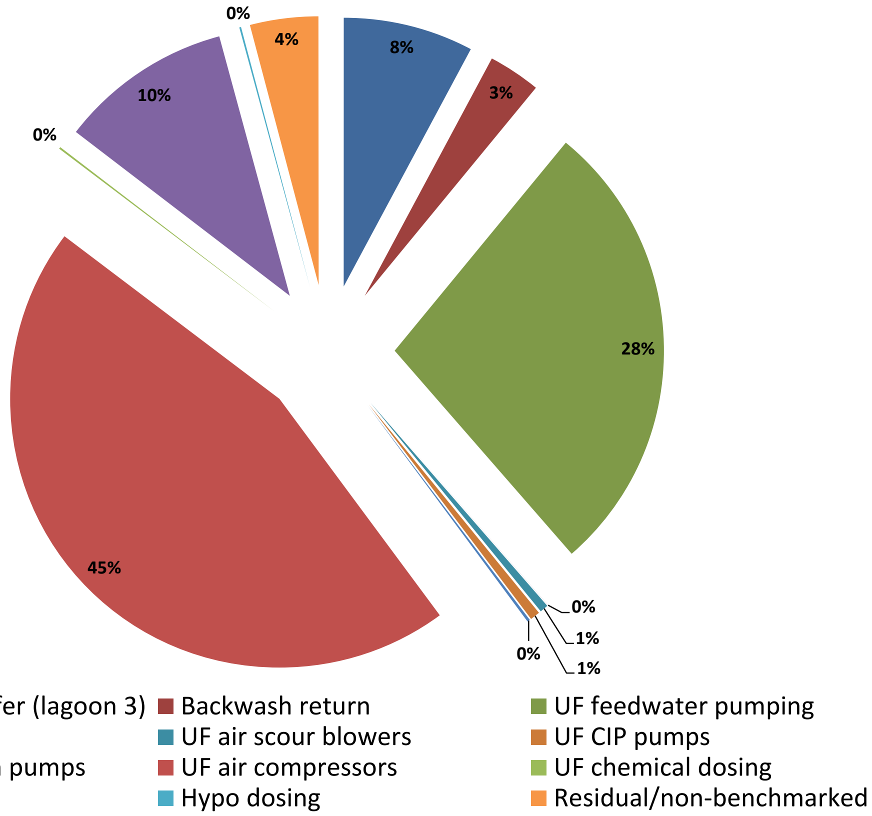


Figure 10. Breakdown of electricity use (percent total) for Aldinga RWTP showing hypothetical relative contributions of each of the major benchmarked processes with plant operating at design capacity (9.1 ML/d). All 2013–14 monitoring data (except 'residual/non-benchmarked' fraction) were linearly scaled up to point of design flow operation.

Looking again at the Aldinga UV system energy use (0.0704 kWh/kL) relative to benchmarks (Table 5), performance was similar to the average of that seen in the literature across all UV systems (0.084 kWh/kL); although was more than two-fold higher than our nominal 50th %ile Guide benchmark and the Target benchmark of Haberkern *et al.* (2008) (i.e. 0.03 kWh/kL). We do note that economies of scale concessions as well as process inefficiencies from 'on–off' operation should be taken into consideration when benchmarking this UV system, as these will adversely affect specific energy consumption (Steele *et al.*, 2013). Having said this, there is likely to be scope for further optimisation of the Aldinga UV system, particularly since electricity is typically one of the largest—if not the single largest—O&M cost burden to UV disinfection systems (Solomon *et al.*, 1998; NYSERDA, 2005).

The Aldinga UV system consists of three (two duty, one standby) Wedeco LBX1000 reactors (14.5 kW ea.) consisting of 40 XLR30 lamps (0.21–0.33 kW ea.). These reactors have been designed to deliver a minimum validated UV reduction equivalent dose (RED) dose of 55 mJ/cm^2 at a UVT of ≥55% and a maximum flow rate of 50 L/s (minimum flow rate 4.4 L/s). It should be noted here that the actual flow set-points for these reactors at Aldinga are a UV dose of 60 mJ/cm^2, 68.5% UVT and 55 L/s maximum flow (Figure 11). Analysis of the UVT data from Aldinga during the 2013–14 period showed that average UVT was consistently above 80%, with a mean value of 85.9% (± 1.92%). The reason for such a high UVT in this case is due to the nature of the high quality feed water coming from Christies Beach WWTP whereby the majority of the inflows come from the C Plant membrane bioreactor. The same data analysis revealed that actual average delivered UV dose across all three reactors was ≈80 mJ/cm^2; highest for reactor 3 (≈93 mJ/cm^2) and lowest for reactor 1 (≈55 mJ/cm^2). Incidentally, an earlier commissioning report for this Plant also made note of the fact that UV doses were “substantially greater than the 54 mJ/cm^2 (Department of Health) compliance criteria level” for each of the UV reactors, noting also that UV dose rates were highest in reactor 3 (≈100 – 115 mJ/cm^2) and lowest in reactor 1 (≈75–85 mJ/cm^2) (United Water, 2011).

Cross-referencing the manufacturer’s specifications for these reactors (Xylem, 2012) shows that for a dose of 40 mJ/cm^2 (at end of lamp lifetime) and UVT 70%, they can accommodate flow rates of up to 272 L/s. Considering the current conservatism in UVT set-point relative to actual UVT, the UV system is most likely overdosing considerably relative to requirements (NB. The above UV doses are assumed to be calculated based on a UVT of 68.5% and are therefore also most likely conservative of the actual delivered dose).

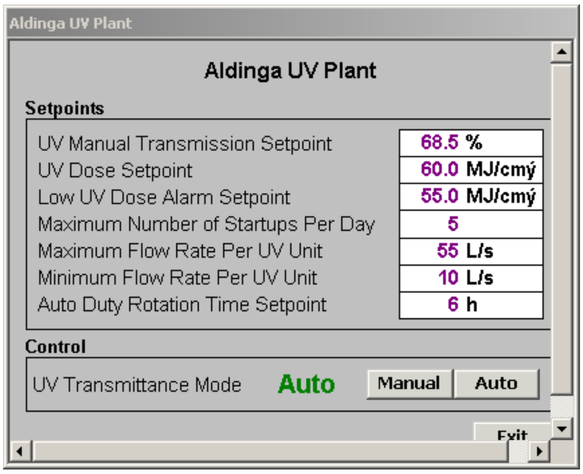


Figure 11. Screenshot of SCADA process control set-points for Aldinga RWTP UV reactors.

Looking at the risk management register for pathogen LRVs for SA Water’s recycling operations (Appendix F), viruses are the likely limiting organism for any changes to process barriers at the Aldinga RWTP (i.e. >6.5 LRV for viruses, 8 for protozoa and 10 for bacteria, relative to respective *Guidelines* health requirements for dual reticulation and municipal irrigation end-use of 6.5, 5 and 5). Cross-referencing the relevant reference document for the South Australian regulator (Department for Health and Ageing) in respect of virus inactivation by UV (US EPA, 2006; see Table 7 below) and considering operating conditions at Aldinga, there is most likely a surplus virus inactivation credit (≥0.5–1.0 log) due to the higher dose being applied and conservatism in UVT set-point.

Table 7. UV dose requirements for inactivation of various target pathogens (millijoules per centimetre squared; mJ/cm^2). Reproduced from Table 1.4 of US EPA (2006) and Table 6 of Hijnen *et al.* (2006).

Target Pathogens	**Log$_{10}$ Inactivation**							
	0.5	**1.0**	**1.5**	**2.0**	**2.5**	**3.0**	**3.5**	**4.0**
Cryptosporidium[1]	1.6	2.5	3.9	5.8	8.5	12	15	22
Giardia[1]	1.5	2.1	3.0	5.2	7.7	11	15	22
Virus[1]	39	58	79	100	121	143	163	186
Campylobacter jejuni[2]		3		7		10		14

[1] Data of US EPA (2006); [2] Data of Hijnen et al. (2006)

With regard to optimising of UV systems, there are several means by which energy use can be reduced. For example, UV ballasts can modulate power supply to conserve energy and avoid overdosing. Investigation of minutely ballast power SCADA data for the Aldinga UV systems indicates that the UV reactors are already operating at low ballast power (50–60%), so further reduction of UV dose and energy use cannot be achieved via further ballast power modulation (variable ballast power range for the LBX1000 reactors is 50–100%). Elsewhere, Daw *et al.* (2012) suggest that for UV systems operating in excess of requirements, surplus reactor banks can be either de-powered of switched off altogether by working with the manufacturer to modify the system (e.g., removing lamps and/or retrofitting de-energizing capacity to ballasts). Case studies in the literature provide instances of where utilities have realised energy savings by taking surplus UV reactors offline, in one case saving the utility some 134 MWh/year (Brandt et al., 2010; pp. 57). The authors point out that this action has the added side benefit of reducing total UV system ballast card and lamp replacement frequency, saving further on UV operation and maintenance costs.

Recommendations from the energy–health benchmarking analyses are that either reactor flow set-point or UVT set-point (or both) be increased to improve energy efficiency and reduce the requirements for the second (and third) reactors to be brought online. Another option could be to take the third reactor offline altogether (i.e. 1 duty/1 standby). Taking the third reactor offline would not only save electricity, but would also reduce the immediate requirements to purchase replacement UV lamps and ballast cards ($310 per lamp, $967 per ballast card + $105 per hour for service provider labour excl. GST) while also extending the life of the asset. Analysis of SCADA data shows that standby power use for these 14.5kW reactors is ≈2.8 kWh/d while idle. Interestingly, total combined active service hours for these three UV reactors during 2013–14 period was ≈475 h or around 1.3 h/day across the three reactors, meaning that 'standby' power use for the UV process was a sizeable portion of the total UV energy budget (≈2.2 MWh, or some 30% of total UV-related energy use). This is in contrast to the Glenelg RWTP which has the same UV reactors with similar daily standby power draw, but where the relative standby power use fraction is only 5% of total UV energy use due to economies of scale buffering from the 20-fold higher recycled water production volumes (refer Section 3.3). Another point for consideration is that while there are operational critical lower limit set-points and operator alarms for UV dose rates (i.e. low UV dose alarm set-point of 55 mJ/cm^2; Figure 11), at the same time there are no such set-points and operator alarms for 'upper dose limits' which could alert operators to excessive UV overdosing.

Another possible area of investigation for further energy optimisation of the UV systems include calibration and maintenance of UV intensity sensors. UV sensors in these reactors are key instruments for controlling the functional performance and efficiency of the UV treatment system. Poorly calibrated and/or fouled sensors may affect the performance of these reactors, resulting in unnecessary UV overdosing and higher than required energy use. The manufacturer recommends calibrating the UV sensor in LBX1000 reactors every 15 months, with sensor replacement required where UV reading is >5% above the value obtained using the reference sensor. It is unclear whether there is an asset management protocol in place for routine maintenance cleaning of the UV sensor in these reactors. Hence, it is possible that additional energy efficiency gains may be realised via periodic/more frequent cleaning of the UV sensors. While it is difficult to estimate the magnitude of these energy savings, they are expected to be considerably lower than those resulting from the previous recommendation of changes to reactor flow set-points.

3.3 Glenelg–Adelaide Recycled Water Scheme (GARWS)

Results from the detailed process-level benchmarking work for the Glenelg site are given in Table 8, Figure 12 and Figure 13 for the RWTP and the scheme-level GARWS which includes effluent distribution via the Glenelg–Adelaide Park Lands pipeline. Comparing the plant-level specific energy use at the Glenelg RWTP (0.31 kWh/kL) with our newly developed Guide benchmark for whole-of-plant recycling (1.1 kWh/kL; Table 5) suggests that the plant is operating quite efficiently relative to recycling plants surveyed from the relevant literature; the plant even outperforms the industry best practice 'Target' benchmark of 0.58 kWh/kL. Remembering that the benchmarks of Table 5 are preliminary at this stage and are not size class-specific nor partitioned according to RWTP configuration and in some cases include distribution pumping energy (see original discussion in Section 3.1), this performance comparison should be treated as indicative until the new benchmarks are further refined. For comparison, the GARWS scheme-level performance benchmark of Table 8 which includes distribution pumping energy (0.737 kWh/kL) falls in the middle of the new whole-of-plant recycling Guide and Target benchmark values.

Looking at the scheme-level data of Figure 13, it is clear that recycled water distribution (PS03) is the single largest energy user at nearly 60% of total GARWS energy for 2013–14. Indeed combining all major pumping processes of Table 8, the total GARWS energy use fraction for pumping requirements is considerable at ≈77%. Benchmarking of the GARWS recycled water distribution pump station (PS03) performance for the 2013–14 period showed that the pump station was achieving an average efficiency of 0.43 kWh/kL (Table 8); for reference the smaller Aldinga SURP distribution pump station achieved an average efficiency of 0.64 kWh/kL (Table 6). These performance values were within the range of pumping SEC values reported in the literature (≈0.2–1.1 kWh/kL) and for the Glenelg site was close to the literature average (≈0.41 kWh/kL) and slightly above our indicative 50^{th} %ile Guide number for generic 'water distribution' (≈0.35 kWh/kL; Table 5). As discussed earlier (Section 3.1), Table 5 benchmarks for water distribution are indicative only as they do not consider variable delivery head/pressures; this is particularly relevant to the Glenelg site as the pumping head is in the order of 100 m (1000 kPa). We should emphasise here that the above energy benchmarking for PS03 was done at the GARWS scheme-level and hence normalised to yearly RWTP flow rather than actual yearly PS03 flow. Given that around 10% of the RWTP feed water inflow is lost as backwash water (fine screens, UF) and a further ≈20% of the recycled product water is used on-site for irrigation and process water requirements, the equivalent PS03 energy benchmark relative actual 2013–14 pumped flow was 0.65 kWh/kL (Table 6). No attempt was made to benchmark pump station electrical performance based on equipment/motor efficiencies relative to manufacturers' specifications or to normalise pumping performance to delivery pressure (Wh/kL·m).

Table 8. Glenelg RWTP benchmarked process energy data for the 2013–14 study period (annual feed water volume ≈2,040 ML).

Functional process group	Sub-functional group/unit process	Total energy use (kWh/yr)	Specific energy use (kWh/kL)	Comments
Major pump stations	Influent pumping (PS01)	113,542	0.0556	Wastewater effluent transfer to feed water basins
	Effluent pumping & distribution (PS03)	869,953	0.426	Benchmarked to yearly RWTP feed water volume; benchmark against yearly PS03 flow only (1,338 ML) is 0.650 kWh/kL
	Fine screens backwash pumps	17,479	0.0086	2×11 kW pumps assumed
	Major pumps total	**1,000,974**	**0.491**	
Filtration	200 μm fine screens (0.18 kW)	2,360	0.0012	Amiad ABF15000; 0.0097 kWh/kL including fine screens backwash pumping
	UF feed water pumping (PS02)	147,712	0.0724	
	UF air scour blowers	4,800	0.0024	
	UF CIP pumps	2,479	0.0012	
	UF CIP waste pumps	312	0.0002	Neutralised water transferred to backwash tank
	Backwash return pumping	14,157	0.007	Total yearly backwash pumping return flow 20.7 ML; equivalent benchmark relative to backwash flow only is 0.69 kWh/kL
	UF air compressors	114,310	0.056	
	Exhaust fans	6,132	0.003	Chemical stores ventilation
	UF total	**292,262**	**0.143**	Includes UF feed pumping
Disinfection	Chlorination	8,140	0.0047	Includes chlorine used for UF membrane maintenance and disinfection
	UV (12×14.5 kW LBX1000 reactors)	108,744	0.0624	Benchmarked to UV process flows; UVT set-point 55%; actual yearly mean UVT 70%; UV RED set-point 15 mJ/cm^2; actual yearly 2013-14 mean UV RED 51 mJ/cm^2
	Disinfection total	**116,884**	**0.067**	
Glenelg RWTP total		**633,705**	**0.311**	Excluding recycled water distribution
Residual/non-benchmarked power		**93,538**	**0.046**	Likely building services/lighting/HVAC, control room, auxiliary equipment (equivalent 10.7 kW constant draw)
GARWS scheme total		**1,503,658**	**0.737**	Including recycled water distribution via Glenelg–Adelaide parklands pipeline

PS – Pump station; UF – ultrafiltration; CIP – clean-in-place; UV – ultraviolet light disinfection; UVT – ultraviolet light transmittance; HVAC – heating, ventilation and air conditioning.

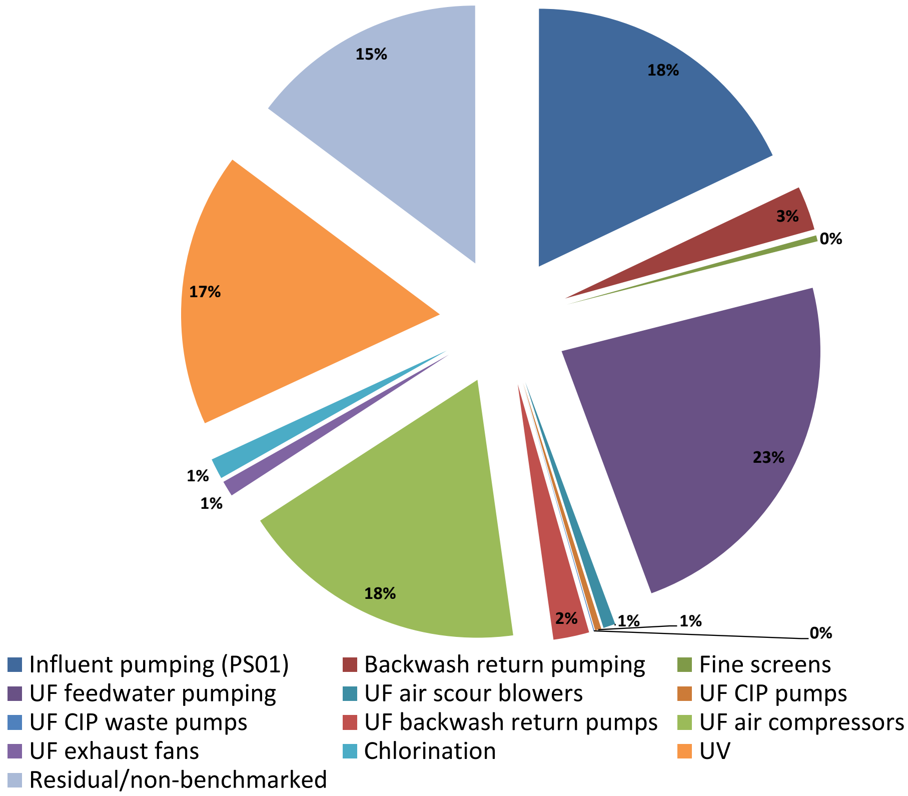


Figure 12. Breakdown of electricity use (percent total) for Glenelg RWTP (excluding effluent distribution PS03 energy) during the 2013–14 period showing the relative contribution of each of the major benchmarked processes.

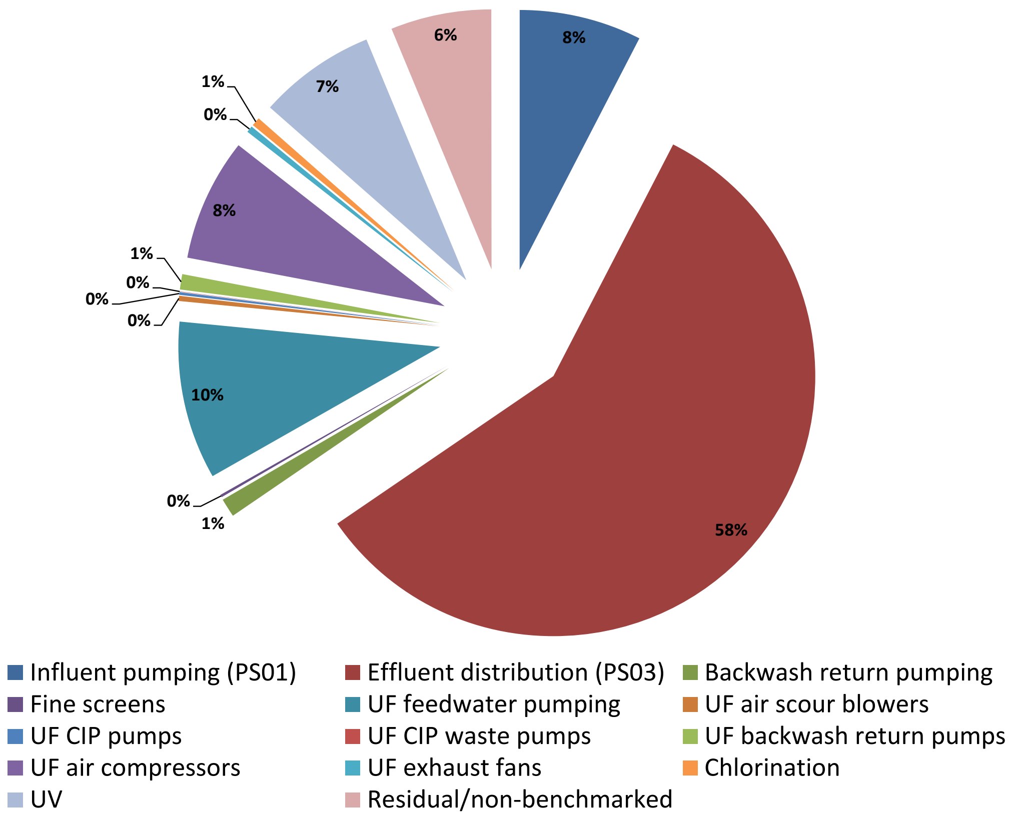


Figure 13. Breakdown of electricity use (percent total) for the Glenelg–Adelaide Recycled Water Scheme (GARWS) during the 2013–14 period showing the relative contribution of each of the major benchmarked processes including effluent distribution PS03 energy.

Looking in detail at the daily energy use and flow profiles for PS03, there appears to be a strong association between daily flow and energy use at flows greater than ≈2–3 ML/d, below which PS03 energy use seems somewhat more independent of flow (Figure 14). Although there was some variability in distribution pressure during the 2013–14 period (set-point ranged from 800–1050 kPa), this appeared to have a marginal influence on the overall PS03 energy use profile. In terms of energy efficiency improvements for PS03 and assuming that the pumps are performing optimally in terms of where they operate relative to the point of best efficiency on the pump curves, the only feasible way to improve PS03 volumetric energy efficiency (kWh/kL) is to move more water throughout the year. In the long term, this means increasing the total customer base for Glenelg recycled water, as well as sourcing more 'off peak' end users (i.e. non-irrigation) to consolidate seasonal energy performance trends (Figure 16) and take maximum advantage of the high PS03 fixed energy requirements. SA Water continues to actively pursue more customers for its recycled water, for example, the new dual reticulation Bowden Village development will come online in 2014.

To once more investigate seasonal trends in RWTP performance, the data of Table 8 are again presented as monthly average SEC alongside mean monthly plant flows for the Glenelg RWTP (Figure 15) and the scheme-level GARWS (Figure 16). Looking at both Figure 15 and Figure 16, and as detailed for the Aldinga site above (Section 1.4), there is a clear seasonal trend in SEC (kWh/kL) relative to plant flow rate. Statistically, this relationship was again supported by the strong anti-correlation between daily plant flow rate and SEC ($r_s = -0.77$; $p < 0.0001$). For the RWTP (Figure 15), these economies of scale discounts translate on average to nearly three-fold lower SEC values under high flow summer months relative to low demand winter periods. Translating these numbers to operational energy costs reemphasises this point, whereby the specific energy cost ($/kL) of water treated varies by a similar order between summer (≈$0.07/kL) and winter (≈$0.17/kL) operation (Figure 17). We should point out here that the analysis of Figure 17 reflects only the electricity cost and does not include other operating costs such as chemicals.

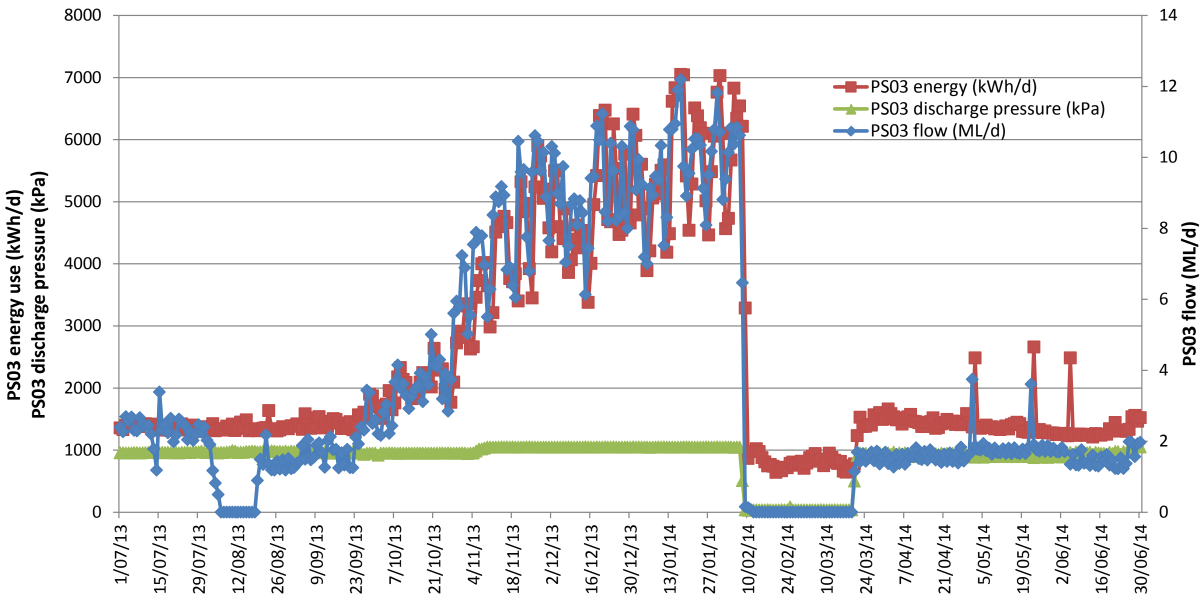


Figure 14. Relationship between the GARWS effluent transfer pump station (PS03) daily energy use profile, daily flow and discharge pressure for the 2013–14 period. NB: the GARWS system was offline for the period of February–March 2014 due to maintenance.

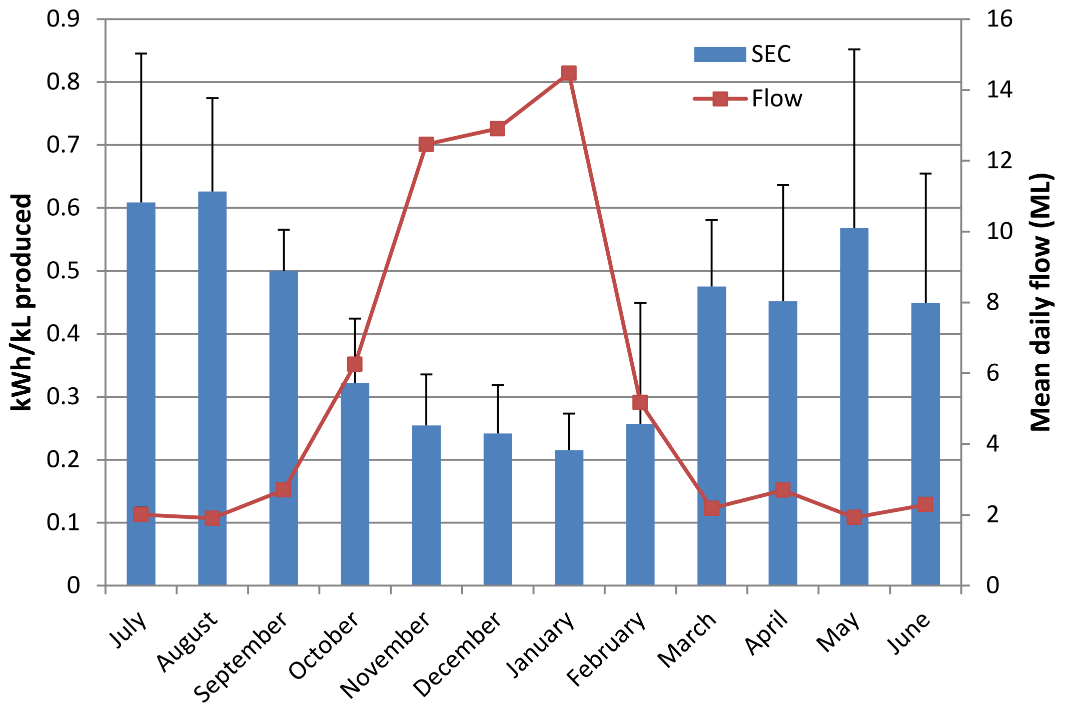


Figure 15. Mean monthly specific energy consumption (SEC; kWh/kL) of the major benchmarked processes at the Glenelg RWTP (excluding distribution pump station (PS03) energy) plotted against mean monthly RWTP flows (ML/d) for the 2013–14 period. Error bars show 1 standard deviation of the monthly mean SEC.

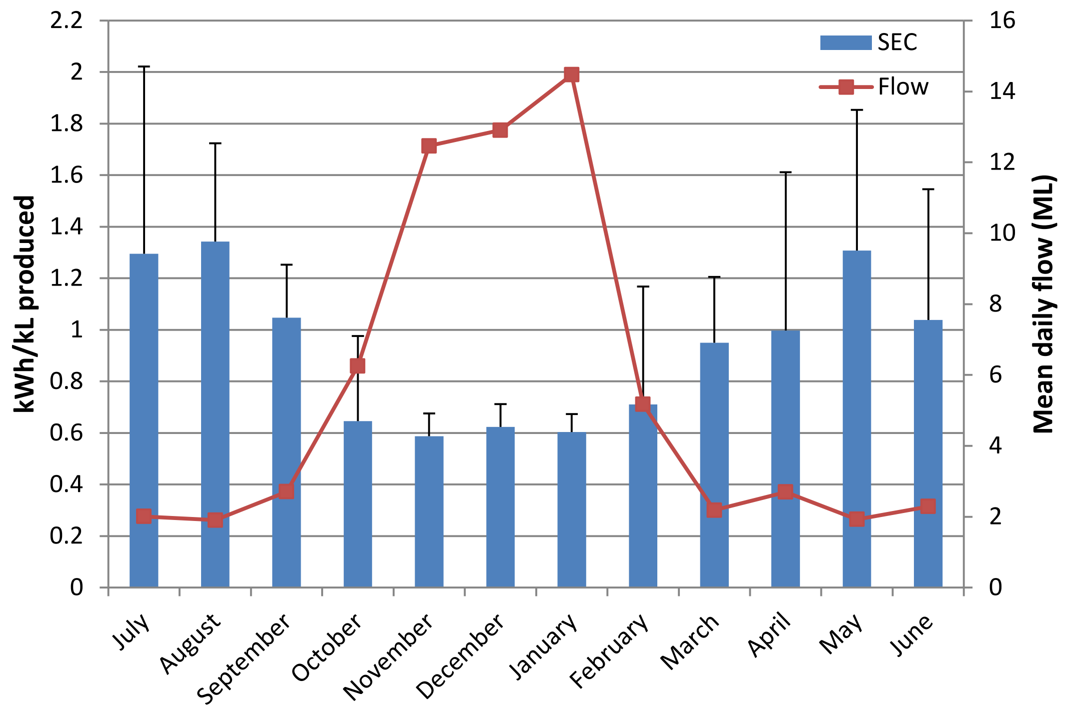


Figure 16. Mean monthly specific energy consumption (SEC; kWh/kL) for the Glenelg–Adelaide Recycled Water Scheme (GARWS) (including distribution pump station (PS03) energy) plotted against mean monthly RWTP flows (ML/d) for the 2013–14 period. Error bars show 1 standard deviation of the monthly mean SEC.

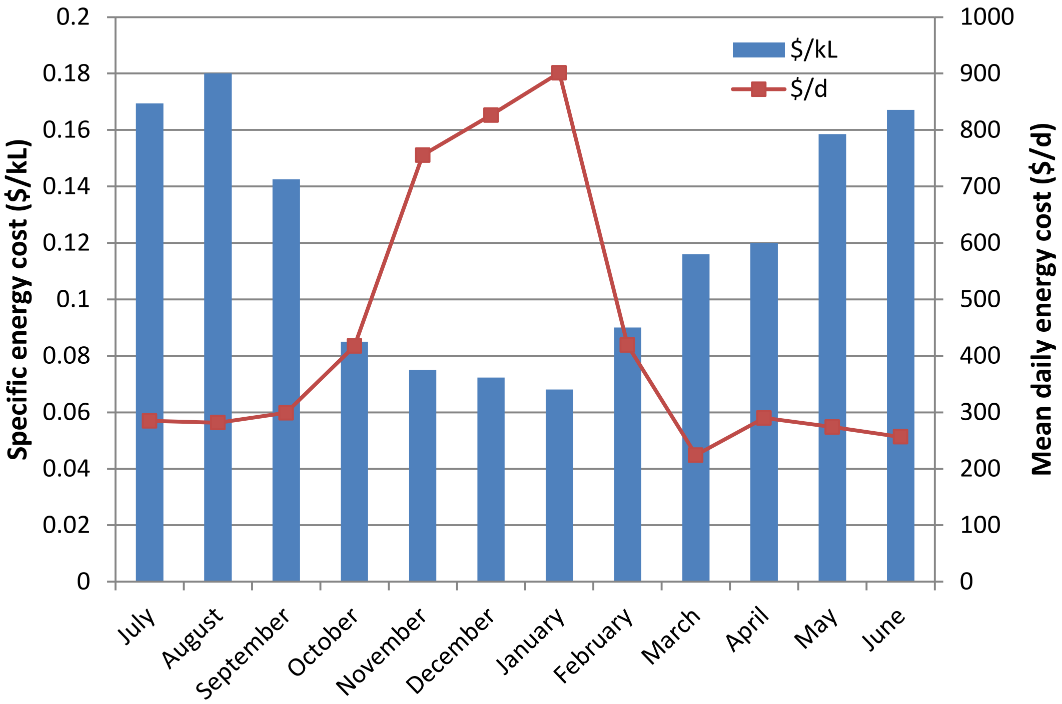


Figure 17. Mean monthly specific energy cost ($/kL) of the Glenelg–Adelaide Recycled Water Scheme (GARWS) including all benchmarked and non-benchmarked energy plotted against mean monthly total plant electricity cost ($/d) for the 2013–14 period.

Looking again at the detailed energy breakdowns of Table 8 and Figure 12, it is clear that the UF process is the primary energy consumer for the RWTP, demanding some 46% of total energy (including PS02 UF feedwater pumping energy). The remaining ≈54% of RWTP electricity is consumed by pumping feed water from the Glenelg WWTP to the balance storage basins via the 200 μm fine screens (18%), UV disinfection (17%) and residual/non-benchmarked processes (15%) which are assumed to relate to building services, lighting and HVAC. Backwash return pumping from the fine screens comprises the majority of the remaining energy balance (2.8%) followed by chlorination (1.3%). If we combine pumping energy across the various RWTP processes it accounts for some 47% of all power used on site, mirroring the findings from recycling operations elsewhere. For example, Jacangelo (2013) reported figures of >50% total energy consumption for pumping in advanced water recycling plants (MF/RO + UV). Jacangelo (2013) also reported similar energy use figures for air compressors/blowers (16%) to those from the Glenelg RWTP benchmarking (19% for UF air compressors + scour blowers). Similarly, Chang *et al.* (2008) report very similar energy use data for UF processes at a drinking water plant at Anthem Water Campus, Arizona, whereby the UF process (membranes only, excluding influent pumping) comprised 14–19% of total plant energy use (≈0.09–0.2 kWh/kL) at flows (≈6–17 ML/d) very similar to those at Glenelg during the monitoring period (≈2–15 ML/d).

Comparing the benchmarked UF process specific energy consumption (0.143 kWh/kL) with the equivalent Guide and Target benchmarks of Table 5 suggests that the UF process is performing above current industry average energy efficiency (0.174 kWh/kL), but below best practice Target performance (0.116 kWh/kL). Again, we emphasise the preliminary nature of these new benchmarks; although in this case we do accept the close alignment of our preliminary benchmarks with existing 'tertiary membrane filtration' benchmarks of Haberkern *et al.* (2008) (Table 5). One thing to note here is that there were some issues with obtaining UF process energy data for the Glenelg RWTP. Energy data for the UF process was derived from a sub-meter (TAG ID: ABSTRACT.GLGRW-UTPD-UV-PLANT-POWER-

USAGE-CALC) which gave aggregated power use data for a number of pieces of plant equipment (i.e. 2×18.5 kW CIP pumps; 2×15 kW instrument air compressors; 2×15 kW UF air scour blowers; 2×11 kW backwash tank pumps; 2×2.2 CIP waste pumps; 5×0.14 kW chemical dosing exhaust fans; 3×0.5 kW sampling pumps; and 2×0.35 sampling pumps). Up until mid-November 2013, this sub-meter readout also included UV energy use, after which time it was isolated on its own sub-meter (TAG ID: GLNGSS.GLGRW-UV-JIT-KWHAVE-DAY). Accordingly, Table 8 energy data for the various UF processes were estimated based on equipment power ratings and daily hours of operation from SCADA and we accept that there may be some inaccuracies as a result of these assumptions/data manipulations. UV energy use for the 12 month 2013–14 period was estimated by extrapolating fractional UV energy use from the sub-metered December 2013–June 2014 period to cover the missing July–November 2013 data.

A similar issue was encountered in respect of chlorine-related energy use data at the Glenelg site (TAG ID: GLNGSS.GLGRW-CDCL-JIT-KWHAVE-DAY / ABSTRACT.GLGRW-UTPD-CHLORINE-POWER-USAGE-CALC). Initial chlorine process energy benchmarking showed very high chlorine-related energy numbers associated with recycling operations (≈0.046 kWh/kL) relative to our preliminary benchmarks of Table 5 (0.001–0.003 kWh/kL), triggering more detailed investigations as to why. Subsequent discussions with site personnel and sourcing of electrical diagrams for the Chlorine Building confirmed that numbers for RWTP chlorine switchboard energy also included those for wastewater-related chlorination at Glenelg. Due to the close proximity of the site's Chlorine Building to the RWTP, the energy data were allocated 100% to the recycling operations, whereas in reality, chlorine demand from wastewater treatment operations (chlorination of secondary effluent) dominated total site use (≈90%). Ultimately, RWTP chlorine-related energy was separated out from the pooled wastewater + recycled water data based on mass of chlorine used at both plants (average of 500 kg/d for the WWTP vs. 36 kg/d for the RWTP during 2013–14), resulting in a 10-fold drop in chlorine-related energy for the RWTP (0.004 kWh/kL) and aligning more closely with our Table 5 benchmarks.

Benchmarking of the UV system revealed a SEC of 0.0624 kWh/kL (Table 8), equating to 17% of Glenelg RWTP energy (Figure 12). Comparing this to the respective Guide and Target benchmarks of Table 5 for low pressure UV lamps (0.012 and 0.031 kWh/kL respectively) suggests that the Glenelg UV system is not performing optimally. As discussed earlier (Section 3.1), however, our new benchmarks for some recycling processes remain preliminary and require further work to consolidate and improve their robustness (in particular the UV benchmarks which require both size class and dose delineation). Adopting the existing Target benchmark of Haberkern *et al.* (2008) (0.030 kWh/kL), the Glenelg UV process is using more than 200% of the Target energy use at a comparable UV dose of 40–50 mJ/cm^2.

The Glenelg UV system was originally designed to deliver a minimum validated RED of 50 mJ/cm^2 (operational set-point of 54 mJ/cm^2) at a minimum UVT of 50% (operational set-point 55%) in order to claim an LRV credit of 1.0 log_{10} for virus inactivation (SA Water, 2010). Following an upstream process modification at the Glenelg WWTP during early 2012 (i.e. switch from molasses to sucrose dosing during activated sludge treatment), the UVT of feedwater to the RWTP improved considerably. For the six months preceding the April 2012 carbon dosing change, the mean UVT was 57.6%, whereas the same value for the six months following the change was 67.2%; the average UVT during the 2013–14 study period was 68.8%. UV reactor ballast power was consistency at a minimum of 50%, which indicated that the UV reactor trains were achieving a RED >25 mJ/cm^2.

Consequent analysis of 2013–14 UV dose rate data from SCADA indicated that the Glenelg UV process is delivering higher than required UV doses across several reactors (on average some three-fold higher dose rates than set-points across the six UV trains). Parallel SCADA analysis of minutely UV ballast power data indicates that the UV reactors are also operating at or close to maximum ballast modulation (≈50% power) when in service, such that further depowering of the reactors is not possible under current operating conditions. As detailed earlier in Section 3.2, the LBX1000 UV reactors can treat up to 272 L/s for a dose of 40 mJ/cm^2 (at end of lamp lifetime) and UVT 70% – well beyond current hydraulic loading rates. Due to the current conservatism in UVT set-point (55%) relative to actual UVT (≈68%), ballast power modulation constraints and likely hydraulic under-loading, the net result is UV overdosing.

Cross-referencing the risk management register for pathogen LRVs for the Glenelg RWTP (Appendix F), the Glenelg UV system is credited with a 1.0 log_{10} virus inactivation at the minimum validated RED of 50 mJ/cm^2 (see also Table 7). Based on Appendix F, the most likely limiting pathogen for UV process changes will be viruses, with a 1.0 log_{10} surplus inactivation credit available relative to respective minimum end-use requirements (6.5 log_{10}). Looking again at Table 7 and Appendix F, a 10-fold reduction in minimum UV RED from 50 to 5 mJ/cm^2 will still satisfy end-use requirements for viruses (6.5 log_{10}), protozoa (5.0 log_{10}) and bacteria (5.0 log_{10}). Accordingly, to further control UV dose and optimise process energy efficiency, it is suggested that a combination of the following changes are implemented: UVT set-point be increased (≥65%); reactor flow set-points/hydraulic loading rates be increased (>200 L/s); turn off the second reactor in each train or decommission surplus reactor trains. Energy savings from taking 50% of the UV reactors offline based on 2013–14 energy data are in the order of 55 MWh/year (≈$5,500 p.a.). Partial UV reactor shutdown will also conserve standby power use while reactors are idle (≈2.8 kWh/d/reactor) as well as extend asset lifespan and reduce O&M costs (refer Section 3.2). This change has not yet occurred as UF membrane performance is being reviewed.

Water utilities today are acutely aware of the energy demands from pumping operations. In terms of possible optimisations for the Glenelg RWTP, the use of premium efficiency motors particularly for UF pressurisation (PS02) would, if not already in place, be an area for further investigation given that this process alone consumes almost 25% of RWTP power ($25,000 p.a. at 2013–14 flows). Operationally, there may be other ways of minimising RWTP power use. For example, operation within defined trans-membrane pressure bands and reducing the requirements for membrane backwashing and scouring will conserve energy (Lazarova *et al.*, 2012a); however, care must be taken to avoid prematurely compromising membrane integrity and to ensure proper fouling control is maintained. Compressed air requirements (for membrane backwashing and process operation) make a significant contribution to total UF process energy use at the Glenelg RWTPs (≈40%). There are various approaches for providing capacity control to air compressors, including modulation, unloading, variable displacement and variable speed control (PG&E, 2006). PG&E (2006) highlight that since annual compressor operating cost is generally near the purchase price of a new unit, it is very important select an appropriately sized compressor with efficient capacity control, especially for variable air flow demand applications. Since the above benchmarking results showed some room for optimising the UF process to reach Target performance (0.116 kWh/kL), there may be scope for compressed air process optimisation. We suggest that the size of existing compressors is re-assessed relative to current RWTP flow rates and process air requirements and/or variable frequency drives installed if not already in place.

Another means of increasing energy efficiency of the UF process is to optimise feed water quality through pre-treatment steps (Chang *et al.*, 2008). For example, adding or optimising upstream coagulation–flocculation pre-treatment steps prior to UF will reduce the solids and organics load to the membranes, reducing membrane fouling and subsequent backwashing/air scouring/process air requirements. Air requirements (blowers + compressors) make up a significant fraction of the total UF process energy use at both the Glenelg and Aldinga RWTPs (≈41% and 61% respectively), therefore, any efforts to improve feedwater quality and/or mitigate process air requirements are likely to yield UF energy efficiency gains. Again, while this may improve UF process energy efficiency and possibly also extend membrane life, it may incur additional material and resource costs upstream and increase the load on WWTP solids handling processes, such that these trade-offs need to be considered holistically and balanced against potential energy savings. Alternatively, some plants may be able to selectively harvest their secondary effluent and optimise feed water quality onto a membrane system. For example, the Glenelg WWTP has three activated sludge plants (known as B, C and D Plants) and the clarified effluent streams are dosed with chlorine prior to discharge to the contact tanks (B; C/D). Historically, the three plants performed differently in terms of their ability to remove nitrogen. A manual drop plate can be installed post-chlorination to select whether B or C/D effluent is pumped to the UF feedwater basins. This activity is undertaken rarely and requires manual intervention, but does provide the opportunity to select higher quality effluent and minimise membrane fouling potential, particularly if there was a significant process upset during upstream secondary treatment.

Another option to improve UF process performance is to operate membranes units at higher production flow rates to exploit economies of scale effects (Chang *et al.*, 2008; Lazarova *et al.*, 2012d). This economies of scale phenomenon (introduced in Section 1.4) is well known and the same effect was observed at the Glenelg RWTP (Figure 18) wherein specific energy consumption is optimal at plant flows above a nominal 5 ML/d. This raises the question as to how best to produce 5 ML/d into the recycled water storage basins, taking into account summer demand and/or low demand periods.

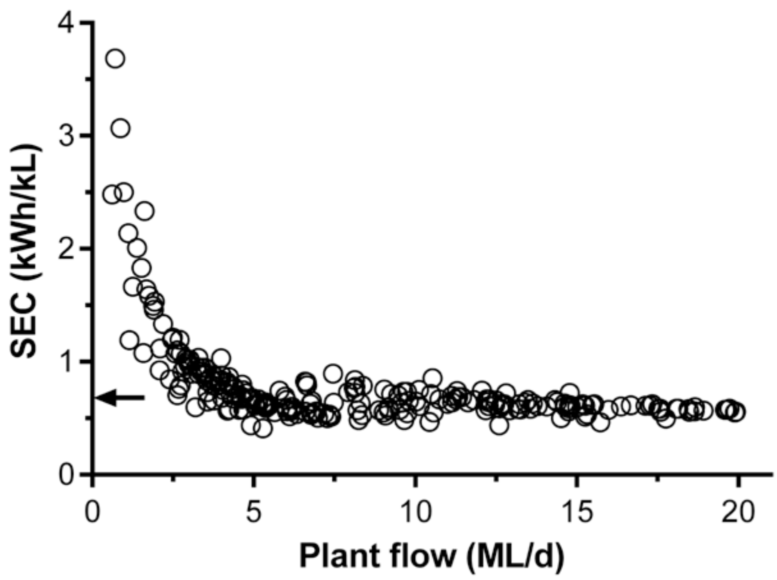


Figure 18. Plot of specific energy consumption (SEC; kWh/kL) against daily volumetric flow for the Glenelg RWTP for the 2013–14 monitoring period showing economies of scale effects under high flows (NB. data set excludes zero volume production days where plant was offline). Arrow indicates average plant-wide SEC.

Both the SURS and GARWS membrane systems operates based on a UF system pressure set-point which controls the number of feedwater pumps and their respective variable speed drive speed/frequency. For GARWS, this becomes complicated, given the number of UF and UV trains (Table 9). Consequently, there are bands of feed water pump requirements to reach pressure set-point and each membrane unit has a feed control valve (FCV) which modulates in order to meet a membrane unit flow set-point (≈64 L/s). If the membrane permeability decreases during filtration as a result of deposition, the FCV opens more in order to reach its flow set-point.

Table 9. Summary of the Glenelg RWTP flow set-points and unit process configurations.

Plant flow set-point (L/s)	Actual flow (L/s)	No. UF feedwater pumps required & VSD%	UF feedwater pump station pressure range (kPa)	No. UF units required	No. UV trains required
120	126	1 @ 65%	120	2	2
180	200	2 @ 65%	150	3	3
240	260	2 @ 75%	150	4	3
300	330	3 @ 75%	200	5	4
360	400	3 @ 77%	200	6	5
400	440	3 @ 80%	200	7	5

Table 9 clearly outlines the relationship between plant flow set-point, UF feedwater pump station pressure range, number of UF feedwater water pumps and their variable speed settings and the number of corresponding UF units and UV trains required. A plant set-point of 120 L/s or 179 L/s will use the same number of pumps (×1) and the same number of UF units and UV trains (×2). The pump speed will however increase. Similarly a plant flow set-point of 240 L/s will result in the same number of UV trains as at 180 L/s (×3). The trade-off between the number of UV trains online versus the number of UF feed water pumps and their respectively speed settings was briefly reviewed in terms of energy use and is presented for the feed water pump station in Figure 19. While some preliminary trends were apparent, these data require further interrogation to draw clear conclusions and for UV energy, require re-analysis due to energy sub-meter changes since the initial analysis was undertaken. The data of Table 9 highlights the need to develop clear recycled water 'production schedules' and to better understand how plant set-point can impact on optimal unit process operation and plant energy use.

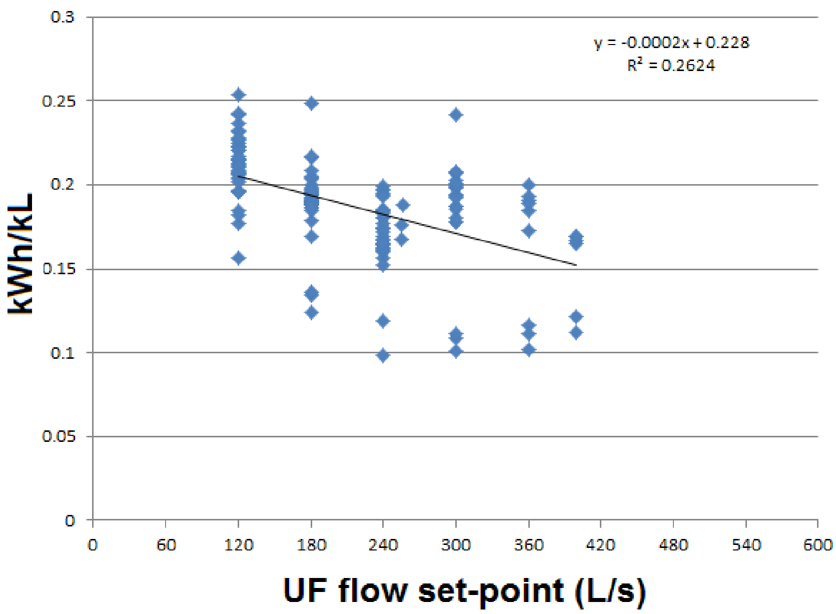


Figure 19. Basic relationship between Glenelg RWTP UF flow set-point (L/s) and specific energy consumption (kWh/kL) for the UF feed water pump station (PS02).

3.4 Christies Beach WWTP

While previous energy benchmarking analyses at the Christies Beach site has been undertaken by SA Water (Krampe and Trautvetter, 2012), this was done prior to the commissioning of the new 'C Plant' MBR. Since then, more recent energy benchmarking work covering the new C Plant has been undertaken (Corena *et al.*, 2014; Langlais and Aguilera Soriano, 2014) and additional SA Water work remains underway at this site to complete the most recent energy audit cycle. While the Christies Beach MBR produces a high quality final effluent suitable for direct reuse by a number of applications in accordance with the *Guidelines* (e.g., irrigation of public spaces, drip irrigation of commercial and non-commercial food crops (SA Water, 2012)), the MBR is first and foremost a WWTP rather than a water recycling plant. This blurring of the lines between wastewater treatment and water recycling processes in MBRs creates challenges for system boundary delineation for recycling systems benchmarking and in the assigning of energy use between the two treatment processes. Hence, and for the purposes of this study, a screening-level analyses was performed for the Christies Beach site, focusing on UV disinfection and MBR air scouring as candidate 'recycling' processes for benchmarking and optimisation.

Results from the detailed process-level benchmarking work for the C Plant are given in Table 10 and presented as relative values in Figure 20.

Table 10. Christies Beach WWTP/RWTP data 2013–14 FY; MBR C Plant annual production volume ≈6,280).

Functional process group	Sub-functional group/unit process	Total energy use (kWh/yr)	Specific energy use (kWh/kL)	Comments
Major pump stations	Influent pumping	n/a	n/a	
	Effluent pumping & distribution	n/a	n/a	Partially accounted for in Aldinga benchmarking analysis
MBR	C Plant ASRs	1,197,500	0.191	
	MBR process pumps (MCC1-2)	142,601	0.023	
	C Plant aeration blowers	1,564,452	0.249	
	Membrane air scour blowers	1,846,239	0.294	
	WAS and MLR pumping	435,400	0.069	
	Blower building services (aeration)	192,880	0.0307	80% allocation of total energy (241.1 MWh) to C Plant
	C Plant general	634,783	0.101	
	MBR chemicals dosing	1,600	0.0003	
	MBR total	**6,049,392**	**0.9633**	
Disinfection	UV (6×19.4 kW Calgon *C^{3}500 D* reactors)	658,887	0.105	UVT set-point 60%; actual yearly mean UVT 67%; UV dose set-point 25 mJ/cm^2; actual yearly 2013–14 median UV dose ≈100 mJ/cm^2
	Chlorination	9,800	0.016	Estimate based on total annual WWTP chlorine energy use multiplied by 50% fractional C Plant flow
	Disinfection total	**668,687**	**0.107**	
Christies Beach C Plant total		**6,684,142**	**1.064**	Excluding product water distribution

ARS – activated sludge reactor; MBR – membrane bioreactor; WAS – waste activated sludge; MLR – mixed liquor recycle; UV – ultraviolet light disinfection

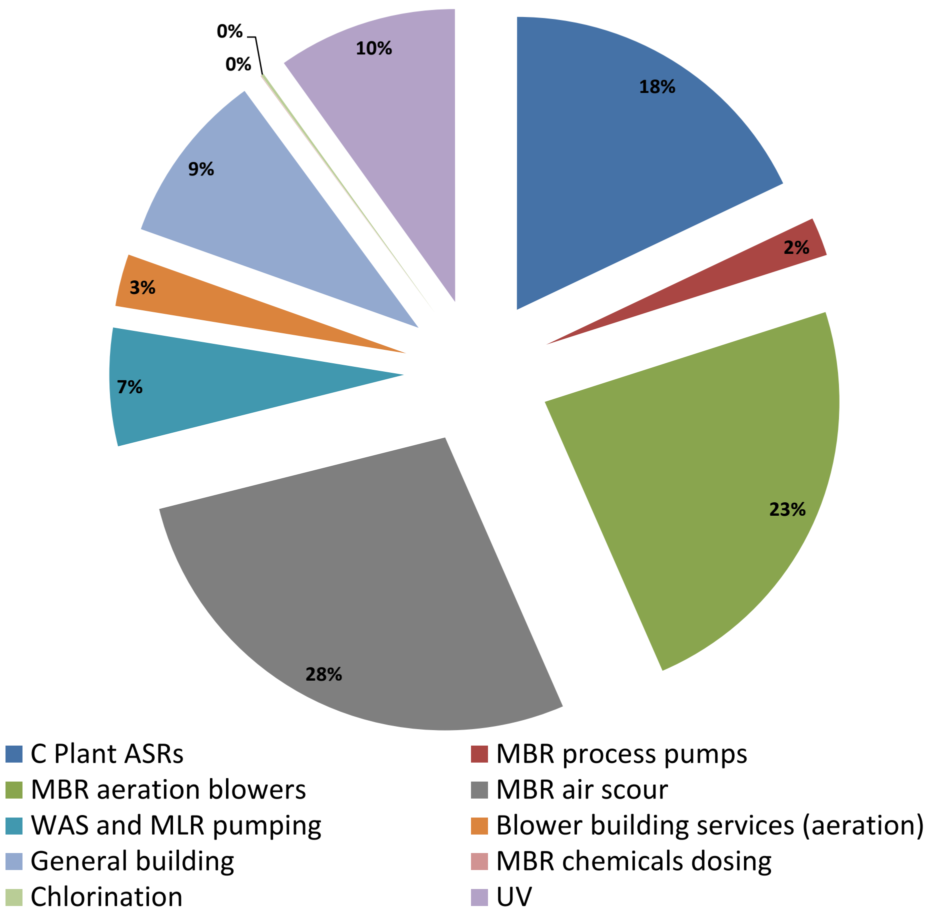


Figure 20. Breakdown of electricity use (percent total) for the Christies Beach C Plant during the 2013–14 period showing the relative contribution of each of the major benchmarked processes (excluding effluent distribution energy).

Recent commissioning and performance test report for C Plant provide useful third party comparisons for our Table 10 benchmarking results. In terms of total benchmarked C Plant energy use, our figures for the 2013–14 period (6.69 GWh) compare reasonably well with those of recent benchmarking work for the same Plant (estimated at 6.33 GWh/year) (Langlais and Aguilera Soriano, 2014). Interestingly, and as noted by Langlais and Aguilera Soriano (2014) in their work, C Plant energy consumption remains virtually constant (≈17–18 MWh/d) regardless of Plant flow rate, indicating large 'fixed energy' requirements and meaning that improvements to the Plant's volumetric energy efficiency (kWh/kL) will be realised passively in line with future increases to the hydraulic load. This large fixed energy fraction for the C Plant can to some extent be seen in Figure 20 whereby the combined energy use of 'C Plant general' and 'blower building services' constitutes almost 15% of total energy use (≈800 MWh/yr). This high fixed energy requirement for membrane systems was noted previously by Lazarova *et al*. (2012d) for recycling systems elsewhere. Notably, this almost constant daily energy use profile for the Christies Beach C Plant is unlike the strong daily/seasonal trends in energy use and specific energy consumption seen for the Aldinga (Figure 8 and Figure 9) and Glenelg (Figure 15 and Figure 16) recycling systems. This stark contrast in energy use profiles between these sites reflects the nature of the recycling systems, with the Christies Beach C Plant primarily a continuous flow WWTP and the Aldinga and Glenelg RWTPs subject to 'on–off' operation in line with seasonal demand.

As suggested by Langlais and Aguilera Soriano (2014) and also Corena *et al.* (2014), there may be scope to direct proportionally more of the Christies Beach WWTP inflows to the C Plant and/or operate a single activated sludge reactor at 100% flow capacity in order to exploit economies of scale discounts relating to these fixed energy costs; however, this is the subject of ongoing investigations elsewhere and is beyond the scope of this report. In the interim, the work of KBR (2012) has already demonstrated significant (≈30%) energy efficiency gains from C Plant aeration and air scour process optimisation activities, so it is likely that further such gains can be achieved while the Plant awaits recept of its ultimate design load.

Looking at the sub-metered energy data for the C Plant UV system (10% total Plant energy), the benchmarked UV process energy use (0.105 kWh/kL) greatly exceeds all performance benchmarks of Table 5 and in particular our newly developed Guide (0.031 kWh/kL) and Target (0.012 kWh/kL) numbers for low pressure lamps as relevant to the Christies Beach system. Contrasting our benchmarked UV energy with the established Table 5 benchmark of Haberkern et al. (2008) (0.03 kWh/kL) for an equivalent UV dose (40–50 mJ/cm^2) reaffirms the high UV energy demand and highlights the scope for energy optimisation. Considering also that the C Plant UV system operates continuously to treat effluent as part of the WWTP and therefore should be afforded economics of scale energy concessions from high volume continuous operation (unlike the previous Glenelg and Aldinga recycling plants which operate intermittently and with lower flows), this again points to poor performance and likely optimisation opportunities.

The C Plant UV system consists of six Calgon *$C^3$500 D* low pressure, high intensity reactors configured in three channels (19.4 kW/reactor; ≈39 kW/channel) (SA Water, 2012). The system was designed and constructed to meet a minimum UV dose of 40 mJ/cm^2 (operating set-point 45 mJ/cm^2) at a UVT of 60% through each channel, with a maximum flow set-point per channel of 360 L/s (i.e. 180 L/s per UV reactor). Initial analyses of UV dose data from SCADA suggested that the UV system was likely to be significantly over-dosing. Additionally, the number of UV reactor trains online at any given time appeared more than required for the channel flow set-points (i.e. one channel can handle 319 L/s, only requiring a second channel to be brought online at flows of 320 L/s or higher). Analysis of historical SCADA data indicated that despite duty channels not seeing these flows, two channels were invariably online, each treating relatively low flows (50–150 L/s), the net result of which was higher dose delivery than required (100–1000 mJ/cm^2 versus ≥40 mJ/cm^2 design dose).

Cross-referencing the risk management register for pathogen LRVs for Christies Beach C Plant (Appendix F), viruses are likely to be the key organism of concern for any proposed changes to the UV process. The design conditions for the UV system (≥40 mJ/cm^2) gave a 0.5 log_{10} inactivation credit for viruses (refer Table 7) with any downward changes to UV dose (below 39 mJ/cm^2) resulting in zero viral LRV for the Christies Beach UV process. The various end-uses of the Christies Beach recycled effluent and their associated minimum pathogen LRV requirements according to the *Guidelines* include:

a. *Commercial food crops* (fruit, nut trees and Vines), requiring 6.0, 5.0 and 5.0 log_{10} removal of V, P and B respectively;
b. *Non-food crops* (flowers), requiring 5.0, 3.5 and 4.0 log_{10} removal of V, P and B respectively;
c. *Municipal irrigation* of Oval and reserves, requiring 5.0, 3.5 and 4.0 log_{10} removal of V, P and B respectively;
d. *Lawn irrigation*, requiring 5.0, 3.5 and 4.0 log_{10} removal of V, P and B respectively.

In the case of Christies Beach and by virtue of the nature of its recycled water end-uses, the majority of the pathogen LRVs come from point-of-use 'on-site exposure reduction' preventative measures rather than engineered treatment barriers as for the dual reticulation Glenelg system (refer Appendix F and Table 3.5 of the *Guidelines* (NRMMC *et al.*, 2006)). For the Christies Beach recycled water, this includes pathogen LRVs of 4.0 log_{10} for drip irrigation and 5.0 log_{10} for drip irrigation of a raised crop end-uses, and 1.0–2.0 log_{10} credits for restricting public access during and after irrigation. Importantly for the Christies Beach UV system, the combination of LRVs from these on-site preventative measures plus the 1.5 $\log_{10}$ virus inactivation credit for the MBR process provides sufficient pathogen (V, P and B) exposure reduction to ensure compliance with the *Guidelines* with a 50% UV system shutdown (i.e. 20 mJ/cm^2 dose). It should be noted that the minimum UV dose to achieve 3.5 $\log_{10}$ protozoa inactivation is 15 mJ/cm^2 and 14 mJ/cm^2 for 4.0 $\log_{10}$ bacterial inactivation (*Campylobacter jejuni* as per SA Health requirements) (Table 7), consequently a UV dose reduction to from 40 to 20 mJ/cm^2 still provides approximately 5 mJ/cm^2 surplus dose inactivation capacity, likely to be equivalent to a further ≥1.0 $\log_{10}$ protozoan and bacterial inactivation credit.

In addition to the above, there are likely UV (reduction equivalent) dose conservatisms linked to the UVT of the Christies Beach C Plant effluent. For example, 2013–14 average and median UVT of the UV influent was 67% compared with a design UVT of 60%. Previous validation studies for the Calgon *$C^3$500 D* reactors at influent UVT values of 45–60% and equivalent plant flows of ≈19–56 ML/d indicate that a single reactor is likely to provide sufficient disinfection capacity at a reduced UV dose of ≥20 mJ/cm^2 and at current C Plant flow rates (≈15 ML/d), assuming UVTs are maintained ≥60% (SA Water, 2012). The same report also suggests that a single reactor should meet a ≥20 mJ/cm^2 UV dose at the Plant's 27 ML/d design flow under a UVT of ≥60%. We do note here that under high flow conditions the Plant is configured to allow for bypassing of the membrane filtration process (i.e. ASR effluent to UV; Figure 4), such that the capacity of a reconfigured UV system to meet regulated dose requirements should be verified. Considering the above, there appears to be considerable scope for UV system turndown/partial shutdown at the Christies Beach site.

In line with these findings, SA Water staff during May 2014 issued a request to the SA Health regulator for a variation to the Christies Beach recycled water supply approval to decrease the minimum UV reduction equivalent operating dose from the design 40 mJ/cm^2 (operating set-point 45 mJ/cm^2) to 15 mJ/cm^2 (operating set-point 25 mJ/cm^2). Following SA Health endorsement of the variation request, a decrease in the RED of the UV system was implemented late July 2014, in which one reactor per channel was switched off, resulting in an effective halving of the UV dose and associated energy use. Analysis of the sub-metered UV energy data before and after the process change confirmed this 50% energy saving (Figure 21). In light of this UV process change, recent suggestions made elsewhere to decommission the Christies Beach UV system and replace with chlorination disinfection to save energy (Langlais and Aguilera Soriano, 2014) may now be less attractive. Even after this partial UV shutdown, we recommend ongoing monitoring of actual delivered UV dose at the Christies Beach site to determine whether additional reactor turndown/shutdown is warranted.

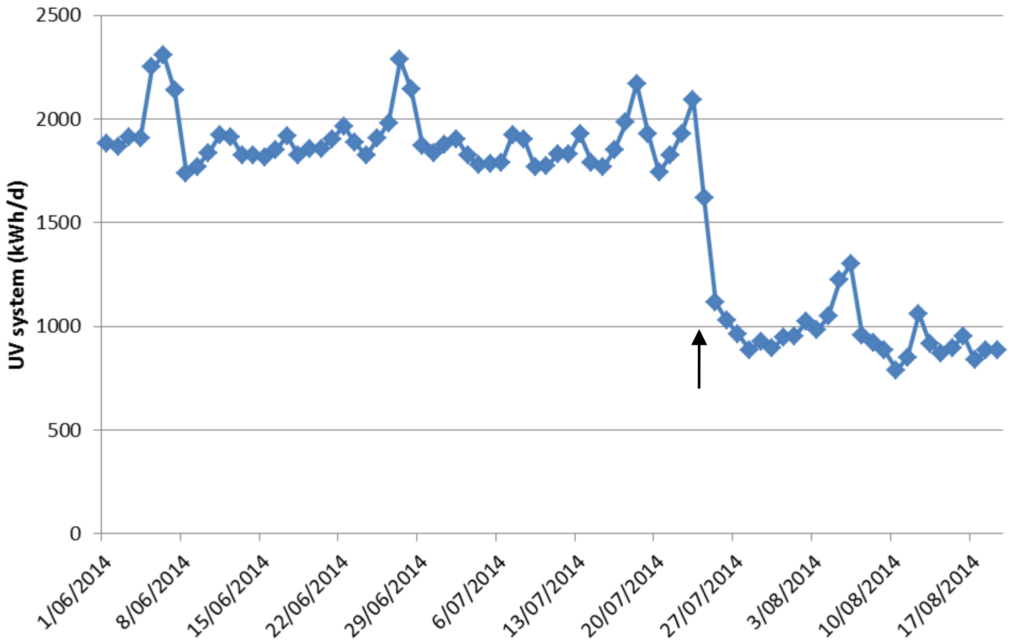


Figure 21. Daily energy use profile (kWh/day) for UV process at Christies Beach C Plant (arrow shows point of UV system RED set-point change).

Turning to the MBR process, the 2013–14 benchmarking analysis revealed a C Plant MBR specific energy consumption of 0.963 kWh/kL (Table 10) which is slightly above our 50th %ile Guide number (0.95 kWh/kL), but considerably higher than our nominal 20th %ile Target performance benchmark of 0.613 kWh/kL (Table 5). This indicates that the C Plant MBR is operating at somewhere around the industry average energy efficiency performance benchmark and suggests that there is considerable scope for further optimisation, most likely relating to bioreactor aeration and air scour processes given the combined ≈55% contribution to the total MBR energy profile (i.e. MBR aeration + air scour + blower building services).

Membrane bioreactors are a variation on the classical activated sludge process, wherein membranes (commonly UF) are placed at the terminal end of an activated sludge reactor and effluent drawn through the membrane modules under vacuum permeate pumps, producing a high quality effluent without the need for traditional secondary clarification. This reduction in physical footprint comes at an energy cost, with MBRs inherently energy-intensive due to the compressed air requirements for membrane aeration and air scouring. This point is emphasised by recent energy benchmarking work for this site, which indicates that the total Christies Beach WWTP site energy use has doubled since C Plant commissioning (Langlais and Aguilera Soriano, 2014).

Previous analyses of MBRs has shown that aeration requirements often account for around 70–80% of the total energy requirements of membrane systems, much of which is used for membrane air scouring for fouling control (Williams *et al.*, 2008; Blair, 2012; Krzeminski *et al.*, 2012). Accordingly, any efforts to effectively reduce MBR compressed air requirements will yield considerable energy savings, with suggested savings of between 20–50% of MBR operating electricity said to be achievable (Williams *et al.*, 2008; Buer and Cumin, 2010; Blair, 2012). For example, continuous improvements to the membrane air scour cycles times by the manufacturers of some MBRs (e.g., GE ZeeWeed system) have led to changes in air scouring cycle times from default ‘10/10’ cycles in earlier models (i.e. membrane air scour valves are cycled on and off every 10 seconds) to ‘10/30 eco-aeration’ cycles in more recent models, increasing the interval between on–off cycles and reducing power use considerably. As well as reducing aeration energy/blower requirements, wear on associated infrastructure (blowers and valves) is also reduced, yielding additional gains from reduced O&M costs and increased asset lifetime.

The amount of membrane scour air needed is a function of the MLSS concentration applied to the membranes, plus a visual assessment of the required surface agitation (KBR, 2012). Given that the biological AS process is currently operating at a MLSS concentration of ≈4,000 mg/L compared to the design concentration of 8,000 mg/L, the C Plant scour air demand process set-points were reduced (Table 11) following previous optimisation work undertaken during Plant commissioning, yielding some 29% energy savings and bringing the original Plant SEC (1.4 kWh/kL) down to 0.995 kWh/kL (KBR, 2012). This work also recommended further changes to membrane air scour set-points (i.e.10/10 and 10/30 mode) in line with future increases to plant load and/or MLSS concentration.

Table 11. C Plant MBR operational air scour blower requirements (adapted from KBR (2012)).

MBR operational configuration	Concept design air scour demand (Nm^3/h)	Commissioning set-point air scour demand (Nm^3/h)
6 Trains in 10/10 aeration	24,000	11,676
6 Trains in 10/30 aeration	12,000	10,920
4 Trains in 10/10 aeration	16,000	7,784
4 Trains in 10/30 aeration	8,000	7,280
2 Trains in 10/10 aeration	8,000	3,892
2 Trains in 10/30 aeration	4,000	3,640

SCADA analysis of MBR air scour regimes (cyclic valve operation times) during June 2014 revealed considerable 10/10 operation; although the plant is designed to operate flexibly between 10/10 and 10/30 as required based on MLSS concentration and fouling potential (KBR, 2012). Information from the manufacturer of the C Plant membranes (GE Zenon) (Jeffery, 2007) indicates that 10/30 air scouring should be able to be maintained at plant flows below the average design flow, with 10/10 air scouring operation required only at peak design flows. Assuming the fouling control algorithm and associated programmable logic controller regulating this flexible air scouring regime is functioning properly, the seemingly high incidence of 10/10 membrane air scouring may be a consequence of unwanted solids carryover from the inlet screens through to the membrane modules as suggested elsewhere (Langlais and Aguilera Soriano, 2014). Given that all six C Plant membrane tanks (Figure 5) appear to be online, they are unlikely to be receiving their design hydraulic loadings such that there may be scope for optimising air scour energy demand by taking some membranes tanks/cassettes offline (i.e. hibernation) to increase the loading on the remaining membranes. This idea was raised as an option by Langlais and Aguilera Soriano (2014; see Table 11) where such a change may also impart additional chemical and O&M cost savings; although the authors do caution about the need for proper risk assessment of membrane hibernation options due to potential membrane integrity issues during storage. In making these recommendations, we acknowledge that changes to membrane configuration and/or air scour regimes will need to be balanced against current Plant Operator concerns regarding the maintenance of adequate air scouring rates for safeguarding of membrane integrity (Corena *et al.*, 2014; Langlais and Aguilera Soriano, 2014).

3.5 System boundary delineation for benchmarking recycled water performance

The issue of system boundary delineation for energy benchmarking of recycled water systems is as yet unresolved; where this boundary is drawn can greatly affect overall system performance. In the context of wastewater treatment, Krampe and Trautvetter (2012)—citing Haberkern *et al.* (2008)—suggest that the boundary for energy benchmarking of wastewater treatment systems should include "*All pumping stations on site (with possible exclusion in* *case of effluent reuse pumping stations or if head is too high*." Elsewhere, Navigant Consulting (2006) discuss how the use of recycled water to displace potable water supplies allows the consideration of recycled water as a supply source, such that the full impacts of supply need to be considered, including energy use associated with pumping recycled water from the wastewater treatment facility to the end user. Lane and Lant (2012) take a similar view in advocating that the consideration (and inclusion) of pumping impacts is important in the supply of recycled water.

Inclusion of water distribution pumping energy in the performance benchmarking of water recycling systems means that local geography can have important implications for overall system performance. For example, energy requirements for recycled water distribution are generally larger than for equivalent conventional potable water systems, because WWTPs are commonly situated in low-lying areas such that distribution requires additional pumping to move recycled water to end users (Navigant Consulting, 2006). This is particularly poignant where conventional potable water distribution is by gravity, as is the case in some Californian regions, resulting in near zero specific energy use for some water supplies (CEC, 2005) and making it difficult for recycled water to 'compete' on an energy basis.

Wherever recycled water offsets other conventional supplies such as potable water or groundwater, there is an effective 'energy credit' realised from this avoided conventional water supply which could be assigned directly to the recycling system where both water systems are operated by the same utility. In the case of California, Park *et al.* (2008) suggest that the avoided energy consumption associated with increased use of recycled water should be based on the avoided energy intensity of the state-wide marginal water supply being displaced. The authors argue that given the ample evidence that the long-run global marginal water supply is desalinated seawater, an avoided energy impact (i.e. energy credit) of −2.76 kWh/kL can be given to recycled water production based on the difference between the average specific energy consumption of recycled (0.49 kWh/kL) and desalinated seawater (3.24 kWh/kL). Park *et al.* (2008) suggest that these numbers for the energy benefit of recycled water and desalination energy consumption are conservative, but favour the adoption of a conservative approach for planning purposes. Applying this approach to the Glenelg–Adelaide Recycled Water Scheme as a local example and assuming that GARWS water offsets potable water supply from the Murray River at 1.9 kWh/kL (Table 2; Spies and Dandy (2012), there is an effective energy credit of some 1.16 kWh/kL realised by SA Water from GARWS supply. If in the future, GARWS water directly offsets water supplied by the Adelaide Desalination Plant, this recycled water energy credit will be even larger again, given that the pumping energy to move desalinated water to the Happy Valley water treatment plant is ≈0.50 kWh/kL (Spies and Dandy, 2012) and desalinated supply is likely to be between 3–5 kWh/kL (Table 2).

The basis for the above 'energy crediting' approach of Park *et al.* (2008) is that the energy used to treat wastewater to levels required by state environmental regulators for safe discharge to the receiving environment would be the same whether or not the treated wastewater is recycled. Therefore, the energy intensity of recycled water production is limited to the incremental additional energy needed to treat and deliver the recycled water to its qualified end-users. While this argument holds true in a strictly energy-based benchmarking context, it does waver when we talk about integrated energy–health performance benchmarking. The approach of Park *et al.* (2008) here is also based around the traditional 'treat and dispose' view of the wastewater management rather than the currently evolving 'resource recovery' paradigm. Under the 'treat and dispose' model, secondary treated wastewater comes effectively energy neutral to water recycling facilities. Under a 'resource recovery' approach, upstream wastewater treatment processes should ideally be assigned fractional energy use given that they effectively serve as pre-treatment stages for water recycling plants. This separation of treatment process energy becomes particularly challenging for MBRs due to the integrated nature of the wastewater treatment and recycling processes. In the present context of integrated energy–health benchmarking, this fractional 'upstream' treatment energy allocation approach also holds true (e.g., WWTP energy could be partially assigned to recycled water based on accredited pathogen LRVs for the various wastewater treatment processes). While it was beyond the scope of this project to fully explore and resolve these methodological issues, this should be the subject of further research.

3.6 Pathogen log reduction and energy use—towards an integrated metric

While it was beyond the scope of this preliminary study to fully explore the interactions between energy use and pathogen LRVs in recycling operations, an initial attempt was made to integrate these key performance variables into a consolidated metric for recycling systems benchmarking (Figure 22). Looking at the analysis of Figure 22, some intuitive trends are apparent. For example, it is immediately apparent that the purpose built water recycling systems (Bolivar DAFF, Aldinga and Glenelg RWTPs, and Mawson Lakes) have relatively lower energy requirements normalised to pathogen LRVs. The Bolivar WWTP is also relatively efficient in terms of energy required per pathogen LRV due to the large size of operations and the use of an extensive, waste stabilisation pond network (≥220 ha) for pathogen inactivation (1.5, 2.0, 2.0 for V, P, B respectively). Future work should investigate the feasibility of energy benchmarking recycled water system/process barrier performance against pathogen LRVs (e.g., $kWh/kL/LRV_{(V,P,B)}$). Such an integrated performance metric may offer a more valid approach for inter-system comparisons and should enable the energy cost of recycled water production to be further interrogated relative to end-use requirements in the pursuit of true fit for purpose recycling.

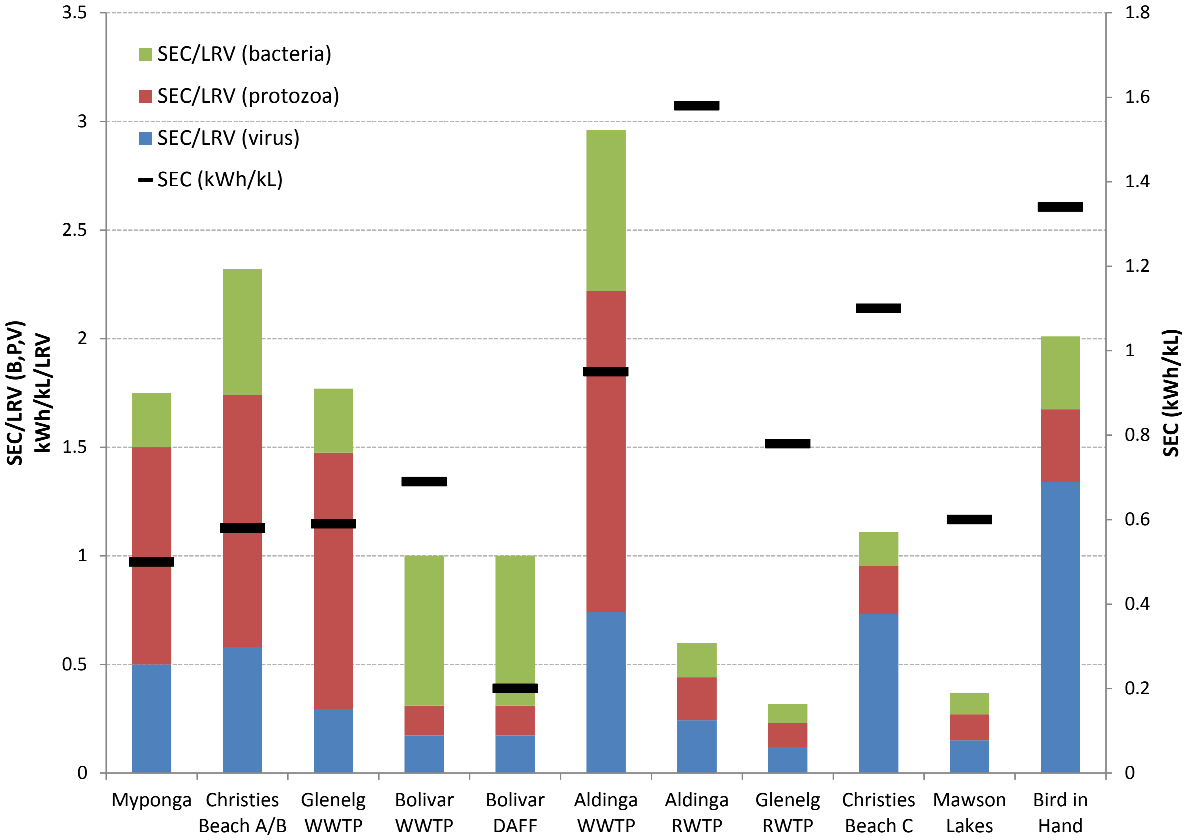


Figure 22. Outputs of preliminary integrated 'energy–pathogen LRV' (log_{10} virus, protozoa, bacteria removal) performance analysis for selected water recycling and wastewater treatment operations at SA Water.

4. Conclusions, recommendations and future directions

This report has presented the outcomes of a preliminary investigation into performance benchmarking of recycled water systems, integrating public health performance criteria with traditional energy use metrics via a new 'energy–health' benchmarking approach. This study constituted the first attempt to develop such an approach for water recycling systems performance assessment. Following a comprehensive literature review, the first steps were made toward the development of new performance benchmarks for energy use among common water recycling process operations. The new benchmarks offered here compared well with existing industry standards where available and are a good starting point for further such benchmark development and refinement.

Application of the new energy–health benchmarking methodology to several case study water recycling systems in South Australia yielded a number of candidate areas for recycling process and/or system optimisation, some of which have already been implemented. A suite of recommendations for potential process optimisation and energy efficiency improvements at each site was also developed and is provided below.

Recommendations for energy optimisation at the Aldinga RWTP:

- Consider UV system maximum reactor flow set-point increase (in consultation with manufacturer, but an increase of at least 100% is considered feasible).
- Consider UV system UVT set-point increase (≥75% suggested).
- Consider taking one UV reactor offline (1 duty/1 standby).
- Consider implementation of an alarmed 'high UV dose' SCADA set-point to alert Plant Operators to UV overdosing and process inefficiencies;
- Crosscheck UF membrane unit flow set-points (currently 25 L/s but originally 53 L/s) as it appears that more UF units are being brought online than required based on SCADA set-points (ALDISS.ALDRW-UF-SYS9500-CNTCPT-UNTREQ/-UNTSER); data shows that when the plant is operational, two membrane units are all that is required to meet plant flow set-point and yet three are invariably in service.
- Cross-check set-point at which second UV reactor is requested. Prior work from another SA Water wastewater treatment plant with identical LBX1000 UV reactors (Steele *et al.*, 2013) indicated that this set-point was 48 L/s. If this is also the case at Aldinga RWTP, then the second UV reactor will be brought online whenever more than one UF unit is online (combined UF flow 50 L/s), leading to probable UV overdosing.
- Alert staff to monitor lighting requirements in main recycling plant building, or install motion sensor/door activation switch to limit the time plant lighting is on when not required.

Recommendations for energy optimisation at the Glenelg RWTP:

- Implement a combination of the following measures for UV system optimisation: increase UVT set-point to ≥65%; increase individual reactor flow set-points/hydraulic loading (>200 L/s); turn off the second reactor in each train or decommission surplus reactor trains to limit overdosing.
- Consider implementation of an alarmed 'high UV dose' SCADA set-point to alert Plant Operators to UV overdosing and process inefficiencies;
- Assess options for reducing distribution pumping energy from PS03 (e.g., distribution network pressure set-point reductions, seek out additional customers to take maximum advantage of fixed daily energy costs (≈1 MWh/d), undertake further investigations pump station electrical performance based on equipment/motor efficiencies relative to manufacturers' specifications and/or benchmark pumping performance to delivery pressure/head (Wh/kL·m))

- Assess the size of existing UF air compressors relative to current RWTP flow rates and process air requirements (with the mind to possibly down-sizing) and/or fit variable frequency drives to existing compressors (if not already in place).
- Consider development of Plant production schedules to fully exploit economies of scale energy discounts (needs to be balanced with seasonal demand and on-site product water storage constraints).

Recommendations for energy optimisation at the Christies Beach C Plant:

- Partial UV system shutdown to avoid overdosing (50% shutdown already implemented);
- Monitor UV dose rates following the 50% shutdown and assess future scope for further UV shutdown/turndown in line with validated reactor performance (i.e. single reactor should satisfy ≥20 mJ/cm^2 UV dose at C Plant 27 ML/d design flow at UVT ≥60%);
- Consider options to reduce air scour energy demand. This could be achieved either by improving inlet screening processes to restrict solids carryover to membranes and limit fouling-induced 10/10 air scour operation, or by increasing the hydraulic load to the membranes by taking some membrane tanks offline to exploit economies of scale discounts and minimise the energy impacts from 10/10 air scour operation (efforts are currently underway in this area).

More broadly, there are several key findings from this research. Energy–health benchmarking, via the *Guidelines*, offers the unique potential to achieve true ‘fit for purpose’ recycled water supply in a flexible and energy efficient manner. Energy–health benchmarking of recycling systems essentially provides a ‘two tiered’ approach for optimising the performance of recycling systems. First, conventional energy benchmarking allows for the identification of low hanging fruit on a process engineering basis (kWh/kL). Following this, process barriers across the recycling system can be reviewed, including any on-site preventative measures, to look for surplus process LRVs (unit process redundancies) from a health perspective which may then be able to be modified and/or substituted to achieve energy efficiency. Ultimately, an integrated energy–health benchmarking approach should help water utilities get the balance right between the intensity of treatment operations for protecting public health (fit for purpose) and the energy/greenhouse gas/cost implications of recycled water supply. Unlike equivalent wastewater treatment energy optimisations which may only require regulatory approval for major process changes (e.g., those impacting nitrogen removal performance), this may not be the case for optimising recycling systems, whereby even small changes to conditionally approved/validated recycling system configurations will require explicit consent from state health regulators to ensure that the overall system integrity/combined barrier LRVs isn’t compromised. This additional external stakeholder consultation step requires close engagement of water industry personnel with state health regulators to maintain stakeholder confidence and ensure effective outcomes.

Recycling systems are often designed and configured for peak flow rates, or for an ultimate capacity in terms of future volumetric production rates, resulting in over-sized unit processes and wasted resources (energy + O&M) while these systems operate at interim production volumes greatly below these ultimate design flows (Steele *et al.*, 2013). Recycling systems may also be designed and built to produce a higher quality water than is presently required (e.g., dual reticulation) based on anticipated future market development or expansion (Radcliffe, 2004); this again presents opportunities for recycling plants to over-treat water while utilities await the arrival of future end-uses/users. The energy–health benchmarking approach here offers an effective means by which to identifying areas of recycling systems where individual treatment processes can be wound back to conserve energy without compromising overall performance in terms of system-wide pathogen LRVs.

Work presented here also highlights the importance of a 'staged' risk-based design approach for recycling systems in line with the quantitative risk-based *Guidelines*. While energy benchmarking the performance of *existing* water recycling systems is worthwhile and will provide utilities with real efficiency gains, there is a need to integrate the core principles of energy–health benchmarking via the *Guidelines* earlier on during the planning and design phase of recycling schemes to reduce the incidence of over-sized unit processes and the need for post-optimisations. For treatment processes such as UV, turndown requirements (e.g., average or low flow operation versus design or peak flow conditions) must be considered at the design stage to ensure sufficient redundancy/turndown capacity is built into the system to cater for intermittent or low flow operation. This will require greater cooperation and engagement between process engineers, design consultants and Plant Operators to ensure true fit for purpose recycled water *by design*, rather than by post-commissioning optimisation.

While the *Guidelines* offer generally agreed performance LRVs for various treatment processes and end-user controls, work presented here emphasises the importance and potential value of process validation and accreditation for water recycling barriers in terms of achieving system-wide energy efficiency. Research presented here also serves to reiterate the value to water utilities afforded by non-engineered, on-site preventive measures within the *Guidelines* where recycled water is supplied for non-residential uses (refer Table 3.5 NRMMC *et al.* (2006)). For example, any substitution of engineered process barriers with equivalent LRVs from end-user controls will have associated energy and resource savings.

5. Reflections on the Centre Fellowship

The key objectives of the Industry & Academic Exchange Program (Centre Fellowship) in respect of this Centre Fellowship project were to:

1. Promote knowledge exchange between industry and academia;
2. Result in outcomes that are of significance and relevance to the Australian Water Recycling Centre of Excellence's Strategic Plan;
3. Benefit UniSA and SA Water by contributing outcomes of relevance to their operations;
4. Create a strong, lasting collaborative relationship between UniSA and SA Water;
5. Contribute to the career development of the Fellow.

Outcomes from this research have directly contributed toward Objective 2, with project outputs feeding into the Centre's Strategic Priority Research Topics across a number of Themes, in particular *Theme 1: Technology, Efficiency and Integration* and *Theme 4: Sustainability in Water Recycling*. Vigorous knowledge exchange and collaborative research throughout the 12 month Fellowship project has helped satisfy Objective 1, while also laying the foundations for achieving Objectives 4 and 5. Outputs from the collaborative research project contained in this report serve to demonstrate the successful achievement of Objective 3.

On a personal note, the Centre Fellowship has been an enjoyable and stimulating experience which provided me with unique 'fly-on-the-wall' access to a large Australian water utility and one with a strong focus on innovation and efficiency. Visits to a number of SA Water's full-scale water recycling facilities provided me with a heightened appreciation for the operational aspects and broader issues surrounding recycled water production in Australia. SA Water staff were most accommodating throughout the Fellowship exchange and I was actively involved in regular meetings and discussions not limited to the Fellowship project. As an academic researcher, the opportunity to be embedded in the water industry for 12 months has provided invaluable context to my research on a number of fronts and has spawned several new research projects with and collaborative ties, both with SA Water and beyond. New knowledge and skills attained during the course of the exchange have also made valuable additions to my portfolio.

While the guidelines for the Industry & Academic Exchange Program stipulate that Fellow relocation is not required, experiences from my own Fellowship have served to emphasise the unique and high value coming from a physical exchange, wherein the Fellow is directly embedded within the industry Partner organisation's day-to-day operations. Based on my own experiences over the past year, this should be the preferred model for any such schemes in the future and I would suggest that priority be given to future Fellows proposing a physical Industry–Academic exchange.

From an industry's perspective, SA Water has gained from the Fellowship exchange in the following ways:

- the project has enabled more staff to be aware of energy efficiency and focus on process improvements (e.g., UV systems);
- enabled interaction with a professional with both broad and specialist knowledge in relation to recycled water microbiological and environmental risks;
- benefited from the Fellow's fundamental knowledge of wastewater treatment and freshwater ecology, particularly in relation to nutrient recycling, microbial drivers and phytoplankton physiology;
- appreciation of data analysis and statistical vigour of a research scientist; and
- exposure to and appreciation of knowledge of the latest scientific literature on many broad topics.

More broadly and by being closely engaged with research providers, utilities benefit from the outcomes of the latest research in terms of the direct impacts it has on process optimisation and energy use. For example, recent work by Rosen and Bartrand (2012) on virus inactivation as a function of free chlorine, turbidity and pH, enabled a review of SA Water's chlorination set-points and pathogen LRVs. These findings cascaded to optimisation of a UV system in relation to virus removal and operational reduction equivalent dose. Additionally, SA Water's Metropolitan Adelaide Operating Alliance partner—Allwater—recently achieved ISO 50001 accreditation and is actively linking into and exploring energy efficiency opportunity initiatives, some of which may stem from the current project.

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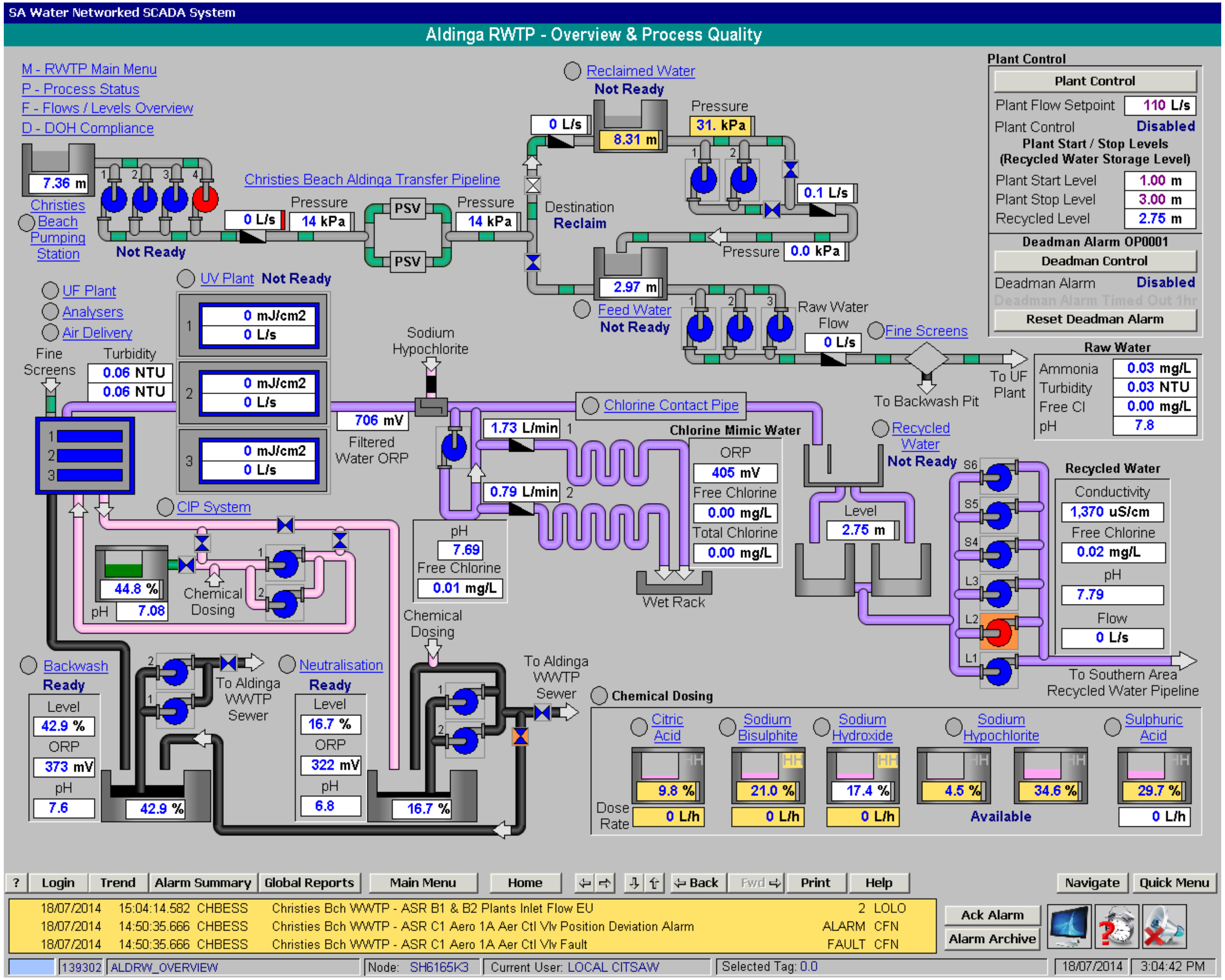
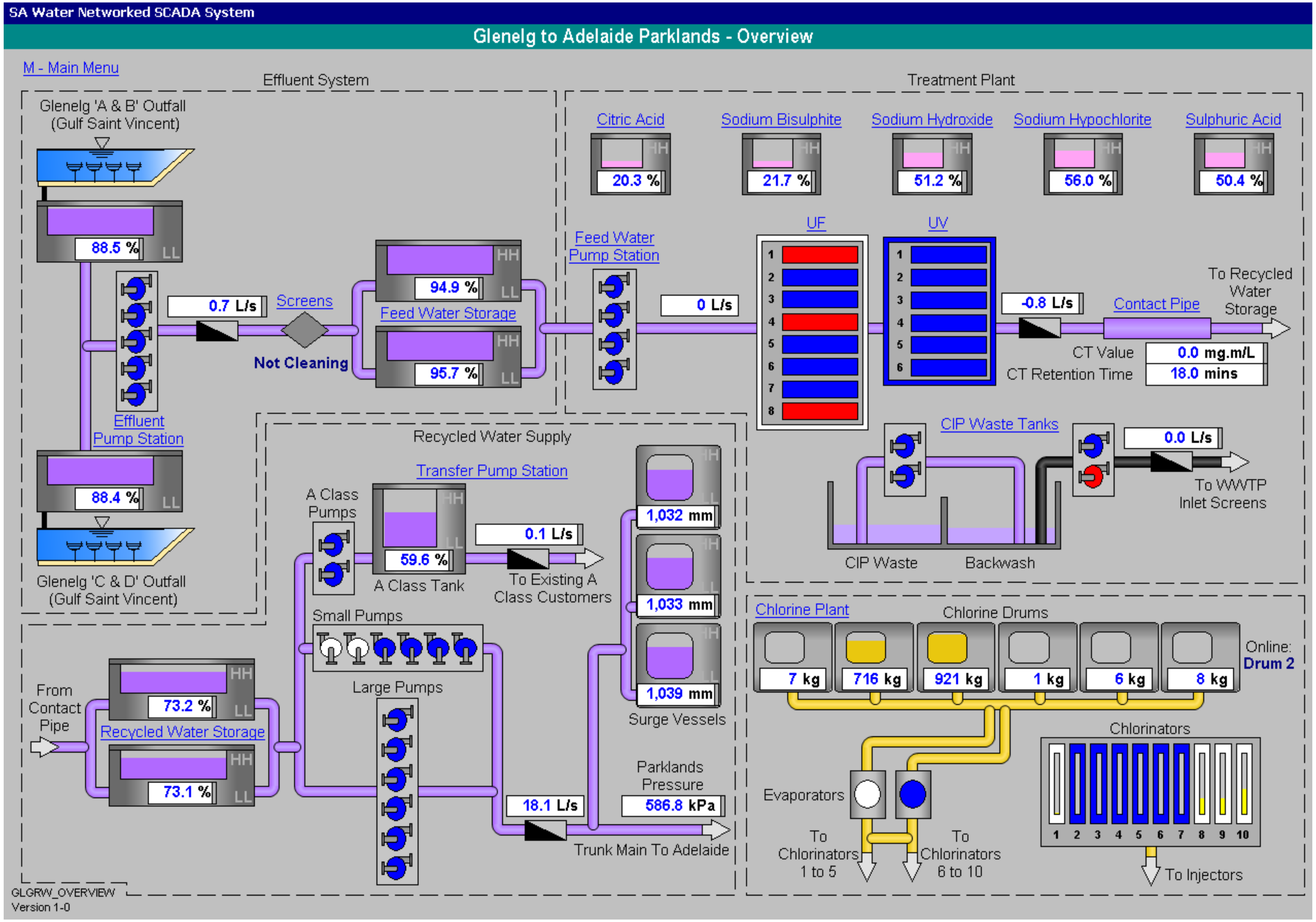
7. Appendices

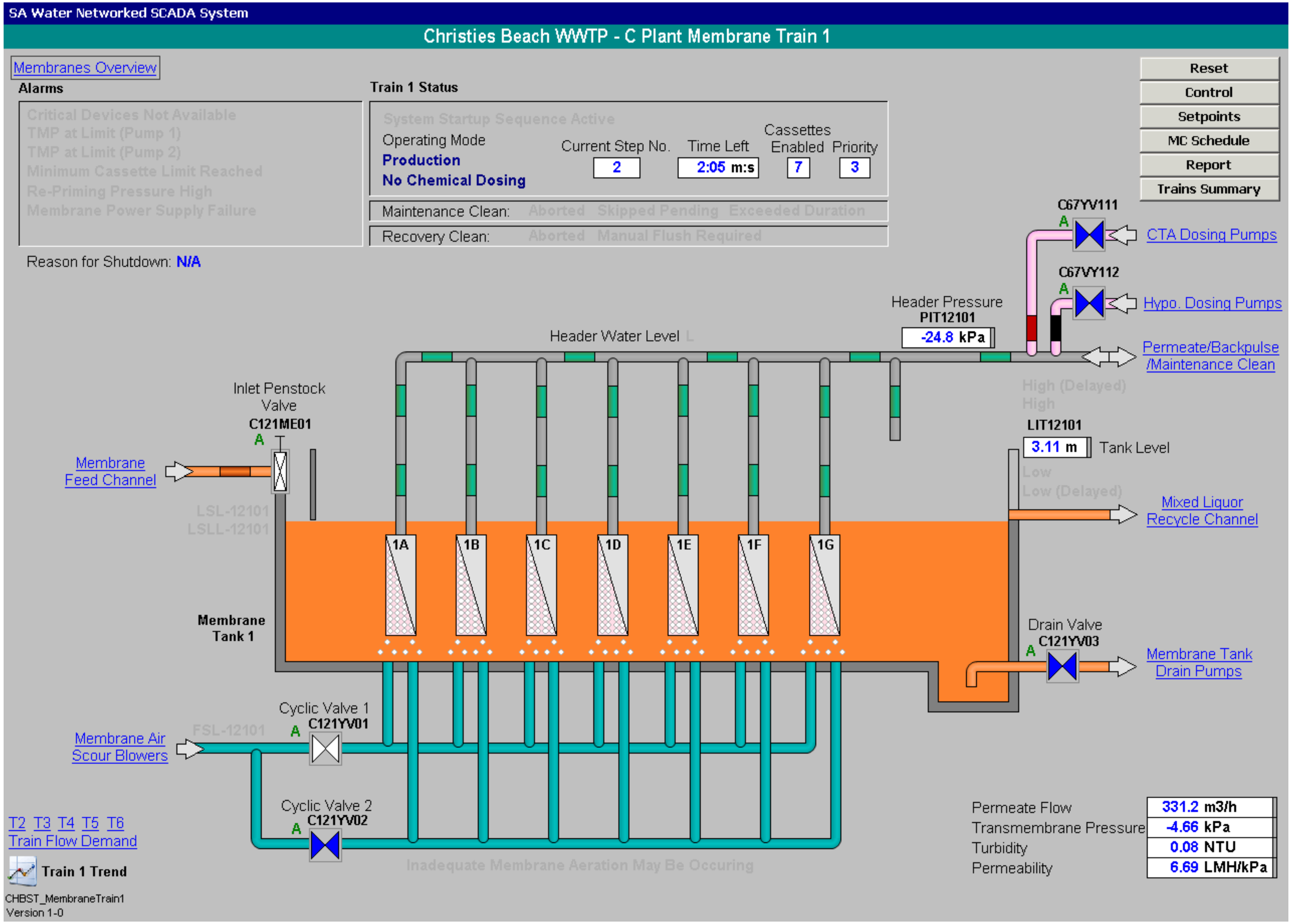
7.1 Appendix A: Screenshot of online supervisory control and data acquisition (SCADA) system for the Aldinga RWTP.



7.2 Appendix B: Screenshot of online supervisory control and data acquisition (SCADA) system for the Glenelg–Adelaide Recycled Water Scheme.



7.3 Appendix C: Screenshot of online supervisory control and data acquisition (SCADA) system for the Christies Beach C Plant membranes.



7.4 Appendix D. International performance benchmark review for water recycling processes.

Technology	Process / component	Specific energy consumption (kWh/kL)	Operating conditions	Factors affecting SEC /	Optimising energy efficiency	Reference	Comments
UV disinfection	Low-pressure	0.020	180 mJ/cm^2	UV dose rate; lamp pressure	Use low-pressure lamps	PG&E (2006)	Guide numbers only. No information provided regarding data pedigree/source.
	Medium-pressure	0.042					
	Low-pressure, high-intensity	0.151 (pre-optimised)	55 mJ/cm^2 at UVT 54%; average plant flow 2.4 ML/d	UV dose setpoint; UVT; ballast power turndown; hydraulic regime (intermittent inflow)	Limit reactor number and size; optimise hydraulic operation; optimise delivered dose relative to UVT; increase reactor flow rates where UVT allows to reduce number of reactors required (increase SCADA flow setpoint)	Steele et al. (2013)	Recycled water production at a South Australian WWTP; high SEC due to intermittent operation and over-design
		0.13 (post-optimisation)					
	Not defined	0.030 0.026–0.30 (min– max)	40–50 mJ/cm^2			Haberkern et al (2008) cited in Krampe and Trautvetter (2012); Steele et al. (2013)	Wastewater disinfection for German WWTPs (in German)
	Low-pressure, high-intensity + 3 mg/L H_2O_2 advanced oxidation	0.0792	MF + RO feed at 326 ML/d; TOC ≈0.1 mg/L; turbidity ≈0.03 NTU; UVT ≈98%; TDS ≈20 mg/L; pH 5.5			Patel (2012)	Advanced water purification facility in Orange County, California, USA
	UV–H_2O_2 advanced oxidation	0.103	Filtered secondary wastewater at 7 ML/d maximum flow	Not defined	Not defined	Sloan (2011)	Direct potable reuse facility (MF + RO +UV–H_2O_2) in Big Springs, Texas, USA
	Low-pressure, high-output	0.0091	South Plant; 74 ML/d flow; UVT ≈68–74%	UVT; UV-absorbing co-discharged industrial wastewater; lamp technology; UV system configuration and size; ballast	Manage industrial discharges in sewer catchment; pre-treatment of water to improve UVT (where cost-effective);	NYSERDA (2009)	SEC for wastewater disinfection at North and South facilities in Albany County, USA
		0.0128	North plant; 81 ML/d flow; UVT ≈58–66%				
	Medium-pressure	0.0445	South Plant; 74 ML/d flow; UVT ≈68–74%				
		0.0443	North plant; 81 ML/d flow; UVT ≈58–66%				

				turndown capacity; lamp cleaning			
	Not defined	0.076–0.089	Not defined	Water quality and standards; type of technology used	Not defined	CPUC (2010); Hallett (2011)	Recycled water production in Orange County District, California
	Medium-pressure high-intensity (Trojan #4L30)	0.0053–0.011 (1 reactor) 0.008–0.016 (2 reactors)	40 mJ/cm^2; design maximum flow rate 95 ML/d per reactor	SEC decreases with increasing flow rate (57–151 ML/d) and increases with number of operating reactors (1–3)	Operate at or near max. flow capacity for reactor setup; avoid overdesign; minimise time operated below max. capacity	Chang et al. (2008)	Quoted SEC range highly dependent on operating conditions (flow rate and number of UV reactors online)
	Low-pressure, high-intensity	0.07–0.21	50 mJ/cm^2; design minimum flow rate 8.7 ML/d per reactor	SEC decreases with increasing flow rate (8.7–45) and number of operating reactors (1–3)	Operate above minimum flow capacity for reactor setup	Chang et al. (2008)	SEC calculated based on estimated 74–82 % energy use of UV within combined UV–peroxide system
	Low-pressure, high-intensity	0.0132	40 mJ/cm^2	Water quality; UV reactor configuration and lamp power	Dose control; minimise fouling	Mackey et al. (2001) cited in Chang et al. (2008); WEF (2010)	Calculated UV dose required for *Cryptosporidium* inactivation in drinking water
	Medium-pressure high-intensity	0.040					
	Not defined	0.014	Not defined	-	Decommission surplus UV trains; software upgrades	Brandt et al. (2010)	Kingston Seymour WWTP, England
	Not defined	0.043	WWTP flow ≈2.4 ML/d; coagulation–flocculation, sand filtration and pre-chlorination	Not defined	Not defined	Meneses et al. (2010)	Production of non-potable recycled water at a small WWTP on the Mediterranean coast
	Medium-pressure, Trojan UVSwift™ 8L24 system	0.112	240 mJ/cm^2; flow rate 12.9 ML/d; UVT ≈98%; ballast power 60%; mean turbidity 0.23 NTU; mean total $CaCO_3$ hardness 54.2 mg/L	Hydraulic operation (intermittent vs. continuous); UVT; turbidity; ballast power; lamp aging/	Validation of UV systems for target pathogens; good UV intensity/UVT sensor calibration and maintenance	NYSERDA (2005)	SEC based on annual data for electricity cost, tariff rate and UV production volume for potable water disinfection at Loudonville, City of

		0.0225	40 mJ/cm^2 dose (hypothetical scenario for above conditions)	output decay; lamp fouling			Albany
	Low-pressure, high-intensity	0.01	40 mJ/cm^2 dose (hypothetical scenario for above conditions)				
	Not defined	0.38	Not defined	DOC concentration	Enhanced coagulation for DOC removal	Brandt et al. (2010)	Drinking water disinfection in Andijk, Netherlands
	Low-pressure, high-output, Wedeco K143HP	0.008–0.012	UVT 90%; ≈3785 ML/d flow; 50% ballast power	Surrogate organism and approach used to validate UV pathogen attenuation	Not defined	Blatchley et al (2008)	SEC estimate based on disinfection of potable water at experimental UV facility at UV Validation and Research Center of New York, Johnstown, NY
	Low-pressure high-intensity lamps	0.017 (median) 0.015–0.018 (min–max)	Not defined	Feed water transmittance, dose rate/requirement, lamp fouling and lamp configuration	Not defined	Cooley and Wilkinson (2012) (data from secondary literature sources)	Common data to that of Chang et al. (2008) and Mackey et al. (2001)
	Medium-pressure high-intensity lamps	0.04 (median) 0.026–0.042 (min–max)					
	Low-pressure high-intensity lamps	0.05	Not defined	UV lamp pressure	Not discussed	Monteith et al. (2007)	Original source of SEC data not stated
	Medium-pressure high-intensity lamps	0.15					
	Not defined	0.077	Not defined	Not defined	Take surplus reactors offline; operate at or near design capacity	Daw et al. (2012)	SEC estimated based on quoted energy and flow data
	Low pressure lamps	0.019–0.026	Not defined	Not defined	Flow-pacing of UV dose	EPRI (1997); Carlson and Walburger (2007)	SEC based on first principles calculation
	Low pressure, high-intensity	0.026	Not defined	Not defined	Not defined	Carns (2005)	No source reference provided for these data

	lamps						
	Medium-pressure lamps	0.040					
	Low-pressure lamps	0.026–0.066	Various full-scale plants surveyed from 1.5–163 ML/d	Feed water quality; lamp fouling; lamp type and configuration	Disinfection performance vs. energy input is non-linear (avoid over-design); optimise pre-treatment; minimise Fe/Al residuals (lamp fouling); turn off surplus reactors	US EPA (2010)	Original data from PG&E (2001) cited therein
	Medium-pressure lamps	0.12–0.15 (0.265 extreme disinfection)					
	low-pressure high intensity (medium pressure lamp SEC given in parentheses)	0.022 (0.10)	50 mJ/cm^2; 65% UVT; 145 ML/d avg.				Results from pilot-scale testing; original data from Salveson et al (2009) cited therein
		0.034 (0.16)	70 mJ/cm2; 65% UVT; 145 ML/d avg.				
		0.064 (0.23)	110 mJ/cm^2; 65% UVT; 145 ML/d avg.				
	Low-pressure, low-intensity	0.030 (1 reactor)	15.1 ML/d design flow; ≈11.5 ML/d actual flow	Not defined	Upgrade low-intensity UV system with high-intensity units; flow-paced UV dose modulation	NYSERDA (2005)	SEC for disinfection of secondary effluent at Wallkill wastewater treatment facility, USA
	Not defined (but most likely low-pressure, high-intensity)	0.13	Activated sludge effluent	Influent water quality	Not defined	Salveson and Mackey (2013)	Suggested “benchmark” SEC for UV disinfection of 45–57 ML/d. Original data source not provided
		0.07	Activated sludge + nitrification effluent				
		0.056	MBR effluent				
	Not defined	≈0.03	40 mJ/cm^2 (19 ML/d)	Not defined	Approx. seven-fold increase in SEC when operated at higher UV dose at 190 ML/d	Sathyamoorthy et al. (2009)	SEC data based on quoted median electricity emission factor for theoretical UV treatment under different flows to meet coliform standards of 200 and 2.2 MPN/100ml (40 and 80 mJ/cm^2 UV dose respectively)
		≈0.014	40 mJ/cm^2 (190 ML/d)				
		≈0.10	80 mJ/cm^2 (19 ML/d)				
		≈0.093	80 mJ/cm^2 (190 ML/d)				
	Not defined	0.13	100 mJ/cm^2; non-nitrified filtered secondary effluent; 55% UVT	Influent water quality (nitrified vs. non-nitrified)	Not defined	Salveson et al. (2013)	SEC data based on Carollo Engineers Inc. internal database
		0.069	100 mJ/cm^2; nitrified filtered secondary effluent; 70% UVT				

		0.056	MBR with nitrification (UV dose and UVT not defined)				
	Low-pressure, high-intensity	0.00085–0.0013	Not defined	UVT	UV dose pacing according to flow and UVT; regular lamp sleeve cleaning can save 10%	NYSERDA (2010)	No primary data source provided
	Medium-pressure	0.0018					
	Not defined	0.24 (avg.)	Actual operating flow ≈1–2.1 ML/d; 9.5 ML/d rated flow	Not defined	Not defined	Williams et al. (2008); Pellegrin and Kinnear (2011)	Fowler water reclamation facility in Georgia, USA.
	Not defined	≈0.015–0.045	For systems with capacity ≈4–30 ML/d	Not defined	Not defined	Mackey and Salveson (2012)	SECs based on secondary literature data. Data are indicative only, as levels of disinfection varied
	Low-pressure, low-output (Wedeco ICH 2X2L)	0.021	Pilot-scale open channel; ≈0.4 ML/d per reactor; 26 mJ/cm^2; UVT min. 60%; TSS max. 20 mg/L	UV lamp fouling; suspended solids; water UVT; UV reactor hydraulics	UV lamp cleaning; optimise pre-treatment for solids attenuation	Plappally and Lienhard V (2012); WEF (2010); NYSERDA (2004)	SEC for wastewater disinfection at the ≈69 ML/d Southtowns WWTP, Erie County, New York State.
	Low-pressure, high-intensity (Wedeco TAK 55 2-1/143)	0.015	Pilot-scale open channel; ≈1 ML/d per reactor; 30 mJ/cm^2; UVT min. 60%; TSS max. 20 mg/L				
	Medium-pressure (Suntech Environmental)	0.066	Pilot-scale open channel; ≈1 ML/d per reactor; 32 mJ/cm^2; UVT min. 60%; TSS max. 20 mg/L				
	Trojan UVMAX (model and lamp pressure not defined)	0.33–0.46	0.011ML/d design flow; Class A+ product water (10 mg/L BOD, TN, TSS; 5 mg/L TP)			Chong et al (2013); Sharma et al. (2012)	Capo di Monte recycling facility, Mount Tamborine, Queensland, Australia
	Not defined	0.031	40 mJ/cm^2; 0.091			US EPA (1996)	Drinking water

			ML/d				application. Each SEC value is the mean of three reported values for three different UV systems. At 40 mJ/cm^2, all UV systems required 2 UV reactors for flows 0.091–2.5 ML/d and 2–4 reactors for 6.8 ML/d. At 140 mJ/cm^2, 2 UV reactors were mainly required for flows 0.091–1.02 ML/d, 2–5 reactors for 2.5 ML/d and 6–10 reactors for 6.8 ML/d.
		0.018	40 mJ/cm^2; 0.33 ML/d				
		0.013	40 mJ/cm^2; 1.02 MkL/d				
		0.012	40 mJ/cm^2; 2.5 ML/d				
		0.012	40 mJ/cm^2; 6.8 ML/d				
		0.064	140 mJ/cm^2; 0.091 ML/d				
		0.048	140 mJ/cm^2; 0.33 ML/d				
		0.043	140 mJ/cm^2; 1.02 MkL/d				
		0.031	140 mJ/cm^2; 2.5 ML/d				
		0.040	140 mJ/cm^2; 6.8 ML/d				
	HGS-200 (1500 kW side burner)	0.025	≈6.7 ML/d (max. flow ≈11 ML/d)	Not defined	Not defined	Kruithof et al. (1992) cited in US EPA (1996)	SEC data from a case study drinking water facility in Zevenbergen, The Netherlands
	GR-16 (most likely low-pressure lamps)	0.0043	≈6.9 ML/d (max. flow ≈11 ML/d)				
	Mercury lamp system	0.0022	0.03 ML/d reactor	Not defined	Not defined	E3T (2013)	SEC for disinfection of high quality drinking water. LED-based UV systems ≈5-fold more energy efficient
	Hypothetical UV-LED system	0.00044	Not defined				
	UV-C light-emitting diode (LED) disinfection	0.2–0.44	Not defined (bench-top investigations)	SEC hindered by low (2%) efficiency in energy conversion	More effective distribution of UV dose in LED-based systems relative to conventional lamps	Salveson et al. (2013)	SECs based on non-peer-reviewed data of Pagan et al. (2011) cited therein
	Not defined	<0.02	Not defined	UVT, suspended solids and turbidity	Dose monitoring and regular maintenance protocols, minimise influent turbidity/solids	Camm et al. (2008)	SEC for drinking water disinfection. Generic best practice guide SEC for well-designed and operated UV systems
	Low-pressure, low-intensity	0.066	≈163 ML/d flow; secondary-level aerobic AS influent;	Manual “on” “off” control only; no turn-down;	Flow-pacing of UV dose/power control; dose turn-down	PG&E (2003)	Various WWTPs in US

			TSS 8 mg/L	effluent limit 200 CFU/100 ml faecal coliforms	capacity		
	Medium-pressure, high-intensity	0.264	79.5 ML/d flow; secondary-level aerobic AS influent with nitrification-denitrification and anthracite filtration; TSS 1 mg/L	High SEC results from stringent effluent limit of 2.3 CFU/100 ml total coliforms; UV turn-down capacity			
	Low-pressure	0.031	11.4 ML/d flow; secondary-level aerobic AS influent; TSS 5 mg/L	UV reactor staging with flow conditions; effluent limit 200 CFU/100 ml faecal coliforms			
	Low-pressure	0.0452	6.8 ML/d flow; secondary-level RBC influent; TSS 7 mg/L	Constant dose power used; effluent limit 200 CFU/100 ml faecal coliforms			
	Medium-pressure, high-intensity	0.123	13.6 ML/d flow; secondary-level aerobic AS influent; TSS 9 mg/L	Flow-paced dose control; effluent limit 200 CFU/100 ml faecal coliforms			
	Medium-pressure, high-intensity	0.142	20.1 ML/d flow; secondary-level aerobic AS influent; TSS 3 mg/L	Flow-paced dose control at high flow; effluent limit 200 CFU/100 ml faecal coliforms			
	Medium-pressure, high-intensity	0.147	1.5 ML/d flow; secondary-level oxidation ditch influent	Flow-paced dose control at high flow; effluent limit 200 CFU/100 ml faecal coliforms			
	Not defined	0.04–0.4	Small WWTP (<1,000 PE) with aerobic biological treatment	Not defined	Not defined	LfU (1998) cited in Chong et al. (2013)	Primary data source in German
	Not defined	0.034	70 mJ/cm^2; 86 ML/d	Suspended solids	Not defined	Remy (2013)	SEC based on full-scale

		0.05	100 mJ/cm^2; 86 ML/d	concentration and UVT			operational data for disinfection of secondary effluent in Germany. SEC for 70mJ/cm^2 dose extrapolated from 100 mJ/cm^2 data.
	Not defined	0.01–0.05; 0.017–0.025	Not defined	Not defined	Not defined	Plappally and Lienhard V (2012)	UV disinfection of surface water for potable supply. Data from secondary literature sources
Chlorination	Liquid dosing	0.0025 (median) 0.0021–0.0026 (min–max)	Not defined	Not defined, but most likely chlorine dosing rate and water quality	Not defined, but most likely optimisation of upstream treatment processes	Cooley and Wilkinson (2012) (data from secondary literature sources)	SEC for potable water treatment. SEC values for dosing only and don't include life cycle energy use for chlorine production
	Chlorination/ dechlorination	0.0021	≈69 ML/d flow	Not defined	Not defined	WEF (2010); NYSERDA (2004)	SEC for chlorination/ dechlorination equipment at the Southtowns WWTP, Erie County, New York State.
	Liquid dosing (booster pumping)	0.0009; 0.0034; 0.0038; 0.0044	≈8.3–37 ML/d	Not defined	Not defined	Wijesinghe (2013)	Various drinking water schemes in Sri Lanka and Thailand
	Liquid dosing	0.0003–0.002	Not defined	Not defined	Not defined	Arpke and Hutzler (2006) based on data of Elliott et al. (2003)	SECs are average data for disinfection of both surface and groundwater for potable supply
	Liquid dosing (pre- and post-chlorination steps)	0.06	NaClO (15%) dosed at 97 g/m^3; WWTP flow ≈2.4 ML/d	Not defined	Not defined	Meneses et al. (2010)	Production of non-potable recycled water at a small WWTP on the Mediterranean coast
	On-site hypochlorite generation	≈0.034–0.06	For systems with capacity ≈4–30 ML/d	Not defined	Not defined	Mackey and Salveson (2012)	SECs based on secondary literature data. Data are indicative only, as levels of disinfection varied

	On-site hypochlorite generation (0.8% NaClO solution)	≈0.011–0.045	For a chlorine dose of 2–8 mg/L	Not defined	Not defined	WEF (2010)	SEC for potable water disinfection. 1.25 kWh/kg chlorine produced
	Off-site NaClO production	0.0176–0.023	For a chlorine dose of 6–8 mg/L; 89 ML/d flow	Not defined	Not defined	NYSERDA (2009)	SEC for wastewater disinfection (excluding transport/dosing energy). 1.25 kWh/kg chlorine produced
	Assumed liquid dosing	0.00241 (max.)	Not defined	Not defined	Not defined	EPRI (2002)	SEC data estimated from quoted average SEC for groundwater supply and chlorination energy contribution
	Gas chlorination	0.0045	Kandy South facility; 18 ML/d flow (max. design flow 32 ML/d)	Plumbing characteristics and elevation difference between chlorine storage and dosing points; booster pump efficiency	Reconfiguration of on-site plumbing to avoid the need for chlorinator booster pumping (although restricted by the maximum pressure limit of chlorinators)	Wijesinghe (2013)	SECs for surface water treatment facilities in Sri Lanka for potable supply. SECs relate to energy requirement of chlorinator booster pumps only
		0.0009	Morontota facility; 8.5 ML/d flow (max. design flow 13.5 ML/d)				
	Liquid dosing	0.00043 (embodied energy SEC estimated at ≈0.0042)	Operating flow 4.2 ML/d	Not defined	Not defined	Hernandez (1978)	SEC for an advanced wastewater treatment plant in Minnesota, USA
Chemical dosing (generic)	Liquid chemicals dosing (chlorine, coagulants)	≈0.0005–0.002	Not defined	Not defined	Not defined	WEF (2010)	SECs based on average data for potable water treatment facilities
	Liquid dosing of $FeCl_3$ coagulant	0.1	86 ML/d secondary effluent flow	Not defined	Not defined	Remy (2013)	SEC for operating chemical dosing pump
	Liquid dosing of chemicals including PAC,	0.0055	Kandy South facility; 18 ML/d flow (max. design flow 32 ML/d)	Not defined	Not defined	Wijesinghe (2013)	SECs for surface water treatment facilities in Sri Lanka and Thailand for

	alum and lime	0.0038	Nakhon Sawan Scheme; 9.6 ML/d				potable water supply
		0.00003	Morontota facility; 8.5 ML/d flow (max. design flow 13.5 ML/d)				
		0.0027–0.0044	Suggested best practice benchmark for Asian facilities				
Ozonation	O_3 generation and dosing	0.03	O_2 generation of O_3; 6 mg O_3/L dose	O_3 generation method (i.e. ambient air or O_2); O_3 dose rate	Not defined	Haberkern et al (2008) cited in Krampe and Trautvetter (2012)	Higher SEC values for higher levels of treatment (e.g., micropollutant removal)
		1.05	Air generation of O_3; 24 mg O_3/L dose				
	O_3 generation and dosing	0.042 (median) 0.032–0.12 (min–max)	Not defined	O_3 generation method (i.e. ambient air or liquid O_2); O_3 dose rate	Not defined, but most likely optimisation of upstream treatment processes	Cooley and Wilkinson (2012) (data from secondary literature sources)	SEC data for ozone generation and disinfection of potable water
		≈0.032–0.145	Wisconsin drinking water facilities	Water quality; system design; process operation	Not defined	WEF (2010)	SEC data from secondary literature sources
		≈0.026–0.106	Not defined				
		≈0.008–0.04	≈5–80 ML/d	Operating O_3 concentration; type of O_3 generator feed (liquid O_2 or air); volumetric production rate	Optimise O_3 dosing; operate at higher O_3 production rates and O_3 concentrations	Brandt et al. (2010)	SEC data for three potable water treatment plants (oxidation and disinfection applications)
		0.11	Medium-to-large plant (O_3 dose 5.0 mg/L)		Use of liquid O_2 for O_3 generation	PG&E (2006)	SEC data for potable water disinfection using pure O_2 generation
		0.20	Not defined	Not defined	Not defined	Radcliffe (2004)	Estimate only; primary data source not defined
		0.045	Not defined	Not defined	Not defined	Carlson and Walburger (2007)	Primary data sourced from EPRI

		0.033 (avg.) (0.026–0.040)	3 mg O_3/L average dose; 19 ML/d plant; O_2-based O_3 generation	O_3 dose (0.5–>5 mg/L); method of O_3 generation (i.e. O_2 or air-derived); water flow rate variations	Optimise flow-paced O_3 dosing; utilise economies of scale effects (on-site O_3 generation from liquid O_2 for large plants)	EPRI (2009)	SEC for potable water disinfection. SEC is approximate only (no primary reference provided for this data)
		0.066 (avg.) (0.053–0.079)	3 mg O_3/L average dose; 19 ML/d plant; air-based O_3 generation				
		0.03–0.15	Not defined	Not defined	Not defined	Arpke and Hutzler (2006) based on data of Elliott et al. (2003)	SEC for ozonation of water for potable supply
		0.0085 (avg.) (0.0053–0.013)	Liquid O_2 feed; 302 ML/d plant; mean dose 1 mg O_3/L; mean site production 123 kg O_3/day (design production capacity 925 kg O_3/day);	O_3 concentration/ production rate; energy use mainly from O_3 generation rather than O_3 destruction	Operate at or near design O_2/O_3 production rate; match unit size to site O_3 requirement; flow-paced O_3 dosing; calibrate gas flow meters, O_3 residual monitors and power meters; proper equipment maintenance	Chang et al (2008)	SEC for potable water production at the Bollman plant, Contra Costa Water District, California
		0.016–0.021	Vacuum/pressure swing adsorption feed; 2.27 GL/d plant; mean dose 1.1 mg O_3/L; mean site production ≈1250 kg O_3/day (design production capacity ≈9000 kg O_3/day);				SEC for potable water production at Alfred Merritt Smith plant, Southern Nevada Water Authority
		0.033 (avg.) (0.029–0.042)	Ambient air feed; 189 ML/d flow; mean dose 0.81 mg O_3/L; mean site production ≈1250 kg O_3/day (design production capacity ≈450 kg O_3/day);				SEC for potable water production at Paul M. Neal plant, Central Lake County Joint Action Water Agency
		0.044–0.072	Not defined	Water quality and standards; type of technology used	Not defined	CPUC (2010)	SEC for potable water disinfection at various facilities in the Contra

							Costa Water District, California
		0.025	O_3 generated with air; assumed intermediate O_3 dose of 1.5 mg/L	Not defined	Not defined	Raucher et al (2007)	O_3 dose rate not defined. SEC for O_3 generation only. Primary data from Rice (1996) cited therein
		0.015–0.018	O_3 generated with liquid O_2; assumed intermediate O_3 dose of 1.5 mg/L	System design flow affects SEC (lower with larger daily flows)	Not defined		
		0.04	3 mg/L O_3 dose; O_3 generated with air	Not defined	Not defined	Carns (2005)	No source reference provided for these data
		0.066	3 mg/L O_3 dose; O_3 generated with O_2				
	O_3 generation only	0.098	7.5 mg/L O_3 dose for pre-ozonation of secondary effluent	Not defined	Not defined	Remy (2013)	SEC from Reid et al. (2009) cited therein. SEC excludes dosing energy and energy associated with liquid O_2 feed
Membrane bioreactors (MBRs)	Not defined	1.3–1.4	Based on full-scale municipal MBR performance data	Not defined	Not defined	Haberkern et al (2008) cited in Krampe and Trautvetter (2012)	Data based on full-scale municipal MBRs operating in Germany
		0.7–0.9	Target SEC value for optimised MBRs				
	GE Zenon ZeeWeed ZW-500d PVDF hollow fibre; 0.04 0.4 μm pore size	1.35 (pre-optimised for 1 ASR and 6 membrane trains)	6 membrane trains; 56 ML/d peak design permeate flux; 42-55 kPa trans membrane pressure; 12 min	Air scouring regime(≈45% total energy); process aeration 25% total energy;	Operating at 10/30 air scour mode rather than 10/10; operate mixed liquid recycle pumps in variable	KBR (2012); Langlais and Aguilera Soriano (2014)	MBR at Christies Beach wastewater treatment plant, South Australia.

		1.00 (post-optimisation)	membrane relaxation cycle; optional 10/10 or 10/30 aeration mode; <1 mg/L TSS; <0.3 NTU	mixed liquor return activated sludge pumping	flow proportional to plant inflow; operate ASRs in intermittent aeration mode where organic loading rates allow		
	Not defined	0.32	Not defined	Not defined	Not defined	Livingston et al (2010)	Quoted theoretical maximum efficiency of MBRs
	Flat sheet membranes	0.5	Not defined	Air scouring (≈65% of SEC)	Install membranes directly in aerated zone with granulates for mechanical cleaning; optimise PLC programming for high membrane flux	Krause and Dickerson (2010)	Data from pilot-scale research; energy demand calculated for a hypothetical treatment plant
	Various municipal MBRs in Germany	0.8; 1.5; 2.15	Not defined	Air scouring dominates SEC (up to 71.5%)	Not defined		Original data from Krause (2005) (in German)
	Submerged UF membranes; 0.035 μm	0.79–1.32 (total) 0.47–1.0 (excl. effluent pumping)	11.4 ML/d rated (30 ML/d peak); influent TSS ≈300 mg/L; BOD_5 ≈400 mg/L	Air scour rate (≈40% SEC); recycled water distribution pumps (≈33% SEC); volumetric production rate	Minimise frequency/rate of air scour; operate at higher volumetric flow rated	Chang et al. (2008)	Plant at Anthem, Arizona
	Zenon submerged UF membranes; 0.1 μm	1.2–2.0 (average 1.7)	9.5 ML/d rated (15 ML/d peak); fine-bubble aeration; influent TSS ≈200 mg/L; BOD_5 200–300 mg/L	RAS pumps (≈33% SEC); air scouring rate (≈27% SEC); aeration blowers (≈9% SEC); volumetric production rate	VFD on RAS pumps; minimise frequency of air scouring; operate at or close to design flow	Chang et al. (2008); Williams et al (2008); Pellegrin and Kinnear (2011)	Plant at Pooler, Georgia; average flow during study period 4.1 ML/d; wastewater screened to 0.5 mm prior to MBR
	Zenon ZeeWeed	1.60 (avg.)	Actual average	MBR accounted	Increase air scour	Williams et al	Cauley Creek water

	500c/500d		operating flow ≈8 ML/d; 19 ML/d rated flow; avg. flux 3.75 L/(m^2.d); peak flux 5.0 L/(m^2.d)	for ≈80% total facility energy use	interval (e.g., 10/10 to 10/30 cycle); increase low flux rate is membrane performance allows.	(2008)	reclamation plant, USA; manufacturer (GE) claims up to 50% power reductions from switching to 10/30 air scour protocol (Ginzburg et al. (2008) cited in US EPA (2010)
	Zenon ZeeWeed 500c	4.2 (avg.) whole of plant 1.42 (avg.) membranes only	Actual operating flow ≈1–2.1 ML/d; 9.5 ML/d rated flow; low membrane flux 9.9 L/m^2/d	Membrane processes accounted for ≈34% total facility energy use, activated sludge 20% and effluent pumping 17%	Fowler facility was operating well below rated flow capacity, so likely gains could be realised by increasing daily treated flow rates		Fowler water reclamation facility in Georgia, USA. Whole of plant SEC includes: headworks; fine screens; anoxic–aerobic reactors; membrane tanks; UV disinfection; side stream screens, aerobic digesters; and biosolids dewatering
	Zenon ZW500d vertical capillary membranes (0.035 μm); design PE 23,150; 18 ML/d peak flow	0.97 (pre-optimisation) 0.77–0.93 (post-optimisation)	Influent pre-screened (1 mm); design flux 37.5 L/(m^2.h); peak flux 50 L/(m^2.h)	Aeration rate	Reduce aeration during dry weather flow conditions	van Bentem et al. (2007); Brandt et al. (2010)	First full-scale demonstration MBR in Varsseveld, Netherlands; SEC data relate to whole plant (MRB components 60–65% total SEC)
	Not defined	0.65	Not defined	Not defined	Not defined		SEC for other Dutch MBRs at Ruurlo and Wehl wastewater treatment plants in Maasbommel
	GE/Zenon membranes	1.43 (avg.) whole of plant	Rated flow of 15.5 ML/d.	Not defined (no sub-metering/unit process breakdown)	Adequate turndown capability and modular MBR construction/ multiple trains; optimise number of trains in operation to maximise membrane	Pellegrin and Kinnear (2011)	Plant in Bonita Springs, Florida. SEC includes: screenings/grit removal; micro-screening; anoxic–aerobic reactors; membrane tanks; chlorine contact; rotary drum thickener; and

					utilisation and influent flow equalisation in order to decrease membrane surface area in use and decrease air scouring demands (needs careful operator control to avoid excess fouling. For MBRs operating at low flux, energy optimisation may be achieved by increasing operating flux if membrane performance allows		centrifuge, dryer and pelletizer facility for biosolids
	Enviroquip/Kubota membranes	1.66 (avg.) whole of plant 0.86 (avg.) membranes only	5.7 ML/d avg. flow; 11.4 ML/d peak flow	43% SEC from membrane scouring, 9% SEC from permeate pumping			Plant in Dundee, Michigan. SEC data includes: headworks; fine screens; anoxic–aerobic reactors; membrane tanks; aerobic digesters and membrane thickeners
	Siemens/Memcor membranes	1.61 (avg.) whole of plant	Actual average operating flow ≈4 ML/d; 7.6 ML/d rated flow; MBR operated at low flux (10.5 $L/m^2/h$)	Not defined (no sub-metering/unit process breakdown)			LOTT plant in Washington, USA. SEC includes: headworks; fine screens; anoxic–aerobic reactors; membrane tanks; chlorine contact chamber (no biosolids).
	Enviroquip/Kubota membranes	2.6 (avg.) whole of plant	Actual average operating flow ≈3.8–13 ML/d; 14.4 ML/d rated flow; 45 ML/d peak flow; MBR operated at low flux (17 $L/m^2/h$)	Not defined (no sub-metering/unit process breakdown)			Plant in Delfos, Ohio. SEC includes: headworks; fine screens; anoxic–aerobic reactors; membrane tanks; UV disinfection; post aeration; autothermal thermophilic aerobic digestion (ATAD); biosolids dewatering
	Siemens/Memcor membranes	1.8 (avg.) whole of plant	Actual average operating flow ≈3.8–13 ML/d; 6.1 ML/d rated flow; 15 ML/d peak flow; MBR operated at low flux (14 $L/m^2/h$)	Not defined (no sub-metering/unit process breakdown)			Plant in Healdsburg, California. SEC includes: headworks; coarse and fine screens; pre-anoxic, anoxic and aerobic reactors; membrane tanks; UV disinfection; Cannibal sludge management process and centrifugal biosolids dewatering

	Not defined	1.3 (pre-optimisation) 0.8–1.0 (mid-optimisation) 0.37 (post-optimisation)	23 ML/d design flow; 3174 kg BOD_5/d; 6–10 g/L MLSS; 6 h HRT; min. SRT 10 d	SRT, MLSS, aeration/scouring rate	Optimisation of sludge retention time, MLSS concentration and recycling, process aeration and membrane scouring rate	Brandt et al. (2010); Tao et al. (2010)	Demonstration MBR plant, Ulu Pandan Water Reclamation Facility, Singapore
	Various MBRs	0.986 (large MBRs) 1.20–1.49 (small MBRs)	Not defined	Aeration regime; air scour regime	Optimisation and tighter control of aeration (via online instrumentation and air diffusers); use of efficient blowers; optimise air scour protocol;	Lazarova et al (2012)	Data from secondary literature sources
	Theoretical optimised MBR	0.296					SEC includes membrane feed pumps, permeate pumps, air scour blowers and other ancillary equipment
	Memcor Memjet membranes	0.73	60 ML/d; influent COD 550 mg/L; BOD_5 280 mg/L; TSS 430 mg/L; TN 65 mg/L; TP 10 mg/L	Utilisation of plant hydraulic capacity (this one has operated at 75–92%)		Lazarova et al. (2013)	BeiXiaoHe water reclamation plant. SEC includes pre-treatment, 1 mm fine screening and UV disinfection.
	Not defined	0.8–1.0	Not defined	Not defined	Reduce aeration by limiting wastage; use of low-energy anaerobic MBRs; use of air lift systems.	Pearce et al. (2008)	SEC values from secondary literature data (Singapore and Netherlands facilities)
	Hollow fibre or plate membrane modules	0.1–0.7	Vacuum pressure 0.1–0.9 bar; permeate flow 20–50 $L/(m^2 \cdot h)$;	Vacuum pressure; aeration pressure	Not defined	ATV (1998)	SEC data based on manufacturer's details
		2–7	Vacuum pressure 1–10 bar; permeate flow 20–300 $L/(m^2 \cdot h)$;				
	Various	0.5–1.8	Not defined	Not defined	Do not operate in excess of 10–20 day SRT (N removal); optimise internal	Oppenheimer et al. (2010)	Various full-scale MBR facilities

					recycle flow; minimise air scour		
	Zenon 500c	Not defined	32 ML/d average design flow ('Regional' MBR) 0.34 ML/d max. design flow ('Septage' MBR)		Optimise air scour regime (10/30); turn off blowers overnight under low loading; optimise membrane vacuum pumping; maintain calibrated DO meters and control loops; install RAS pump VFD control	Blair (2012)	Results from optimisation of two MBRs in Michigan, USA: Traverse City Regional Wastewater Treatment Plant; and Grand Traverse County Septage Treatment Facility
	Flat sheet membranes	1.23	Design flow 3.4 ML/d; permeate flow 1.09 ML/d; membrane flux 11.8 L/m^2/h ; sludge age 16.6 d; air flow to bioreactor and membranes 109 and 992 Nm^3/h respectively	Membrane aeration 53% SEC; recirculation pumping 28% SEC; mixing 13% SEC; bioreactor aeration 6% SEC	Use of hollow fibre membranes for reduced aeration energy; use of simultaneous nitrification–denitrification design for lower bioreactor aeration energy; optimise mixing processes	Wang et al. (2009); Brannock et al. (2010)	SEC for MBR permeate production. MBR treats untreated municipal wastewater and provides recycled water for local reuse
	Hollow fibre membranes	0.982	Design flow 2 ML/d; permeate flow 1.1 ML/d; membrane flux 14.3 L/m^2/h ; sludge age 9.9 d; air flow to bioreactor and membranes 419 and 918 Nm^3/h respectively	Membrane aeration 32% SEC; recirculation pumping 43% SEC; mixing 5% SEC; bioreactor aeration 20% SEC			SEC for MBR permeate production. MBR treats primary sewage from local WWTP and provides recycled water for local reuse
	Flat sheet membranes (Toray)	0.8–1.2	Max. design flow ≈2.4 ML/d; membrane flux 23.4 L/m^2*h; SVI 90–120 mL/g; permeate BOD_5 1 mg/L; permeate TN ≈1–6 mg/L	Membrane air scouring	Optimise membrane air flow capacity	Mulder (2009)	Hybrid MBR treats 25% wastewater from village of Heenvliet, the Netherlands
Microsieving,	10 μm microsieve	0.0293	86 ML/d flow; avg.	Influent water	Not defined	Remy (2013)	SEC for pumping (2 m

microstraining, rotary drum screening	modules; 30 filter discs per module		effluent quality 2.5 mg/L TSS, 35 mg/L COD, 63 µg/L TP	quality; backwash frequency			head) and combined auxiliary equipment required for microsieve operation (backwashing and pressure spraying)
	Rotary drum screens (300 µm)	0.001	86 ML/d flow	Not defined			SEC for drum screen rotation and cleaning
Micro-, ultra- and nano-filtration	Tertiary membrane filtration	0.1–0.15	Target SEC for optimised system	Not defined	Not defined	Haberkern et al (2008) cited in Krampe and Trautvetter (2012)	Data based on full-scale operations in Germany
	Low-pressure submerged ultrafiltration membranes	0.09–0.20 (membranes only) 0.62–1.2 (incl. influent & effluent pumps)	30 ML/d rated flow; mean turbidity 3.3 NTU and TDS 620 mg/L. Influent pre-screened 2 mm	Production rate; pre-treatment (coagulation–flocculation reduced SEC); UF ≈14–19% of total plant power use (pumps balance)	Optimise pumping efficiency; regulate air scour rates according to feedwater turbidity; operate at higher flow rates	Chang et al. (2008)	Drinking water plant at Anthem Water Campus, Arizona. UF SEC was 14–19% total plant SEC with influent and effluent pumping 81–86% total SEC. SEC data relates to flows of ≈6–17 ML/d
	Low-pressure ultrafiltration membranes	0.13–0.26	Mean influent turbidity 2.4 NTU and TDS 28 mg/L	Production rate; high influent TDS	Shut down surplus UF trains under low flow; operate at higher flow rates	Chang et al. (2008)	Drinking water plant, Kamloops Centre for Water Quality, British Columbia. SEC includes UF + DAF + ancillary chemicals but excludes influent and effluent pumping. SEC data relates to flows of ≈36–125 ML/d

	Low-pressure ultrafiltration (Inge dizzer® XL 1.5 MB 40W; polymer membrane; 40 m^2 per module	≈0.085 (total) 0.056 (feed pumps) 0.016 (backwashing) 0.008 (valve operation) 0.004 chemical cleaning	390 ML/d peak flow; 0.02 μm pore size; ≈9 psi transmembrane pressure; 75 $L/m^2 \cdot h$ peak flux rate; 95% recovery ratio; effluent quality <0.1 mg/L TSS; 26 mg/L COD; 23 μg/L TP; >4 log virus/bacteria removal	Pipe pressure loss; influent water quality; pre-coagulation efficiency; backwash frequency	Not defined	Remy (2013)	SEC for 300 µm screened, coagulated (8 mg/L Fe^{3+}) secondary effluent filtration
	Low-pressure ultrafiltration membranes	0.13	Not defined	Backwashing; air scouring	Minimise backwash frequency/duration; optimise air scouring; optimise pre-treatment steps	Mackey et al. (2001) cited in Chang et al. (2008)	Drinking water application
	Low-pressure ultrafiltration membranes	0.05–0.48	Not defined	Backwash frequency; hydraulic flow rate	Minimise backwash frequency; optimise pre-treatment steps	Jacangelo et al. (1992) cited in Chang et al. (2008)	Drinking water application
	Ultrafiltration	0.264	Not defined	Not defined	Not defined	EPRI (1997); Carlson and Walburger (2007)	Original data source: Californian Energy Commission, Electric Power Research Institute (EPRI)
	Nanofiltration	0.48					
	Low-pressure microfiltration	0.026					
	Low-pressure membrane filtration	0.04–0.132	Potable water production	Not defined	Not defined	WEF (2010)	SEC data from AwwaRF (2001) cited therein
	Microfiltration	0.026	10 psi	Not defined	Not defined	Carns (2005)	No source reference provided for these data
	Ultrafiltration	0.21	80 psi				
	Nanofiltration	0.33	125 psi				
	Low-pressure UF/MF membranes	0.13 (median) 0.085–0.20 (min–max)	Not defined	Operating below design capacity, water temperature and turbidity	Not defined	Cooley and Wilkinson (2012) (data from secondary literature sources)	SEC for potable water treatment. Common data to that of Chang et al. (2008) and Mackey et al. (2001).
	Ultrafiltration	0.068–0.103 (0.086 avg.)	Not defined	Not defined	Water pre-treatment; use of premium	PG&E (2006)	SEC data relates to potable water production

					efficiency motors for filtration pressurisation or vacuum		
	Microfiltration	0.20–0.22	Not defined	Pumping pressure	Not defined	CPUC (2010); Hallett (2011)	Recycled water production in Orange County District, California.
	Microfiltration	0.11	Not defined	SEC increases with decreasing membrane pore size and increasing final effluent quality standard	Not defined	Griffiths (2003) cited in Radcliffe (2004)	
	Ultrafiltration	0.17					
	Nanofiltration (microfiltration pre-treatment)	0.41					
	Ultrafiltration	0.8	Not defined	Not defined	Not defined	Rothausen et al. (2011)	SEC data based on secondary literature source; potable water supply
	Microfiltration	0.18	Not defined	Not defined	Not defined	Arpke and Hutzler (2006) based on data of Elliott et al. (2003)	SEC for microfiltration of water for potable supply
	Microfiltration	≈0.1	51 ML/d facility (conventional AS feed)	Not defined	Not defined	Pearce et al. (2008)	SEC data from secondary literature sources (facility in Orange County, CA)
	Microfiltration (Siemens/Memcor CMF-S; 0.2 μm pore size)	0.275	Secondary effluent at 326 ML/d; instantaneous design flux 0.83 $m^3/m^2 \cdot d$. Effluent turbidity <0.2 NTU	SEC increases with membrane fouling	Operate within defined trans-membrane pressure band; effective membrane cleaning protocols	Lazarova et al. (2012)	Advanced water purification facility in Orange County, California, USA
	Microfiltration + reverse osmosis	0.938	Filtered secondary wastewater at 7 ML/d maximum flow	Not defined	Not defined	Sloan (2011)	Direct potable reuse facility (MF + RO +UV–$H_2O_{2)}$ in Big Springs, Texas, USA
	Membrane treatment (generic)	0.026–0.37 (avg. 0.0793)	Not defined	Raw and finished water quality requirements;	Membrane material improvements; innovative multi-	EPRI (2009)	SEC for potable water treatment. SECs are approximate only (no

				membrane pressure; membrane fouling	treatment configurations for fouling control and to target specific contaminants		primary reference provided for these data)
	Microfiltration	≈0.16	≈70 ML/d. Influent water quality ≈5 NTU; TDS ≈900 mg/L; TN 4 mg/L	Not defined	Not defined	Lazarova et al. (2013)	SEC interpolated from Figure 28.9 data and stated total average plant SEC (Bundamba advanced water treatment plant, Brisbane, Australia).
	Nanofiltraiton (spiral wound polyamide, Osmonics, GE)	0.343 (NF only)	Six NF trains, ≈7.6 ML/d total permeate flow; TDS 560 mg/L; pH 7.4; feed pressure ≈120 psi	Throttling valve for first stage permeate flow	Reduce permeate throttling pressure for first stage permeate within fouling restriction limits	Veerapaneni et al (2011)	Estimated SEC for potable water production at North County Regional Water Treatment Plant
	Micro-/ultrafiltration	0.2–0.4	Permeate flow 40–100 L/(m^2·h); pressure 0.5–3 bar	Not defined	Not defined	ATV (1998)	SEC data according to manufacturer's details
		0.25	Permeate flow 70 L/(m^2·h); pressure 0.5–1.5 bar				SEC data from long-term operations
Whole of plant water recycling	Conventional tertiary (filtration + disinfection)	0.42 (median) 0.40–0.45 (min–max)				Cooley and Wilkinson (2012) (data from secondary literature sources)	SEC values exclude distribution
	Membrane treatment (UF/MF + UV)	1.1 (median) 0.98–1.2 (min–max)					
	Full literature range	0.26–2.2 (min–max)					
	Pre-chlorination; 2 mm screening, microfiltration (Memcor CMF-S L10)+ RO	≈1.2–1.3 (whole of plant) 1.093 (MF+RO only)	16.7 ML/d design flow; MF recovery 90%; RO recovery 80%; effluent TDS <0.1 g/L; pH ≈7; turbidity <1 NTU	Organic fouling; variations in influent pressure, temperature and water quality	Proper membrane cleaning and maintenance; utilise influent pressure and minimize influent flow throttling; use of lower pressure/rejection RO membranes	Veerapaneni et al (2011)	Secondary wastewater treatment at Kwinana water reclamation facility, Western Australia

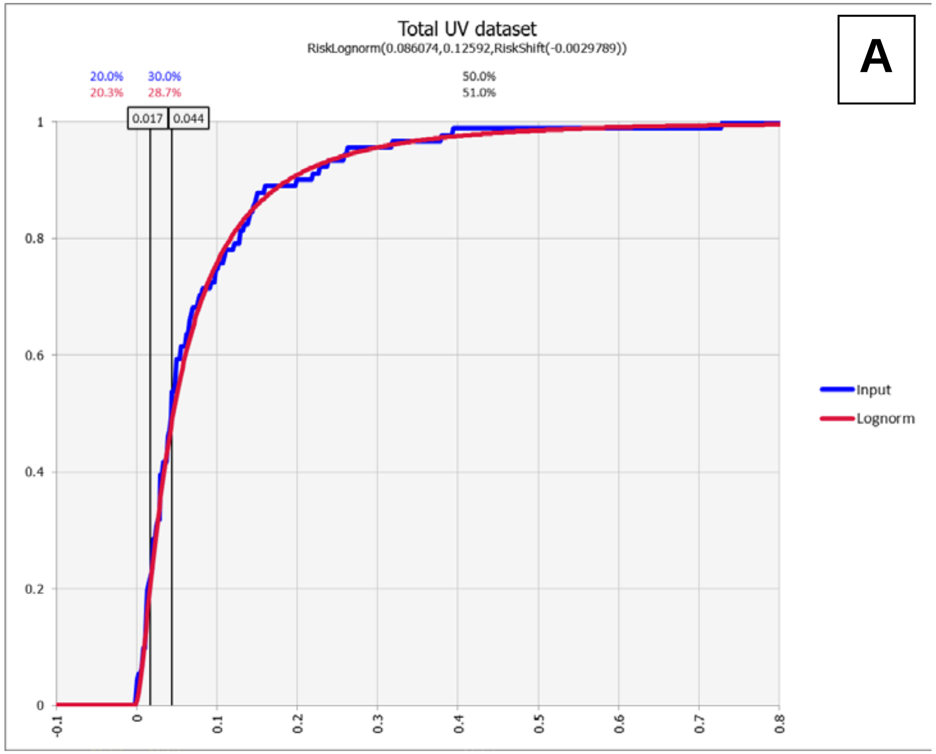
	Wet-well holding tank; submerged flat sheet MBR (Kubota FS-25 0.1 µm; Aquatec Maxcon, Australia); alum dosing UV + chlorination	15.6 (pre-optimisation) 11 (post-optimisation) 6.17 (excluding inefficient chlorine mixing)	0.011ML/d design flow; Class A^+ product water (10 mg/L BOD, TN, TSS; 5 mg/L TP)	High mechanical energy demand of pumps, sitrrers and blowers; MBR aeration; small-scale of facility. For this system, an inefficient chlorine mixing pump was responsible for ≈60% of the energy use	Larger plants offer energy efficiency gains from economies-of-scale effects	Chong et al (2013); Sharma et al. (2012)	Capo di Monte recycling facility, Mount Tamborine, Queensland, Australia
	Anoxic mixing + MBR aeration + RAS pumping only	5.25–6.0					
	In-series septic tanks; BioTube® filtration; Orenco AdvanTex® AX100 filter; 0.2 µm MF; UV+ chlorination	1.90	0.051ML/d design flow; Class A^+ product water 10 mg/L BOD, TN, TSS; 5 mg/L TP)	Not defined			Currumbin Ecovillage, Currumbin Valley, Queensland, Australia
	Clarification (incl. silica adsorption on $Mg(OH)_2$), pressure sand filtration + UF + RO	1.07–1.41	≈21 ML/d; membrane flux L/m^2·h; influent water quality 25°C; 800 mg/L TDS; 125 mg/L COD; 10 mg/L BOD_5	Influent TDS; degree of plant hydraulic capacity utilisation		Lazarova et al. (2013)	Panipat Naphtha Cracker water recycling plant (India) secondary effluent and cooling tower blowdown water
	UF/RO+UV	0.98	≈42 ML/d; influent TDS 552 mg/L; effluent TDS 26 mg/L	Pumping was single greatest contributor to SEC (>50%), followed by blowers (16%)	Not defined	Jacangelo (2013)	Industrial and indirect potable reuse
	Not defined	0.49	Nominal average SEC based on three Californian water recycling plants	Not defined	Not defined	Park et al (2008)	SEC values include distribution
	Filtration + chlorine disinfection	0.45				Stokes and Horvath (2009)	SEC values exclude distribution

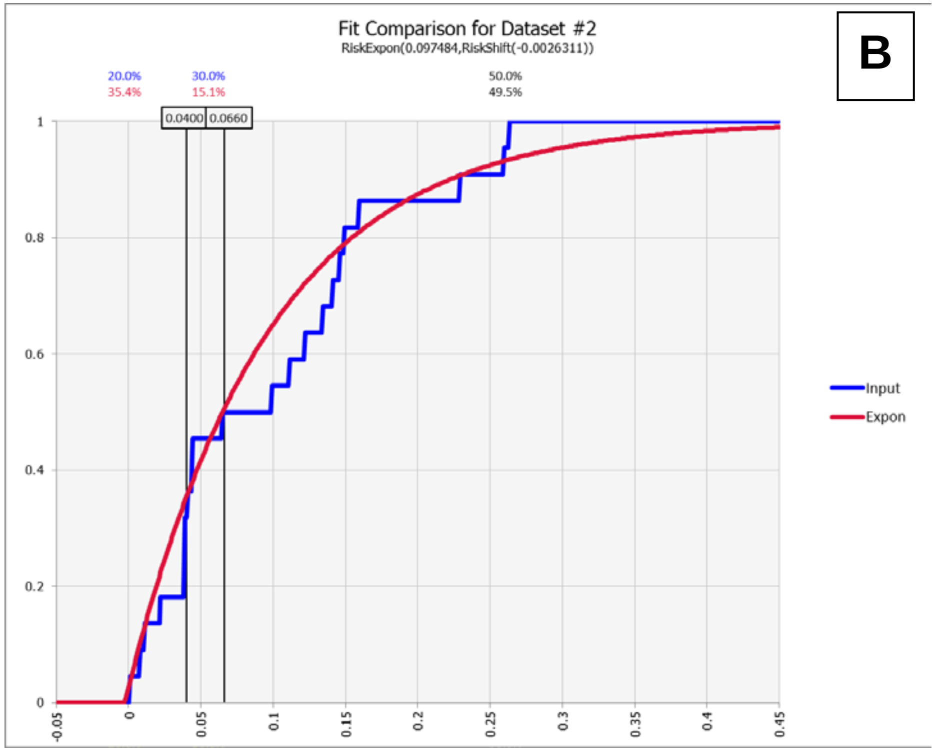
	Not defined	0.33 ;0.57; 0.73; 0.76; 0.21; 1.86	Not defined	Not defined	Not defined	Plappally and Lienhard V (2012)	SEC data for several water recycling plants in California. Data from secondary literature
	Conventional AS + MF/UF + RO	0.8–1.2	Not defined	Not defined	Not defined	Pearce et al. (2008)	SEC values exclude distribution
	Various	1.1 (excl. distribution)	Brushy Creek reuse scheme, Yarra Valley Water, Victoria, Australia	Not defined	Not defined	Cook et al. (2012)	SEC data includes distribution energy except where otherwise noted
		1.84					
		1.1	Sydney, Australia				
		1.26	Melbourne, Australia				
	MF + RO +UV–H_2O_2 advanced oxidation	1.04	Filtered secondary wastewater at 7 ML/d maximum flow	Not defined	Not defined	Sloan (2011)	Direct potable reuse facility in Big Springs, Texas, USA
	High-rate Actiflo clarification, 0.15 *µm* MF + RO + UV–H_2O_2 advanced oxidation	1.18 (assumed whole-of plant)	100 ML/d capacity; influent TDS ≈1.25–1.5 mg/L	Not defined	Not defined	GWRC (2009)	SEC for secondary-level industrial wastewater reuse at Gibson Island, Murrarie, Australia
	Ozone–biological activated carbon (BAC). Plant receives high-quality denitrified and DAF/F treated secondary effluent	0.703	≈7 ML/d average flow; 10 ML/d peak design flow; final effluent quality TN <1mg/L, <0.1 mg/L TP, TDS 576 mg/L, TSS <2 mg/L. On-site O_3 generation dosing at 2 –9 mg O_3/L for organics removal and disinfection			Lane et al. (2012); Halliday (2006)	South Caboolture water reclamation plant, Queensland, Australia. SEC excludes recycled water distribution to supply network
	Not defined	1.22	San Diego Project	Not defined	Not defined	Navigant Consulting (2006)	SECs based on secondary data of Dale (2003) cited therein. Unclear whether data includes distribution energy
		1.87	Orange County Plant				

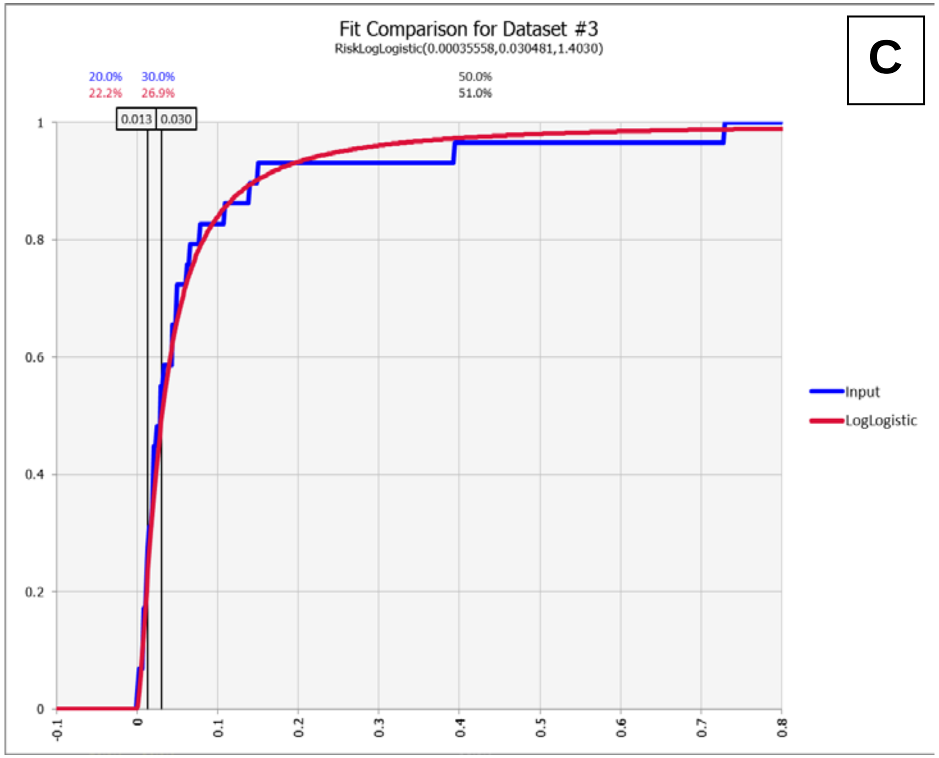
Water distribution only	Various	0.37 (median) 0.26–0.79 (min–max)		Elevation of recycled water facility relative to distribution network/customer s		Cooley and Wilkinson (2012) (data from 13 case study literature sources)	
	Potable water distribution	0.066 (min) 0.32 (max)	Min value assumes mostly gravity-fed distribution	Pumping elevation	Not defined	Griffiths-Sattenspiel and Wilson (2009)	Data for generic water pumping SEC
	Non-potable use; pumping distance 35 km	0.19				Stokes and Horvath (2009)	Data for a hypothetical case study system
	West Basin Municipal Water District, California	0.23	Not defined		Not defined	Wilkinson (2007)	
	Not defined	0.6	Not defined	Not defined	Not defined	Pearce et al. (2008)	Typical SEC for water distribution in UK based on secondary literature data
	Generic	0.32–0.76	Not defined	Topography and distance from supply to customer	Not defined	Navigant Consulting (2006)	SEC values based on few data points
	Combined source + product water pumping	0.36	Facility production 7 ML/d maximum flow	Not defined	Not defined	Sloan (2011)	Direct potable reuse facility (MF + RO +UV–H_2O_2) in Big Springs, Texas, USA.
	Potable water distribution	0.175	50% gravity-pressurised network	Pumping head; % gravity pressurisation; ageing and leaky distribution infrastructure	Not defined	Cohen et al. (2004)	SEC data for water distribution by San Diego County Water Authority, California
	Potable water distribution	0.35	100% electricity-pressurised network	Pumping head; % gravity pressurisation; ageing and leaky distribution infrastructure	Not defined Offset pumping energy requirements by energy recovery during wastewater treatment	Cohen et al. (2004); GWRC (2009)	SEC data for water distribution by San Diego County Water Authority, California SEC data for respective water and wastewater distribution in the cities of Sydney, Perth and
	Recycled water distribution	0.762	North City water recycling facility				
	Potable water pumping	0.25; 0.31; 0.11	Not defined				

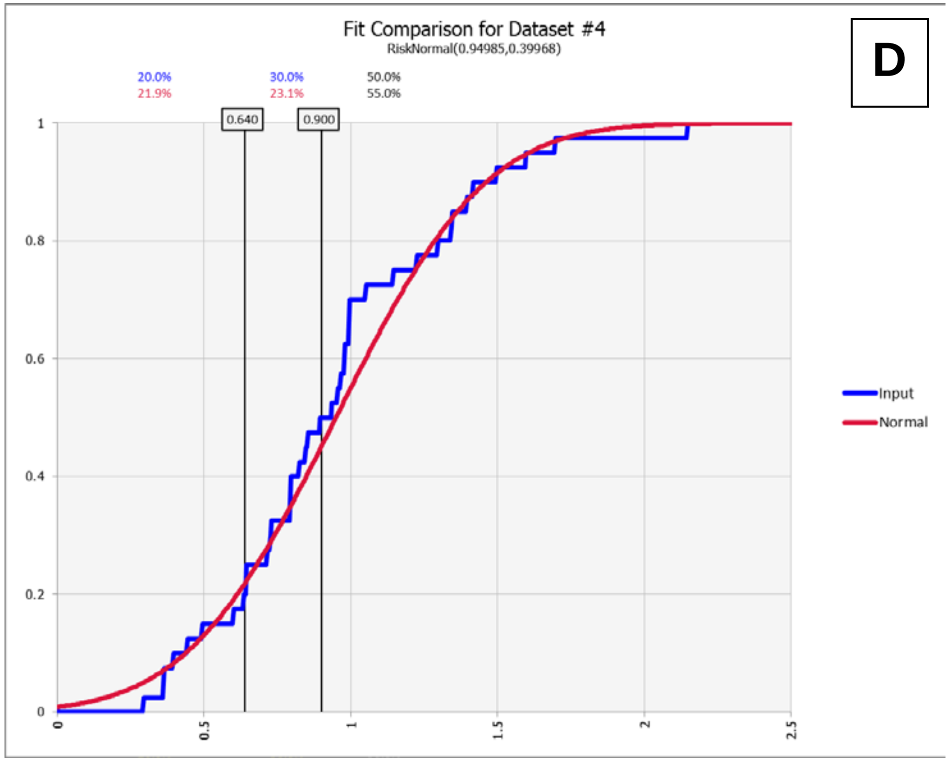
							Melbourne, Australia
	Wastewater pumping	0.07; 0.20; 0.55	Not defined	Topography and pumping head; pumping distance and discharge point elevation	Offset pumping energy requirements by energy recovery during wastewater treatment	GWRC (2009)	SEC data for respective water and wastewater distribution in the cities of Sydney, Perth and Melbourne, Australia

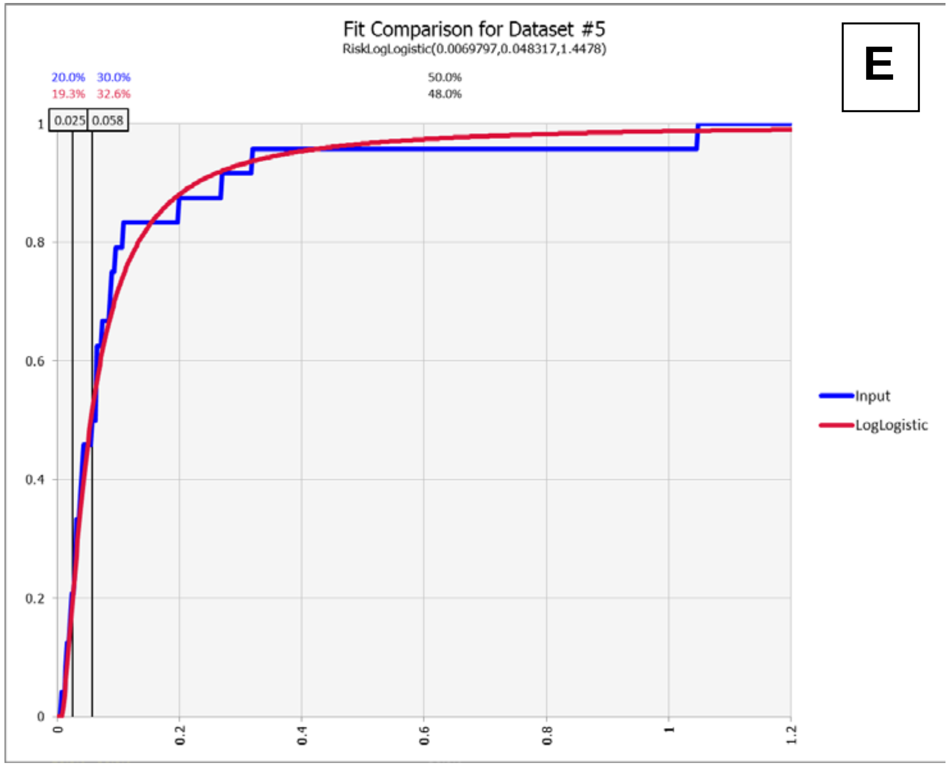
7.5 **Appendix E.** Probability–density functions (PFDs) for Guide (50th %ile) and Target (20th %ile) performance benchmarks for water recycling processes (based on data of Appendix D): (A) UV combined; (B) UV medium pressure; (C) UV low pressure; (D) MBR; (E) Ozonation; (F) Chlorination; (G) Membrane filtration combined; (H); microfiltration; (I) Ultrafiltration; (J) Whole-of plant recycling; (K); Water distribution.

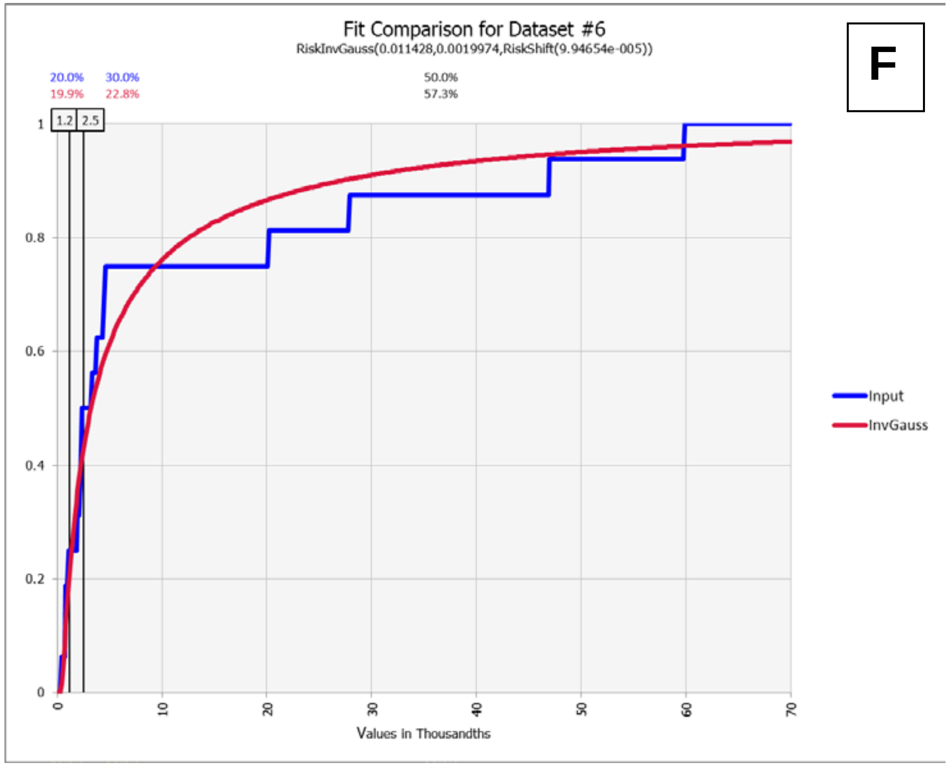


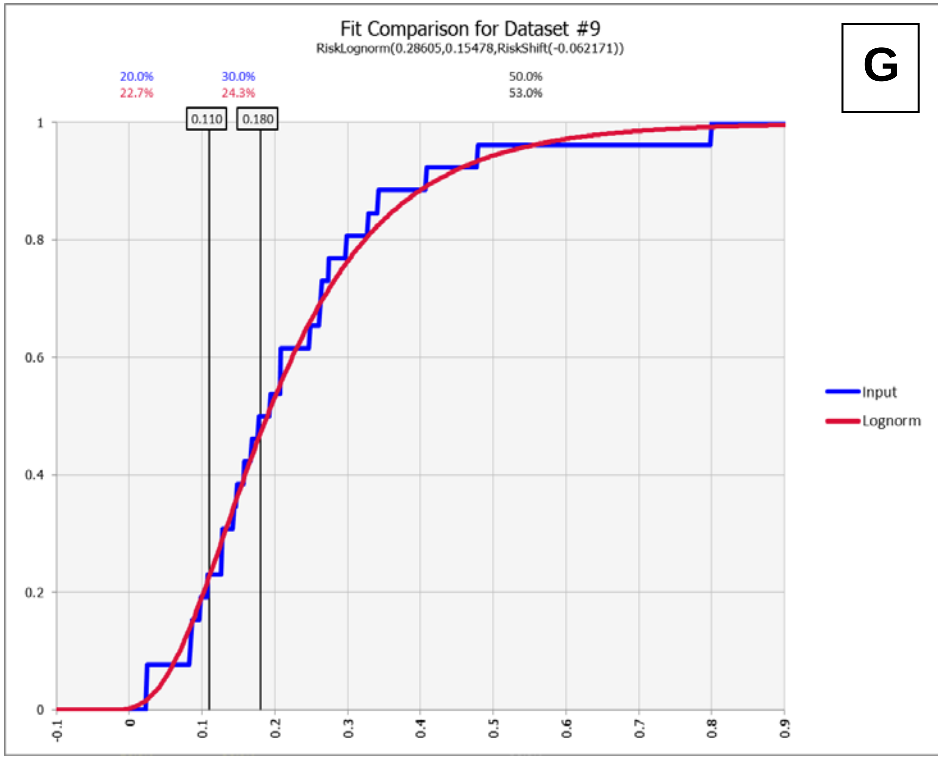


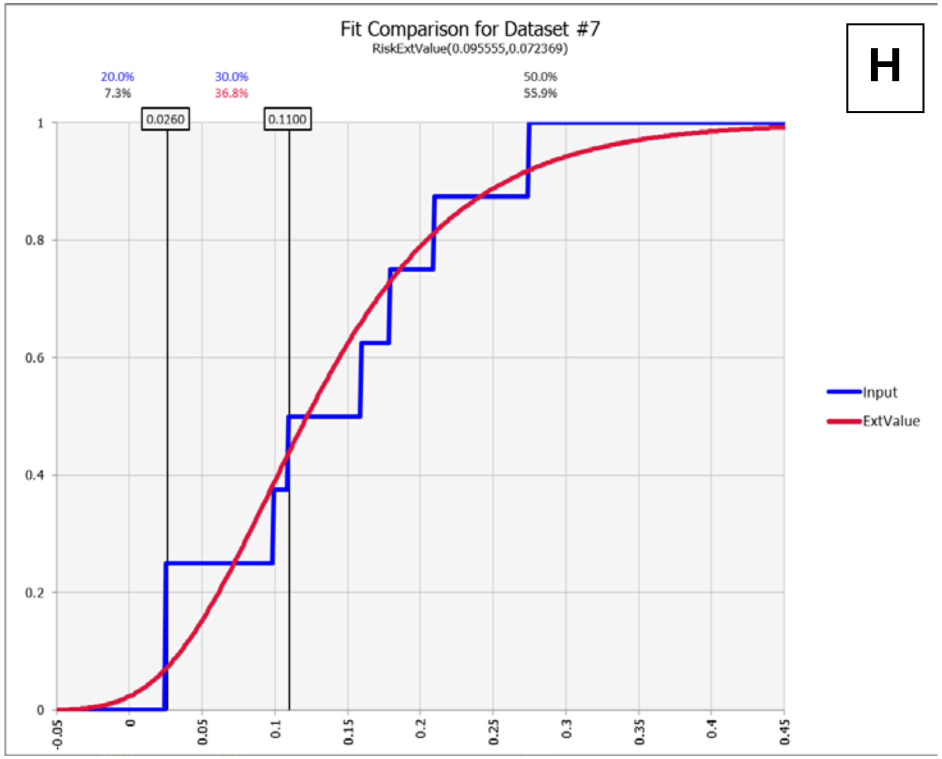

C
Fit Comparison for Dataset #3
RiskLogLogistic(0.00035558,0.030481,1.4030)
20.0% 30.0% 50.0%
22.2% 26.9% 51.0%
0.013 0.030
Input
LogLogistic

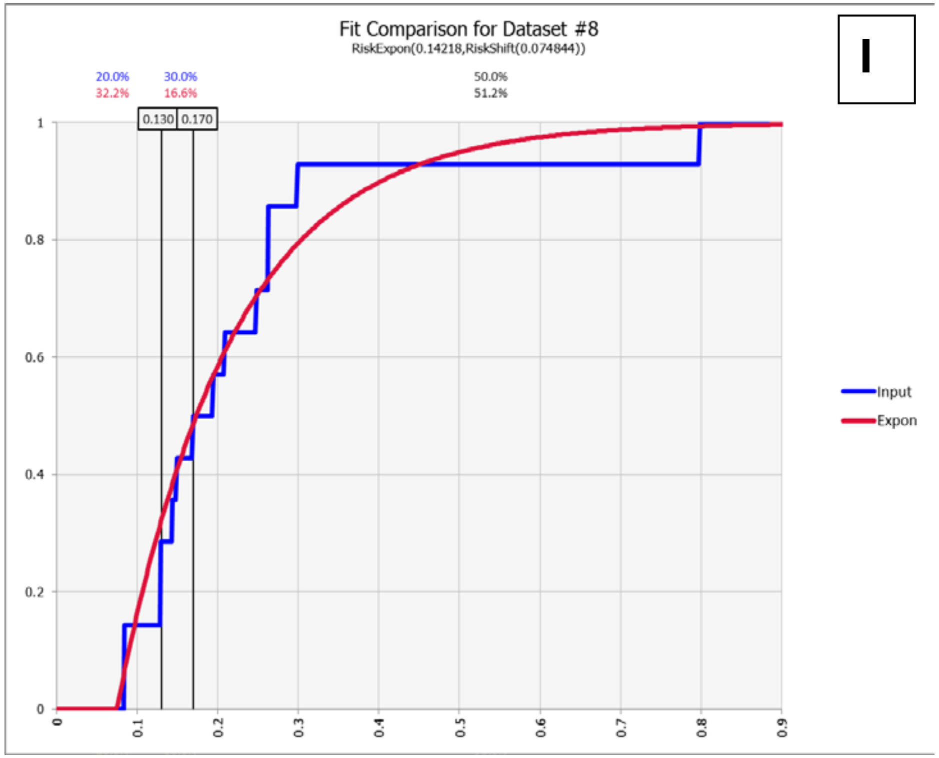

D
Fit Comparison for Dataset #4
RiskNormal(0.94985,0.39968)
20.0% 30.0% 50.0%
21.9% 23.1% 55.0%
0.640 0.900
Input
Normal

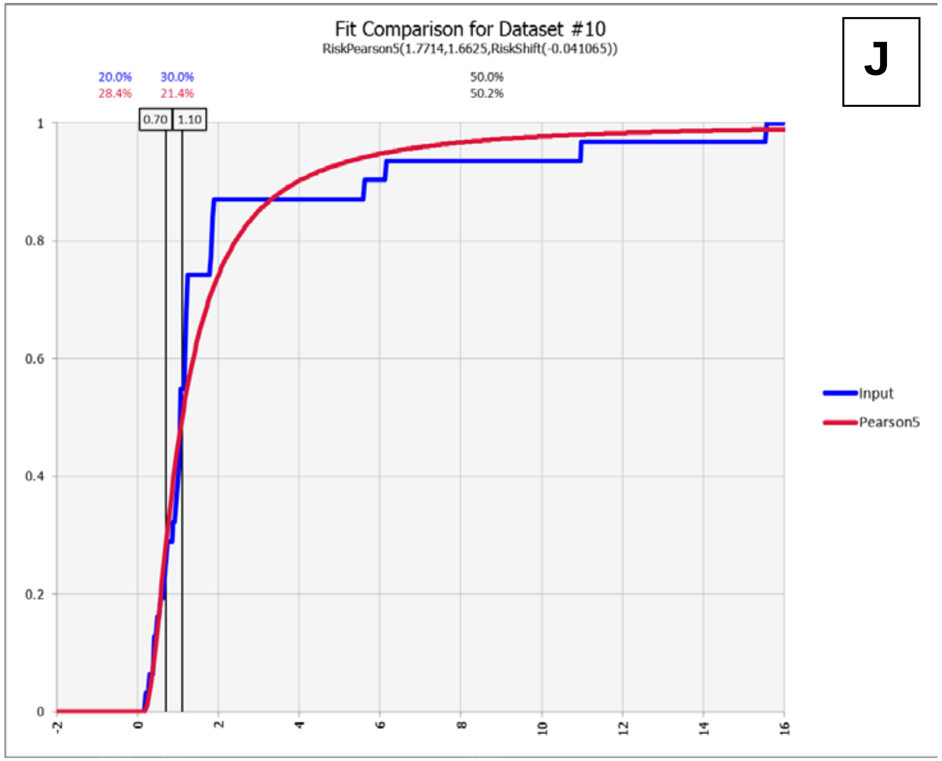

Fit Comparison for Dataset #5
RiskLogLogistic(0.0069797,0.048317,1.4478)
E
20.0% 30.0%
19.3% 32.6%
50.0%
48.0%
0.025 0.058
Input
LogLogistic

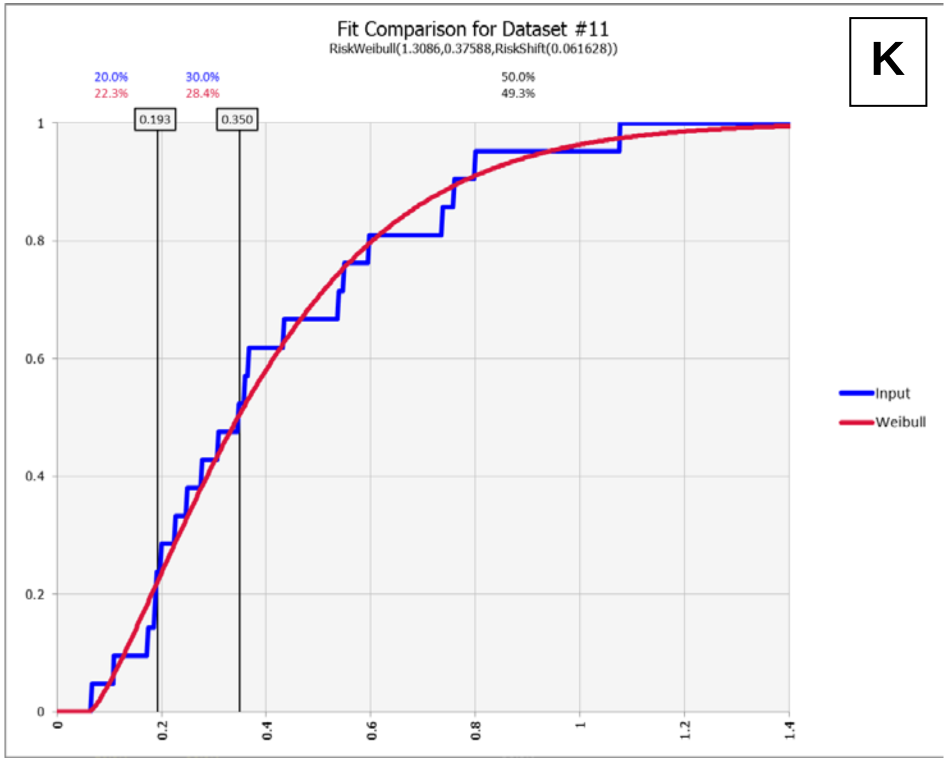

Fit Comparison for Dataset #6
RiskInvGauss(0.011428,0.0019974,RiskShift(9.94654e-005))
F
20.0% 30.0%
19.9% 22.8%
50.0%
57.3%
1.2 2.5
Values in Thousandths
Input
InvGauss


Fit Comparison for Dataset #9
RiskLognorm(0.28605,0.15478,RiskShift(-0.062171))
G
20.0%
22.7%
30.0%
24.3%
50.0%
53.0%
0.110
0.180
Input
Lognorm


Fit Comparison for Dataset #7
RiskExtValue(0.095555,0.072369)
H
20.0%
7.3%
30.0%
36.8%
50.0%
55.9%
0.0260
0.1100
Input
ExtValue


Fit Comparison for Dataset #8
RiskExpon(0.14218,RiskShift(0.074844))
I
20.0%
32.2%
30.0%
16.6%
50.0%
51.2%
0.130
0.170
Input
Expon


Fit Comparison for Dataset #10
RiskPearson5(1.7714,1.6625,RiskShift(-0.041065))
J
20.0%
28.4%
30.0%
21.4%
50.0%
50.2%
0.70
1.10
Input
Pearson5



Fit Comparison for Dataset #11
RiskWeibull(1.3086,0.37588,RiskShift(0.061628))
20.0%
22.3%
30.0%
28.4%
50.0%
49.3%
0.193
0.350
K
Input
Weibull

7.6 **Appendix F:** Pathogen log reduction value (LRV) risk management register for wastewater treatment and recycling operations in metropolitan Adelaide. LRVs based on data from the Australian Guidelines (NRMMC *et al.*, 2006), the SA Health and SA Water validation studies.

					PROCESS BARRIERS									ON-SITE BARRIERS								Animal controls
Plant	Enduse	Pathogen	Min LRV	Total LRV	Lagoons	ASP	ASP & chlorination Cl2	MBR	Media filtration	UF membrane filtration	UV disinfection	Cl_2 disinfection	Other	Drip irrigation of raised crops with no ground contact (5 log)	Witholding periods for irrigation of parks (1-4 h) (1 log)	Spray drift control (1 log)	Drip irrigation of plants/ shrubs (4 log)	No public access during irrigation (2 log)	Buffer zones (25m) (1 log)	Decay over 24 (0.5 log)	Cross-connection management (0.5 log)	With holding period/ pasture insilation
GLENELG-ADELAIDE PARKLANDS	SETPOINTS				n/a	BOD<20 mg/L, SS<30 mg/L	Free Cl_2 ≥0.3 mg/L, *E. coli* <1,000/100 mL	n/a	n/a	Turbidity incident criteria <0.15 & 0.3 NTU	RED≥10 mJ/cm[2] (SP=15)	Free C.t ≥13 mg.min/L	n/a	n/a	n/a		n/a		n/a	n/a	n/a	n/a
	Dual reticulation	V	6.5	6.5		1.0				2.5	0.0	3.0										
		P	5.0	6.5		0.5				3.5	3.0	0.0										
		B	5.0	10.0		1.0				3.0	3.0	3.0										
	Unrestricted municipal	V	6.0	6.5		1.0				2.5	0.0	3.0										
		P	5.0	6.5		0.5				3.5	3.0	0.0										
		B	5.0	10.0		1.0				3.0	3.0	3.0										
	Restricted municipal	V	5.0	5.0		1.0	1.0									1.0		2.0				
		P	3.5	3.5		0.5	0.0									1.0		2.0				
		B	4.0	5.0		1.0	1.0									1.0		2.0				
	Restricted onsite	V	5.0	5.0		1.0	1.0									1.0		2.0				
		P	3.5	3.5		0.5	0.0									1.0		2.0				
		B	4.0	5.0		1.0	1.0									1.0		2.0				
CBWWTP A/B Plant	SETPOINTS				n/a	n/a	BOD<20 mg/L, SS<30 mg/L, *E. coli* <1,000/100 mL, Total Cl_2>0.0 mg/L	n/a	n/a	n/a	n/a	n/a	n/a							n/a	n/a	n/a
	Commercial food crops (WBW)	V	6.0	6.0			1.0							5.0								
		P	5.0	5.5			0.5							5.0								
		B	5.0	6.0			1.0							5.0								
	Non-food crops (plants & flowers	V	5.0	5.0			1.0										4.0					
		P	3.5	4.5			0.5										4.0					
		B	4.0	5.0			1.0										4.0					
	Restricted municipal	V	5.0	5.0			1.0								1.0	1.0		2.0				
		P	3.5	4.5			0.5								1.0	1.0		2.0				
		B	4.0	5.0			1.0								1.0	1.0		2.0				
	Onsite	V	5.0	5.0			1.0								1.0			2.0	1.0			
		P	3.5	4.5			0.5								1.0			2.0	1.0			
		B	4.0	5.0			1.0								1.0			2.0	1.0			
CBWWTP C Plant	SETPOINTS				n/a	n/a	n/a	Turbidity <0.5 NTU, BOD<10 mg/L	n/a	n/a	RED≥15 mJ/cm[2] (SP=20)	n/a	n/a							n/a	n/a	n/a
	Commercial food crops (WBW)	V	6.0	6.5				1.5			0.0			5.0								
		P	5.0	10.0				2.0			3.0			5.0								
		B	5.0	12.0				3.0			4.0			5.0								
	Non-food crops (plants & flowers	V	5.0	5.5				1.5			0.0						4.0					
		P	3.5	9.0				2.0			3.0						4.0					
		B	4.0	11.0				3.0			4.0						4.0					
	Restricted municipal	V	5.0	5.5				1.5			0.0				1.0	1.0		2.0				
		P	3.5	9.5				2.5			3.0				1.0	1.0		2.0				
		B	4.0	11.0				3.0			4.0				1.0	1.0		2.0				
	Onsite	V	5.0	5.5				1.5			0.0				1.0			2.0	1.0			
		P	3.5	9.5				2.5			3.0				1.0			2.0	1.0			
		B	4.0	11.0				3.0			4.0				1.0			2.0	1.0			
ALDINGA RWTP	SETPOINTS				n/a	n/a	*Based on CBWWTP A/B plant +/-MAR +/-L3 +/-Aldinga WWTP &L1*	n/a	n/a	Turbidity incident criteria <0.15 & 0.3 NTU	RED≥55 mJ/cm[2]	Free C.t ≥20 mg.min/L	n/a		n/a	n/a	n/a	n/a	n/a	n/a	n/a	n/a
	Dual reticulation (Seaford Meadows)	V	6.5	>6.5			*>1.0*			2.5	1.0	2.0										
		P	5.0	>8.0			*>0.5*			3.5	4.0	0.0										
		B	5.0	>10.0			*>1.0*			3.0	4.0	2.0										
	Unrestricted municipal (Seaford Meadows)	V	6.0	>6.5			*>1.0*			2.5	1.0	2.0										
		P	5.0	>8.0			*>0.5*			3.5	4.0	0.0										
		B	5.0	>10.0			*>1.0*			4.0	4.0	2.0										
	Commercial food crops (S. Wines)	V	6.0	>11.5			*>1.0*			2.5	1.0	2.0		5.0								
		P	5.0	>12.5			*>0.5*			3.0	4.0	0.0		5.0								
		B	5.0	>15.0			*>1.0*			3.0	4.0	2.0		5.0								

7.7 **Appendix G:** Details of presentations given during the course of the Fellowship.

1. Internal presentation given to the SA Water Wastewater Treatment and Design group (August 2013, SA Water House) to introduce the project, its goals and scope (10 minutes, eight attendees).
2. Internal presentation given to the SA Water Senior Manager, Water Quality and Treatment Strategy (August 2013, SA Water House) regarding detailed/strategic project aspects from industry perspective (15 minutes; three attendees).
3. Presentation given to the Allwater Plant Manager at the Glenelg Wastewater Treatment Plant (October 2013, Glenelg Wastewater Treatment Plant) to discuss potential operational changes for energy efficiency gains based on Fellowship investigations (10 minutes, four attendees).
4. Internal presentation given to Dr John Radcliffe (CSIRO) (October 2013, SA water House) on the progress of the Fellowship project to date (60 minutes, five attendees).
5. Presentation given at the annual SA Water / Trility/ Allwater Wastewater Treatment Plant Operator Forum (6–7 November 2013, Victor Harbor). The seminar sought to stimulate ideas from Plant Operators in relation to energy efficiency improvements (10 minutes; 20 attendees).
6. Internal presentation given to the SA Water Energy Management Coordinator and Climate Change Coordinator (19 December 2013, SA Water House) regarding the Fellowship project and to seek funding support for a collaborative external research proposal (20 minutes, four attendees).
7. Presentation given to the SA Water WA/SA/NT Wastewater & Recycled Water Network Meeting (24 March 2014, SA Water House). This workshop was attended by around 25 water industry professionals from three states and provided good industry exposure for the Fellowship project and the Fellow.

7.7 **Appendix G:** Details of presentations given during the course of the Fellowship (continued…)

8. Presentation made at the CSIRO Land and Water Seminar Series (9 April, 2014, CSIRO Seminar Room, Building 1, Waite Road, Urrbrae). This presentation was recorded for broader dissemination; however, problems with the audio recording prevented this from occurring. This seminar was attended by some 15–20 audience members from a mixed background.

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Energy benchmarking for sustainable water recycling operations

Michael Short; Rudi Regel; Ben van den Akker; Chris Saint

Australian Government
Water for the Future

UniSA

Government of South Australia

SA Water

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The Fellowship and me

- Based at SA Water on 12 month AWRCoE Industry–Academic Exchange Program (Centre Fellowship) via UniSA CWMR
  → get academics into industry (& *vice versa*) to foster ideas exchange and long-term Industry–Academic collaborations
- 2008–2013 UNSW Water Research Centre
- United Water-sponsored PhD at Flinders Uni (Bolivar WSPs)

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Water recycling refresher…

- Commonplace nowadays (inter)nationally as part of balanced and secure 'climate-independent' urban water supply portfolio
- Many types of wastewater inputs, technologies and product recycled water qualities – 'fit for purpose' is the aim today
- Many end-uses for recycled water, broadly categorised:
  - urban/industrial reuse; agricultural irrigation; environmental flows; groundwater recharge/ASR; (in)direct potable reuse
- Water recycling overview…

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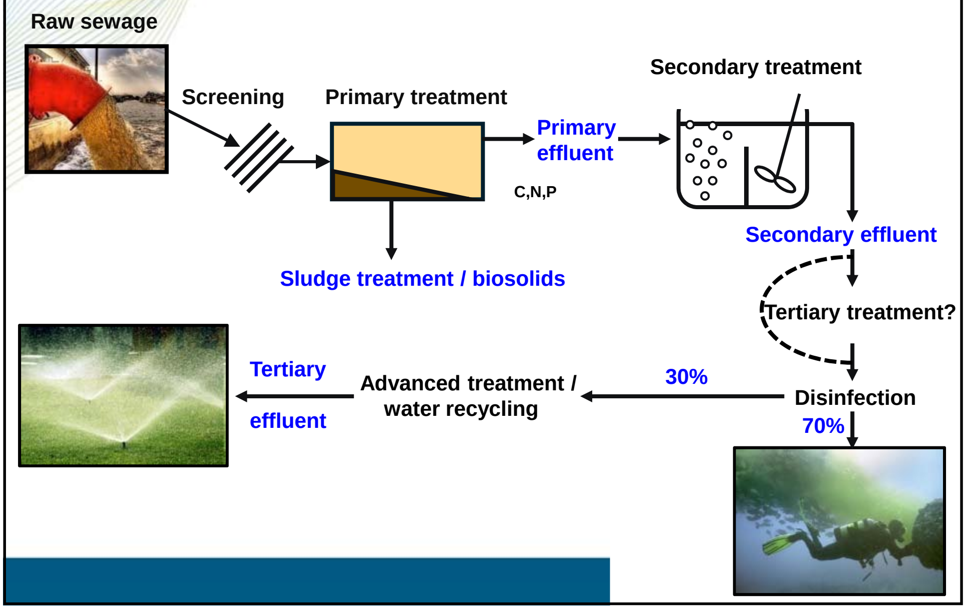

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Water recycling technologies

- Recycled water via:
  - Micro-, ultra-, nano-filtration membranes
  - Disinfection (e.g. chlorine)
  - Advanced oxidation (e.g. UV-H_2O_2)
  - Membrane biological reactor
  - DAF/F

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Water recycling refresher…

Source	Operating cost ($/kL)	Energy consumption (MWh/ML)	Greenhouse-gas emissions (tonnes CO2-e/ML)
Mt Lofty Ranges	0.20	[illegible]	0.24
River Murray	0.42*	[illegible]	1.54*
Desalination	1.00	5.0	4.10
Stormwater harvesting	0.55	0.8	0.65
Wastewater reuse	0.70	1.3	1.05

- Lots of progress in recycling during past 20 years; however, still a long way to go…
  - AU ≈10% of <u>urban</u> water is recycled in origin (Spies and Dandy 2012
  - SA leads the way nationally (≈25% of metropolitan Adelaide's wastewater is recycled)
  - In US recycled water represents <1% of <u>total</u> national water use (Cushing et al., 2014)
- Water recycling plays a valuable role in water security and resource recovery; however, can be relatively energy-intensive
  - trade-off between supply security vs. resource demands
- Industry need to provide 'fit-for-purpose' recycled water at lowest energy, economic, environmental burden

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Similar numbers interstate…

Table 13 - Estimated energy intensity of different water supply sources

City (region)	Traditional water sources (kWh/kL)[31]	Desalination (includes pumping) (kWh/kL)	Recycled (includes pumping) (kWh/kL)	Stormwater (includes pumping) (kWh/kL)	Wastewater treatment and pumping (kWh/kL)	Rainwater pumping (kWh/kL)[32]
Sydney	0.44	4.43	1.1		0.77	1.5
Melbourne	0.45	5.62[33]	1.26[34]		1.16	1.5
SEQ	0.37	4.02	1.84		0.91	1.5
Perth	0.54	5.33	1.53[35]		1.16	1.5

Source: Cook et al. (2012)

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Energy benchmarking – drivers and benefits

- Energy use is now a major issue for utilities internationally
  - rising energy costs are now a primary driver for action (secondary environmental / CO_2 cost driver)
  - water utilities often biggest single municipal energy users
- *Can manage only what you measure*, so first step is to measure current energy performance – i.e. 'benchmarking'

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Energy benchmarking – the how and why

- Benchmarking is simply the process of measuring current performance and comparing it with other similar processes and/or industry standards
  - allows for identification of operational inefficiencies and helps prioritise future optimisation investment / efforts
  - good way of picking low-hanging energy fruit (studies show rapid RoI/payback times [months to several years])
    → end goal is plant-wide 'best practise' performance at the individual process-level
  - provides data 'baseline' for future improvements and helps identify 'data gaps' in utility operations (sub-metering needs)
  - helps promote organisational optimisation & efficiency 'culture'

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Energy benchmarking @ SA Water

- SA Water's Energy Efficiency Opportunities program (2007) put the focus on energy – since then…
  - SA Water now the national leader in energy benchmarking work
  - extensive energy benchmarking of wastewater treatment plants since 2010 → many efficiency improvements identified to date
  - significant investment in energy 'sub-metering' infrastructure
    …can manage only what you measure
- AWRCoE Fellowship project to extend prior wastewater benchmarking work to recycled water

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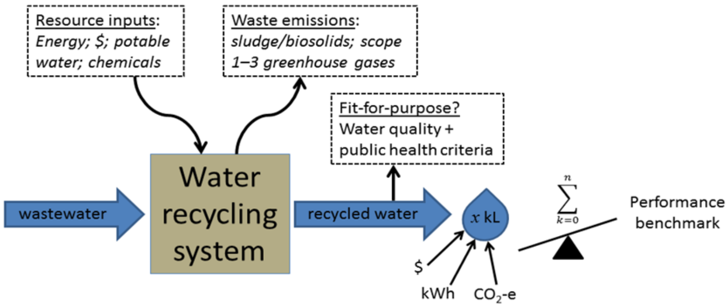
Sustainable benchmarking Fellowship project

- Several key Objectives:
  1. Develop holistic recycled water benchmarking methodology, integrating public health, energy and environmental (GHG) criteria



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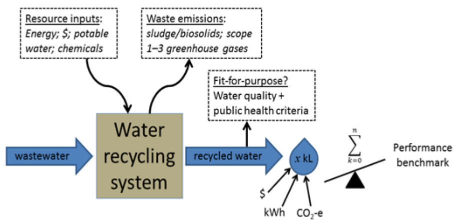
Sustainable benchmarking Fellowship project

- Several key Objectives:
  1. Develop holistic recycled water benchmarking methodology, integrating public health, energy and environmental (GHG) criteria

Different recycled water end-uses demand different performance metrics (i.e. kWh/kL, kWh/LRV, CO_2-e/kL...); fairer performance comparisons with common system denominators (take better account of differing system configurations..?)



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Sustainable benchmarking Fellowship project

- Several key Objectives:
  1. Develop holistic recycled water benchmarking methodology, integrating public health, energy and environmental (GHG) criteria
  2. Apply methodology to full-scale case study water recycling systems
  3. Establish ‘best practise’ energy benchmarks for Australian water recycling operations
- SA Water operates several water recycling systems (Glenelg, Christies Beach, Bolivar)
  - initial focus on Glenelg recycling plant

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Glenelg–Adelaide Recycled Water Scheme (GARWS)

- $76 million Scheme commissioned Dec 2009
- 3.8 GL/yr high quality Class A recycled water
- Offset traditional potable supply for parklands / CBD irrigation
- Divert 50 t/yr N emissions to Gulf St Vincent (seagrass + EPA = ☺)

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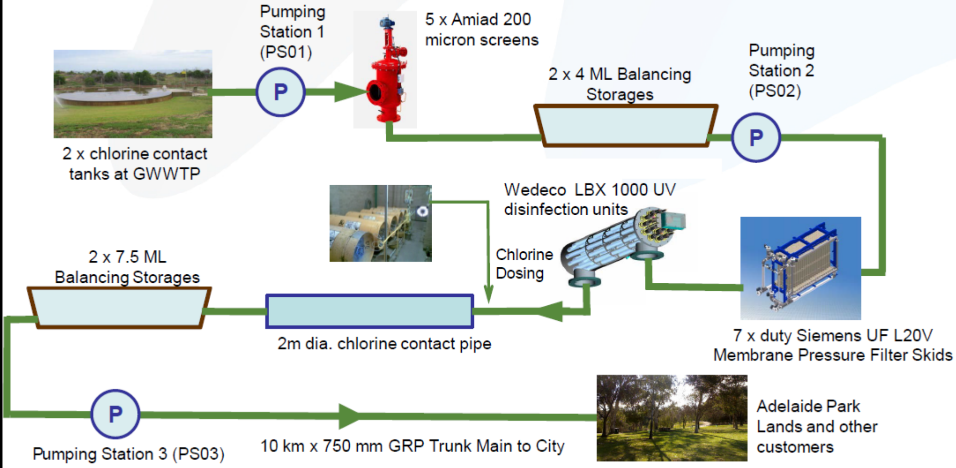

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Glenelg–Adelaide Recycled Water Scheme (GARWS)

Glenelg–Adelaide Recycled Water Scheme (GARWS)

- Plant-wide energy data analysed from 2010–present
- Strong seasonal (flow) trends in specific energy use (kWh/kL)

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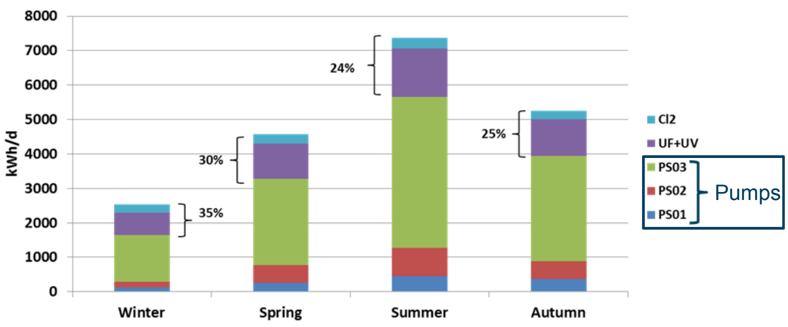
Glenelg–Adelaide Recycled Water Scheme (GARWS)

- Pumping dominates (65–70% winter–spring; >75% summer–autumn)
- Recycling plant optimisation opportunities relatively greater under low flow conditions (plant operating furthest from max. design flow)



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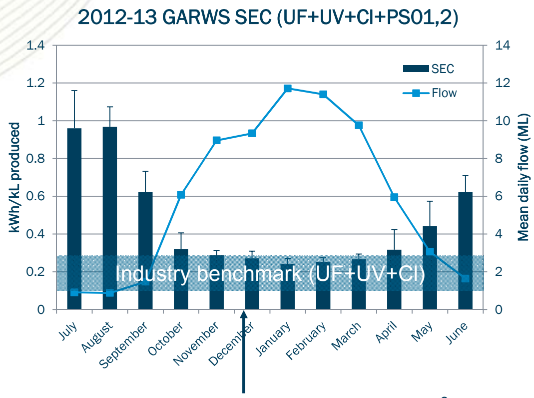
GARWS energy profile 2012-13 example



UV setpoint change (54→15 mJ/cm²) – no change in SEC – what's going on?

- July-Aug 2012 = 1 ML/d avg. ($170/ML energy cost)
- Jan-Feb 2013 = 13 ML/d avg. ($45/ML energy cost)

→ 'economies of scale' effects (V8 with 1 vs. 5 passengers)

→ better energy efficiency per unit vol. at high flow rates

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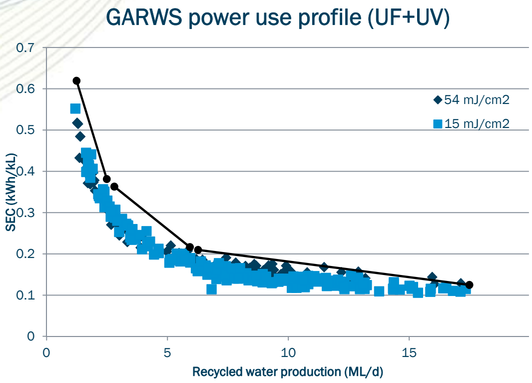
GARWS UF+UV power use pre- & post-setpoint change



- Volumetric efficiency 'bands' (reflects literature trends)
- No measurable change in SEC post UV setpoint change..?
- UV ballast power already at 50% (max. turndown)

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GARWS benchmarking outcomes

- Plant was designed to produce a certain recycled water quality based on the influent (wastewater) quality of the day…
  - since design, changes in Glenelg WWTP operations led to improved effluent quality (design UVT 50% → today 65–70%)
  - UV system unnecessarily over-dosing (= energy $)
  - ballast already de-powered; identified UV turndown / shutdown without impacting recycled water quality (= energy $ savings)
- Economies of scale effects may inform plant production schedules
  - operate close to max. rated flow; run plant less often at higher flows during non-peak periods (15 ML balance storage constraints…)
- Distribution network supply pressure
  - CBD customers want better sprinkler flows, but at what cost..?

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Benchmarking – key points

- Critical to compare apples with apples (or at least with Nashi pears)
  - need relevant performance benchmarks (similar unit process & size)
  - Fellowship work critically reviewed international literature and produced range of energy performance data / benchmarks for various water recycling technologies/ system configurations – world first)
  - unfair system comparisons may yield unrealistic/unattainably strict energy benchmarks (or *vice versa* will set the efficiency bar too low)
  - small differences in water recycling process configurations and size can dramatically alter specific energy use profile (strong flow vs. SEC association – economies of scale)
- Significant energy savings can be realised simply by collecting / looking at the data
  - logical, but industry only just beginning to appreciate this

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Future extensions / questions

- What are the impacts of future centralised energy supply/grid mix on recycled water impacts/costs (e.g., under 80–100% renewables grid mix in 2030, what does this mean for economic/ energy/ environmental performance of recycled water systems?)
  - scenario modelling useful here
  - chemicals may be the primary factor in environmental performance
  - WWTPs will be offsetting more energy in future – impacts?
- If we suggest changes to water recycling operations in pursuit of energy optimisation, what are labour/capital depreciation impacts
  - need to ensure we're realising net benefits rather than optimising energy efficiency at the expense of other business areas
- Economics of recycled water supply will remain paramount
  - Recent SEQ water recycling rollbacks cost-driven (while the dam's full)
  - holistic economic evaluation methods needed (recent progress…)

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Reflections on the Centre Fellowship

- Unique opportunity for 'fly-on-the-wall' access to water utility
- Invaluable water industry perspective to university-based research
- Forged new and strengthened existing relationships with water industry personnel (SA and beyond)
- Room with a view!

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Acknowledgements

- Australian Water Recycling Centre of Excellence
- SA Water
- UniSA (CWMR)
- UNSW

UniSA   Government of South Australia   SA Water   UNSW THE UNIVERSITY OF NEW SOUTH WALES

7.7 **Appendix G:** Details of presentations given during the course of the Fellowship (continued…)

9. Presentation given at the annual SA Water Research & Innovation Forum (25 September 2014, Adelaide Oval – Ian McLachlan Room) regarding the outcomes of the Fellowship project. The presentation was attended by around 100 water industry professionals, consultants and academics.

Benchmarking the Energy–Health nexus for efficient water recycling

Michael Short, Rudi Regel,
Ben van den Akker

Friday, 26 September 2014

Research context – *Centre Fellowship*

- 12 month Fellowship exchange through the AWRCoE
- Get academics into industry (& *vice versa*) to foster ideas exchange and long-term Industry–Academic collaborations
- One of three 'Centre Fellowships' offered to date
  - unique personal opportunity for access / insights into water industry practice / perspectives
  - embedded in day-to-day operations of research-active utility
  - new relationships forged and strengthened existing ones with water industry personnel

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Water recycling refresher…

- Commonplace today (inter)nationally as part of balanced and secure ‘climate-independent’ water supply portfolio
- Various configurations (wastewater & technology type) and recycled water qualities – ‘fit for purpose’ is the main aim
- Many end-uses for recycled water, broadly:
  - domestic/industrial reuse; irrigation; environmental flows; groundwater recharge/ASR; (in)direct potable reuse
- Quick water recycling overview…

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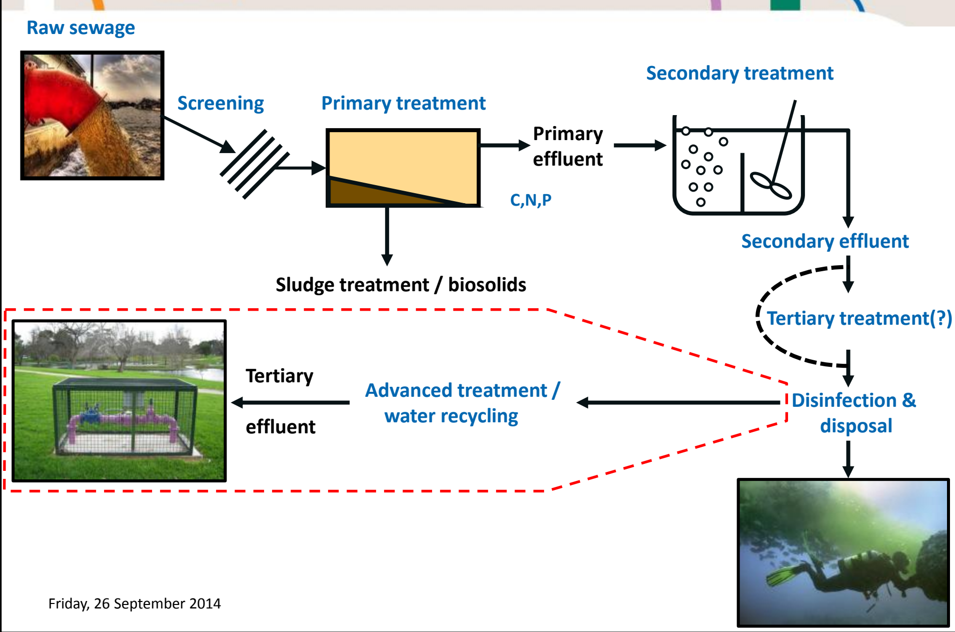

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Water recycling – current state of play

- Lots of progress in recycling during past 20+ years, but still lots of room for expansion…
  - AU ≈10% of urban water is recycled in origin (Spies and Dandy, 2012)
  - US <1% total national water use is recycled water (Cushing et al., 2014)
- SA is the national leader: ≈33% of metropolitan Adelaide's wastewater recycled in 2012–13
  - 75/15/10% Bolivar/Christies Beach/Glenelg WWTPs
  - vast majority of recycled water for irrigation end-uses

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SA Water

Water recycling – a trade-off

- Water recycling plays a valuable role in water security & resource recovery, but can be relatively energy-intensive
  - <0.5 to >1.5 kWh/kL depending on scale/process config./end-use
  - trade-off between supply security & resource/energy demands

Water source	Specific energy consumption (kWh/kL)
Conventional surface	0.3–0.6
River Murray (pump + treat)	1.9
Rainwater	1.0–1.6
Stormwater	0.8
Recycled wastewater	**<1.0–1.8**
Desalinated seawater	3.5–5.0

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Towards true *fit for purpose* recycling

- Recognised need to provide 'fit for purpose' recycled water at least cost (energy, economic, environmental)
- Labour costs dominate economics of recycling operations (≈50%), but energy is also significant (≈15–30%)
- Lots of scope for optimisation for energy savings, but first need to *benchmark* current performance

Energy benchmarking – the what, how & why

- Process of measuring current energy performance and comparing it with other similar processes/industry standards
  - *Can manage only what you measure*; ISO50001:2011 EMS
  - Best done at process level (sub-metering)
- Why benchmark?
  - Identify operational inefficiencies, prioritise future optimisation efforts
  - Helps you pick low-hanging energy fruit first
  - Energy savings can deliver rapid RoI/payback times (months to years)
  - Provides data 'baseline' for future improvements; helps identify data gaps in operational monitoring (→sub-metering)
  - Promote organisational optimisation and efficiency 'culture'

Energy benchmarking at SA Water

- *Energy Efficiency Opportunities* program put the focus on energy since 2006–07 FY (EEO Act 2006 – repealed)
  - Identify/implement cost-effective EEOs and improve energy management systems (≈14 GWh of savings identified in first cycle)
  - EEO key initiative in delivering SA Water's Strategic Plan 2012–16 across three of the four strategic priorities (*Quality and Delivery*, *Business Success* and *Planning for the Future*)
- SA Water has led the way in energy benchmarking nationally
  - extensive benchmarking of WWTPs since 2010 → many efficiency improvements identified/implemented so far
  - significant investment in energy sub-metering (SCADA)

SA Water Networked SCADA System

Christies Beach WWTP - Power Monitoring Status

To Main Menu	Switchboard/Tag Description		Current Actual kW	Current Hour Average	Current Day Average	Current Month Daily Average	Previous Month Daily Average
Supply							
ETSA Supply 1 - Port Stanvac	C02HVSB01		995 kW	950 kWh/h	28,898 kWh/d	26,310 kWh/d	29,366 kWh/d
ETSA Supply 2 - Port Noarlunga	C02HVSB02		0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d
Consumption							
Inlet Works (from C02LVSB03)	C10MCC01A	Power Monitor	0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d
Inlet Works (from C02LVSB02)	C10MCC01B	Power Monitor	90 kW	86 kWh/h	2,051 kWh/d	2,082 kWh/d	2,061 kWh/d
Primary Sedimentation Tanks	C20MCC01	Power Monitor	3 kW	3 kWh/h	38 kWh/d	32 kWh/d	36 kWh/d
A/B Plant Activated Sludge Reactors	C30MCC01	Power Monitor	0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d
A Plant Clarifiers	C40MCC01	Power Monitor	8.5 kW	9 kWh/h	539 kWh/d	373 kWh/d	719 kWh/d
B Plant Clarifiers	C40MCC02	Power Monitor	7.5 kW	9 kWh/h	237 kWh/d	234 kWh/d	221 kWh/d
A/B Plant Aeration Blowers	C30BL11/12/13		152 kW	155 kWh/h	3,654 kWh/d	3,681 kWh/d	4,102 kWh/d
C1 Plant Activated Sludge Reactors	C30MCC04	Power Monitor	58 kW	59 kWh/h	1,418 kWh/d	1,569 kWh/d	1,467 kWh/d
C2 Plant Activated Sludge Reactors	C30MCC05	Power Monitor	1 kW	1 kWh/h	14 kWh/d	20 kWh/d	17 kWh/d
C Plant Aeration Blowers	C30BL21/22/23/24		198 kW	199 kWh/h	4,968 kWh/d	4,650 kWh/d	4,280 kWh/d
C Plant Membrane MCC 1	C120MCC01	Power Monitor	4 kW	4 kWh/h	102 kWh/d	182 kWh/d	153 kWh/d
C Plant Membrane MCC 2	C120MCC02	Power Monitor	7 kW	8 kWh/h	171 kWh/d	166 kWh/d	155 kWh/d
C Plant Membrane Air Scour Blowers	C30BL31/32/33/34		213 kW	215 kWh/h	4,901 kWh/d	5,527 kWh/d	4,864 kWh/d
C Plant General	C93MCC01	Power Monitor	100 kW	76 kWh/h	1,573 kWh/d	1,866 kWh/d	1,608 kWh/d
Blower Building Services (Aeration Control)	C30MCC03	Power Monitor	32 kW	22 kWh/h	524 kWh/d	550 kWh/d	519 kWh/d
C Plant UV Disinfection	C92LCP01	Power Monitor	90 kW	89 kWh/h	1,647 kWh/d	1,897 kWh/d	1,762 kWh/d
Dissolved Air Floatation Thickener	C50MCC01	Power Monitor	47 kW	47 kWh/h	671 kWh/d	789 kWh/d	668 kWh/d
Mechanical Sludge Hydrolysis	C101LCP01		0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d
Digester 1 & 2	C80MCC01	Power Monitor	59 kW	62 kWh/h	1,503 kWh/d	1,171 kWh/d	1,521 kWh/d
Digester 3	C80MCC02	Power Monitor	58 kW	56 kWh/h	1,345 kWh/d	1,517 kWh/d	1,347 kWh/d
Sludge Dewatering	C110MCC01	Power Monitor	17 kW	16 kWh/h	364 kWh/d	343 kWh/d	302 kWh/d
Power Generation Building	C03MCC01	Power Monitor	13 kW	13 kWh/h	256 kWh/d	264 kWh/d	291 kWh/d
Distribution							
A/B Plant	C02LVSB01A	Power Monitor	0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d
	C02LVSB01B	Power Monitor	99 kW	106 kWh/h	5,527 kWh/d	3,622 kWh/d	4,744 kWh/d
Blower Building	C02LVSB02A	Power Monitor	0 kW	0 kWh/h	0 kWh/d	0 kWh/d	1,873 kWh/d
	C02LVSB02B	Power Monitor	911 kW	882 kWh/h	20,180 kWh/d	21,607 kWh/d	18,686 kWh/d
Sludge Dewatering Building	C02LVSB03A	Power Monitor	0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d
	C02LVSB03B	Power Monitor	168 kW	166 kWh/h	2,956 kWh/d	3,194 kWh/d	2,848 kWh/d
Generation							
Digester Gas Engine	C03GN01		318 kW	315 kWh/h	194 kWh/d	4,008 kWh/d	140 kWh/d
A/B Plant Diesel Genset	C03GN03		0 kW	0 kWh/h	0 kWh/d	2 kWh/d	6 kWh/d
Blower Building Diesel Genset 1	C03GN04		0 kW	0 kWh/h	0 kWh/d	0 kWh/d	26 kWh/d
Blower Building Diesel Genset 2	C03GN05		0 kW	0 kWh/h	0 kWh/d	0 kWh/d	0 kWh/d

Energy benchmarking at SA Water

- Previous benchmarking work excluded recycling operations
  - Wastewater treatment energy >>>> recycling energy
  - Lack of available performance benchmarks for recycling processes
- Wastewater benchmarking approach irrelevant to recycling
  - Wastewater treatment for C,N,P removal & environmental health protection; recycling for pathogen removal & public health protection
  - Invalid performance metrics (kWh/PE_{BOD60}/y; kWh/PE_{COD120}/y)
  - Specific energy consumption (kWh/kL) relevant, but misses the key underlying public health dimension of recycling operations (pathogen log reduction values (LRVs) – viruses, bacteria, protozoa (V,P,B))

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Recycled water benchmarking – gaps & needs

- Lack of consolidated performance benchmarks

  → New energy benchmarks needed for recycling processes
- No suitable method for integrated performance benchmarking

  → New approach needed to integrate energy & public health performance metrics for recycling systems

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Project overview

- Extensive literature review to inform benchmark development
- Three case study recycling schemes targeted for ‘energy–health’ benchmarking
  - Glenelg; Aldinga; Christies Beach
  - Process-level benchmarking at each site:
    - pumping (feed, backwash, distribution)
    - screening / filtration
    - process aeration / scouring
    - UV, chlorination
    - building / HVAC

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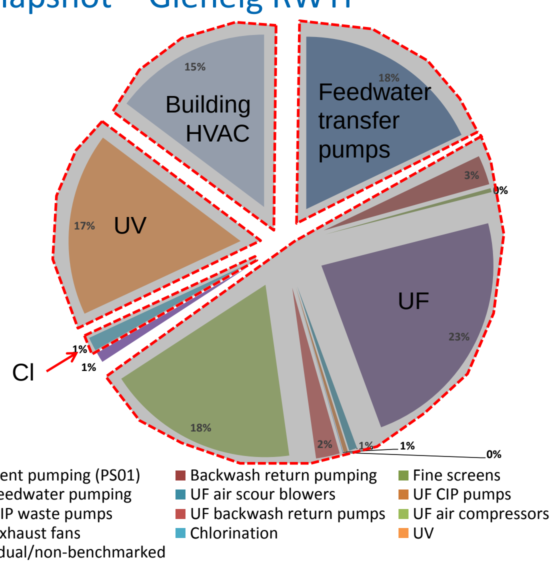
Results snapshot – Glenelg RWTP



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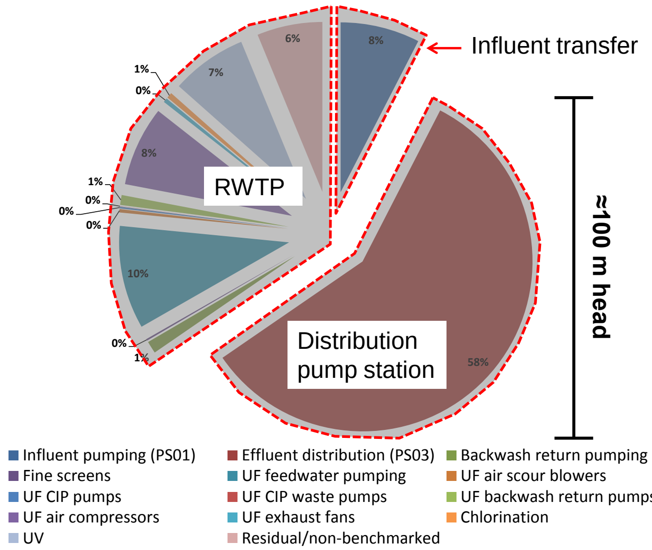
Results snapshot – Glenelg RWTP + effluent pumping



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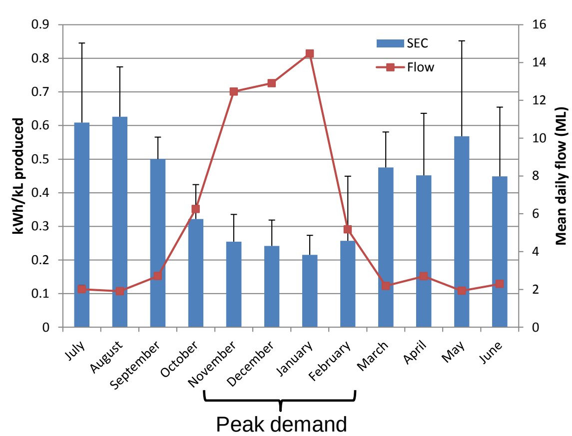
Results snapshot – Glenelg RWTP

- Strong seasonality in energy performance (well established)
  - on–off vs. continuous operation; volumetric loading vs. fixed energy req.



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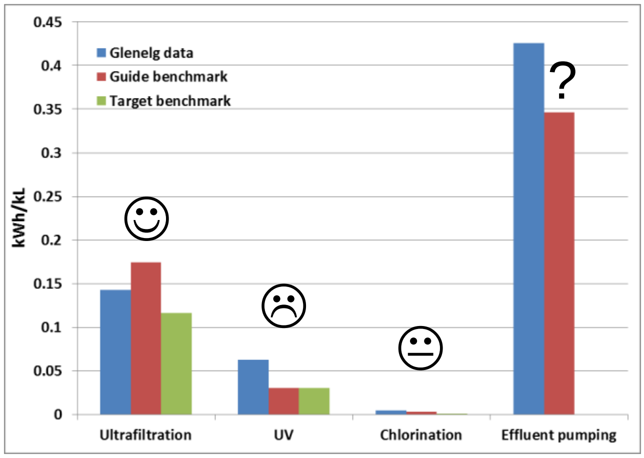
Results snapshot – benchmarking Glenelg RWTP



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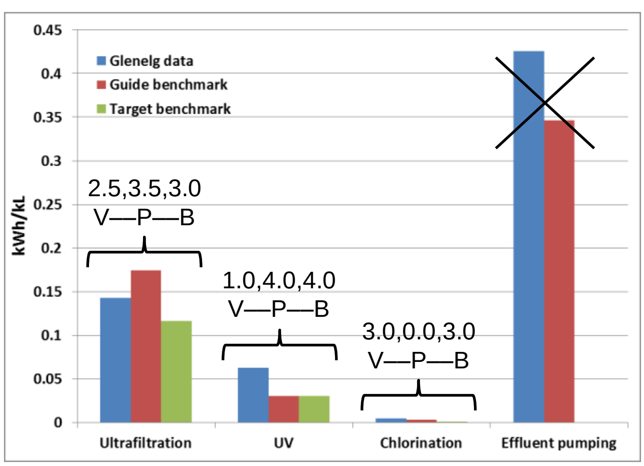
Results snapshot – benchmarking Glenelg RWTP



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Energy–health benchmarking: let's look at UV…

- Glenelg UV system by design:
  - UV dose ≥50 mJ/cm^2 @ UVT ≥50% (× 2 reactors/train @ 25 mJ/cm^2 ea.)
  - 1.0 LRV for viruses, 4.0 LRV for protozoa, 4.0 LRV for bacteria
  - scheme LRVs 7.5–8.0–11.0 for V–P–B (need 6.5–5.0–5.0 for dual retic.)
- Upstream WWTP process change since increased UVT ≈69%
  - UV system exceeding required RED (>>50 mJ/cm^2; >>25 mJ/cm^2 ea.)
  - lamp ballast power at a min. (50%), therefore can't depower further
- Ok, so what if we reduce UV dose 5-fold to 10mJ/cm^2?
  - zero LRV for V, 3.0 LRV for P & B, but still meets dual retic. LRVs ☺
  - 50% power saving (1 reactor/train only) + O&M savings
  - options to bolster virus LRV if required (0.5 $\log_{10}$ for cross-connections management/BFP devices; conservative virus inactivation credits for Cl)

Getting maximum value from the recycling *Guidelines*

- The *AGWR* provide unique opportunities for tailoring/ optimising recycling systems to achieve energy efficiency
  - value of process 'barrier' LRV validation becomes clear, as does the value of on-site preventive measures for end-uses (hard vs. soft controls)
  - risk-based design for recycling systems (bottom-up vs. top-down [*E. coli*])
  - Netherlands only other country to have adopted full QMRA-based guidelines for public health regulation of recycled water schemes
- Real potential in *AGWR* for optimising recycling operations, but utilities must be closely engaged with state health regulators
  - minor RWTP process changes require health approval unlike equivalent WWTP process changes – EPA consultation for **major** changes

Water recycling – challenges & future directions

- Seasonality in operations creates optimisation challenges
  - fixed energy costs more difficult to control (HVAC/standby power draw)
  - find more off-peak customers (easier said than done)
- New performance metric for energy–health benchmarking
  - kWh/$\log_{10(V,P,B)}$ for recycling process 'barriers'?
- Benchmarking of MBRs is a grey area
  - where does the WWTP stop and the RWTP begin?
  - energy allocation based on BOD/N removal or pathogen LRVs (or both)?
- Energy offsetting/crediting for recycled water
  - Glenelg recycled displaces River Murray water = −1.0 kWh/kL
  - recycled water displaces desalinated supply, effective energy credit to recycled supply (approx. −3 kWh/kL) → opportunity cost?

Water recycling – challenges & future directions…

- Need for fit for purpose recycling by design
  - reduce need for benchmarking and post-optimisation; more emphasis on staged design approach rather than building for ultimate capacity
  - need to minimise costly end-point monitoring (QMRA-based *Guidelines* should ultimately support this)
- Landscape and goalposts are constantly shifting
  - climate alters emphasis on recycling (La Niña vs. El Niño)
  - economics always key (Pimpama RWTP decommissioned Jan 2017 on economic grounds; monetising externalities remains a challenge)
- Chemicals are next in line after electricity in terms of embodied energy/environmental impacts from recycling operations
  - less interesting without C pricing mechanism..?
  - gratuitous plug for ARC LP

Acknowledgements

- This study was co-funded by the Australian Water Recycling Centre of Excellence and UniSA
- SA Water (Nick Swain; Nirmala Dinesh; Grant Lewis; Mike O'B)
- Jörg Krampe (SAW / TUW)
- UniSA – Centre for Water Management and Reuse (Chris Saint)

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