

Life-cycle energy impacts for adapting an urban water supply system to droughts



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ABSTRACT

In recent years, cities in some water stressed regions have explored alternative water sources such as seawater desalination and potable water recycling in spite of concerns over increasing energy consumption. In this study, we evaluate the current and future life-cycle energy impacts of four alternative water supply strategies introduced during a decade-long drought in South East Queensland (SEQ), Australia. These strategies were: seawater desalination, indirect potable water recycling, network integration, and rainwater tanks. Our work highlights the energy burden of alternative water supply strategies which added approximately 24% life-cycle energy use to the existing supply system (with surface water sources) in SEQ even for a current post-drought low utilisation status. Over half of this additional life-cycle energy use was from the centralised alternative supply strategies. Rainwater tanks contributed an estimated 3% to regional water supply, but added over 10% life-cycle energy use to the existing system. In the future scenario analysis, we compare the life-cycle energy use between “Normal”, “Dry”, “High water demand” and “Design capacity” scenarios. In the “Normal” scenario, a long-term low utilisation of the desalination system and the water recycling system has greatly reduced the energy burden of these centralised strategies to only 13%. In contrast, higher utilisation in the unlikely “Dry” and “Design capacity” scenarios add 86% and 140% to life-cycle energy use of the existing system respectively. In the “High water demand” scenario, a 20% increase in per capita water use over 20 years “consumes” more energy than is used by the four alternative strategies in the “Normal” scenario. This research provides insight for developing more realistic long-term scenarios to evaluate and compare life-cycle energy impacts of drought-adaptation infrastructure and regional decentralised water sources. Scenario building for life-cycle assessments of water supply systems should consider i) climate variability and, therefore, infrastructure utilisation rate, ii) potential under-utilisation for both installed centralised and decentralised sources, and iii) the potential energy penalty for operating infrastructure well below its design capacity (e.g., the operational energy intensity of the desalination system is three times higher at low utilisation rates). This study illustrates that evaluating the life-cycle energy use and intensity of these type of supply sources without considering their realistic long-term operating scenario(s) can potentially distort and overemphasise their energy implications. To other water stressed regions, this work shows that managing long-term water demand is also important, in addition to acknowledging the energy-intensive nature of some alternative water sources.

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1. Introduction

Many regions have faced serious water stress in recent years, including southeast Australia (Van Dijk et al., 2013) and southwest United States (Prein et al., 2016). Some cities in these regions

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explored and introduced alternative water sources to cope with their water crises (Aghakouchak et al., 2014). These water sources include seawater desalination, potable water recycling, inter-basin water transfers, and decentralised water sources. Most new sources are more energy intensive than conventional water sources (Rothausen and Conway, 2011; Wakeel et al., 2016), and have significantly increased the long-term energy footprint of some water supply systems (Lam et al., 2016; Li et al., 2016).

South East Queensland (SEQ) in Australia, for example, experienced a decade-long drought, known as the Millennium Drought (Van Dijk et al., 2013). The drought was most profound between 2001 and 2009 with the average annual inflow to the major reservoirs less than 20% of the long-term average (Water Services Association of Australia, 2013). A wide range of supply-side and demand-side responses were used to cope with the drought (Head, 2014). On the supply-side, there were four major strategies – i) building a seawater desalination plant, ii) constructing an indirect potable water recycling system, iii) connecting four distinct water supply networks with three bulk water transfer pipelines, and iv) promoting a large-scale uptake of residential rainwater tanks. On the demand-side, strategies such as outdoor water restrictions, water-efficient appliance rebate programs and water conservation educational campaigns were employed.

Prior research in SEQ has examined the energy impacts of some of these supply-side changes. Poussade et al. (2011) quantified the life-cycle energy impact of some parts of the newly commissioned desalination system and indirect potable water recycling system. Hall et al. (2011) performed a future scenario analysis based on a water strategy set out during the drought. Lane et al. (2015) conducted a detailed life-cycle assessment of a subset of the SEQ urban water system. These studies were based on empirical data and information available during the drought. More recently, Kenway et al. (2015) conducted a systemic analysis of water-related energy use in SEQ and Lam et al. (2016) quantified the direct energy use of the SEQ's water supply system through and after the drought.

Building on these earlier efforts, this paper addresses two gaps in literature concerning life-cycle energy implications of alternative water sources based on the post-drought SEQ context and new empirical data. First, previous studies typically defined and compared scenarios assuming a high utilisation of specific alternative water sources (Hall et al., 2011; Lane et al., 2015; Lundie et al., 2004; Mo et al., 2014; Shrestha et al., 2011), not accounting for possible influence of climate/water variability on operations over a long assessment period. While an “upper bound” scenario can capture the maximum impact of using a specific alternative water source, more realistic scenarios should also be evaluated to understand the more likely long-term energy impacts on urban water systems. For instance, most new desalination plants in Spain were idle as of 2012 (March et al., 2014) and only two out of the six desalination plants built in Australia during or shortly after the drought were still in high utilisation as of 2016 (Turner et al., 2016).

Further, limited research has been conducted on regional life-cycle energy impacts of a large-scale uptake of rainwater tanks. Previous studies focused predominantly on evaluating single rainwater harvesting systems (Cook et al., 2013; Devkota et al., 2013; Racoviceanu and Karney, 2010) without examining how these individual results would scale in a regional evaluation. In addition, few studies compare the regional life-cycle energy use of decentralised systems (i.e., typically rainwater harvesting in SEQ) with that of the centralised systems. It is important to understand how much they can contribute to the overall energy use of urban water supply systems. Decentralised systems have gained popularity in recent years and a number of empirical studies have found that rainwater harvesting systems are more energy intensive than conventional centralised water supply systems, e.g., (Vieira et al.,

2014). The rapid implementation of rainwater harvesting in SEQ provides a wealth of empirical data to explore these two aspects.

This work presents a life-cycle energy assessment of the urban water supply system in SEQ. The goal is to assess the relative life-cycle energy impacts of the four alternative water supply strategies introduced during the drought. Current post-drought and future energy impacts of the strategies under various utilisation and water demand scenarios are quantified. This study provides insight for developing more realistic scenarios to evaluate the life-cycle energy impacts of drought-adaptation centralised water supply sources and regional decentralised water sources. The discussion focusing on the experience in SEQ is highly relevant to other water-stressed regions where they may be exploring future alternative water supply strategies to cope with supply constraints (e.g., drought) or increasing water demand.

2. Case study background

South East Queensland (SEQ), where the Queensland state capital Brisbane is situated, is an urbanised region on the eastern coast of Australia. It has more than 60% of the state's population. Its traditional water source is surface water from major reservoirs such as Lake Wivenhoe, Lake Samsonvale and Advancetown Lake. Its water supply system was designed to have a high carry-over capacity (i.e., the total storage capacity was estimated to be over six times the annual urban water demand (Marsden and Pickering, 2006)). Between 2001 and 2009, the region experienced its longest recorded continuous period with below average rainfall (more than 80% lower than the long-term average). The unprecedented low catchment inflows led to a water crisis. These pre-drought surface water supplies are referred to as the conventional supplies. In response to the drought, four water-supply strategies were introduced to the regional water supply systems to augment the supply (Turner et al., 2016).

Firstly, three bi-directional bulk water transfer pipelines were built to connect four previously segregated water supply networks. The Southern Regional Water Pipeline connects the Greater Brisbane system to the Gold Coast system; the Northern Pipeline Interconnector connects the Greater Brisbane system to the Sunshine Coast system; and the Eastern Pipeline Interconnector connects the Brisbane-Logan system to the Redland system. Forming a bulk water supply network improved regional water supply flexibility and was estimated to increase the overall regional water supply system yield by 14% compared to the pre-drought system prior to integration (Queensland Water Commission, 2010).

Secondly, a 125 ML/day capacity reverse osmosis seawater desalination plant (the Gold Coast Desalination Plant) and a 25 km product water pipeline were built. The potable effluent is fed into the Gold Coast system and can be transferred to the other parts of the SEQ system through the newly-built Southern Regional Water Pipeline. In 2010, the desalination system had the potential to increase the system yield by approximately 9% (Queensland Water Commission, 2010).

Thirdly, a 232 ML/day capacity indirect potable water recycling system (the Western Corridor Recycled Water Scheme) was built. The system includes three advanced wastewater treatment plants and over 200 km of bulk water pipelines. The system provides recycled water treated to potable water quality standards, well beyond what is necessary for the cooling purposes, to two major power plants in the region which were drawing water from drinking water supplies during the drought. It also can feed the highly-treated potable recycled water into Lake Wivenhoe (the major reservoir in SEQ). However, due to easing of the drought and political pressure, this indirect potable water use option has not been implemented. In 2010, the water recycling system had the

Table 1
Summary data for water balances in South East Queensland.

Component	Year	Volume (ML/year)				Source
		“Normal” scenario	“Dry” scenario	“High water demand” scenario	“Design capacity” scenario	
Urban water demand ^a	2014	295,877	295,877	295,877	295,877	(Bureau of Meteorology, 2016)
	2023	364,000	332,000	437,000	357,000	DSSO model (Section 3.3)
	2033	422,000	385,000	506,000	415,000	DSSO model (Section 3.3)
Centralised water sources						
Conventional sources ^b	2014	293,160	293,160	293,160	293,160	(Bureau of Meteorology, 2016)
	2015–2033 ^d	364,000	261,000	426,000	230,000	DSSO model (Section 3.3)
Desalinated water	2014	1,435	1,435	1,435	1,435	(Bureau of Meteorology, 2016)
	2015–2033 ^d	1,435	29,800	8,000	45,000	DSSO model (Section 3.3)
Potable recycled water	2014	1,282	1,282	1,282	1,282	(Bureau of Meteorology, 2016)
	2015–2033 ^d	1,282	43,400	5,400	84,000	DSSO model (Section 3.3)
Additional water transfers						
Bulk water transfer pipelines: NPI, EPI and SRWP ^c	2014	22,053	22,053	22,053	22,053	Operation data from utility
	2015–2033 ^d	18,000	14,900	22,300	18,000	DSSO model (Section 3.3)
Decentralised water sources						
New rainwater tanks	2014	8,100	8,100	8,100	8,100	See Section 3.2
	2015–2033 ^d	8,100	6,400	9,700	15,200	See Section 3.2

^a This is the urban water demand from the centralised water supply system managed by Seqwater. See Table 3 for details.

^b The conventional supply is predominantly sourced from surface water, with less than 5% groundwater supply.

^c The bulk water transfer pipelines convey water across different sub-systems of the wider water supply system in SEQ (e.g. transferring water from the Gold Coast system to the Greater Brisbane system).

^d The volumetric throughputs shown are the annual averages over the period. The annual throughputs vary from year to year, unless assumed to be steady (Table 3).

potential to increase the system yield by approximately 16% (Queensland Water Commission, 2010).

Lastly, over 250,000 new rainwater tanks were installed between 2006 and 2008 through the Home WaterWise Rebate Scheme (Walton and Holmes, 2009). The tanks were required to be 3,000 L or greater in size to fulfil the rebate requirement. In addition, the Queensland Development Code Mandatory Part 4.2, introduced in 2007 and enforced until late-2012, requires any new Class 1 building (including single dwellings) development to have higher water efficiency (Siems and Sahin, 2016). One way to meet the requirement is to install an internally-plumbed rainwater tank of at least 5,000 L capacity. As a result of both measures, the percentage of households considered suitable for installation (which mostly include separate, semi-detached, terrace or town houses) that own a rainwater tank increased from 18.4% (2007) to 47% (2013) in Brisbane (Australian Bureau of Statistics, 2013).

The drought ended with a return of more normal rainfall patterns in 2009. Between 2010 and 2011, reservoir elevations returned to the pre-drought levels, and both the desalination system and the recycled water system were placed in “standby” mode. Since 2014, the desalination plant has been operated at its minimum throughput while the potable water recycling system was expected to remain idle for the next decade (Seqwater, 2013). The drought has led to significant reforms in the regional urban water management. After the drought, the regional water supply system, comprised of all of these supplies, is managed by one bulk water supplier (Seqwater) and five water distributors.

3. Methods

3.1. Scope of study

This study conducted a life-cycle energy assessment on the urban water supply system in SEQ with a focus on the four alternative supply strategies introduced during the Millennium Drought. The study is divided into two parts. In the first part, the current post-drought life-cycle energy use of the system was quantified based on the operation status of the system in the 2013–14 fiscal year (referred to as 2014 throughout). That year was chosen for study

because the actual water balance and operation data are available, and the water demand is representative of the post-drought volume. In the second part, future scenario modelling was utilised to quantify the potential long-term average life-cycle energy use of the system between 2014 and 2033 under four different scenarios. The future water balances under different scenarios were simulated from a utility's water balance model (Section 3.3). The regional water yield from rainwater tanks was estimated from a local rainwater tank study and water use surveys (Section 3.2). The water balances form the basis for the energy assessment (Table 1).

This life-cycle energy assessment of the SEQ water supply system considers the direct and indirect energy use in the construction phase and the operation phase of five system components - the conventional system as well as the four alternative water supply strategies. The conventional system includes necessary conveyance infrastructure, water treatment plants and water distribution networks. Table 2 gives an overview of the key components included in the inventory and data sources. Detailed inventories can be found in the Supplementary Material. All energy results are in terms of primary energy and account for energy losses in conversion and transmission.

For the construction phase, the infrastructure specifications of the conventional system and the three new centralised system strategies were based mostly on utility, government and material supplier documents listed in the Supplementary Material. Data gaps were filled using previously published literature (Lane et al., 2015). The results for the construction phase were annualised based on the assumed lifespans. For the operation phase, data were obtained directly from Seqwater (the bulk water agency in SEQ) or from local studies based on data from operators. Data for second-order inventories (e.g., electricity supply, material supply, material transportation) were based predominantly on the Australasian LCI database (lifecycles, 2015) which adapted Ecoinvent data (Hischier and Weidema, 2010) to the Australian context, unless noted in Table 2. The regional estimation of the current rainwater tank usage in SEQ was based on a national water survey (Australian Bureau of Statistics, 2013) and a detailed rainwater tank study in SEQ (Siems and Sahin, 2016). The estimation is detailed in Section 3.2 and the Supplementary Material.

Table 2
Key inventory included and data sources.

Component	Construction phase ^{a, b}	Operation phase ^a
Conventional system	Water supply network ^c ; Water treatment plants ^d	Electricity use for raw water abstraction, water treatment ^e and water distribution (Lam et al., 2016); Chemical use ^e
Seawater desalination system	Desalination plant ^d ; Product water pipeline ^d	Electricity use for raw water abstraction, water treatment and water distribution ^e ; Chemical use (Lane et al., 2015)
Water recycling system	Three advanced wastewater treatment plants ^d ; Feed water pipelines ^d ; Product water pipelines ^d	Electricity use for raw water pumping, water treatment and water distribution (Poussade et al., 2011); Chemical use (Lane et al., 2015)
Rainwater tanks ^f	New tanks; Small pumps; Plumbing adjustment	Electricity use (Siems and Sahin, 2016); Tank water usage (Siems and Sahin, 2016); Percentage of tanks in use (Australian Bureau of Statistics, 2013); Percentage of internally-plumbed tanks (Australian Bureau of Statistics, 2013)

^a Assumed 100 km distance for all material transportation, unless specific data are available. Energy use estimated from Australasian LCI database (lifecycles, 2015).

^b Considered excavation work. Energy use estimated from Stokes and Horvath (2010).

^c Based on the length of water mains in SEQ in 2013–14. Energy use scaled from the Gold Coast system (Lane et al., 2015).

^d Specifications from utility, government and/or material supplier documents. See the Supplementary Material.

^e Measured operations data provided by the infrastructure operators.

^f The regional estimation of new rainwater tanks installation and operation status is based on several key references (Australian Bureau of Statistics, 2013; Moglia et al., 2014; Siems and Sahin, 2016; Walton and Holmes, 2009). The detailed description of the estimation can be found in Section 3.2.

3.2. Rainwater tanks

This study quantified the number of new rainwater tanks being installed in SEQ in response to two government strategies introduced during the drought – Home WaterWise Rebate Scheme and Queensland Development Code Mandatory Part 4.2. The total number of new tanks (at least 3,000 L) that were rebated through the scheme between July 2006 and December 2008 was 257,094 (only 17,025 of them were reported to be internally plumbed, or plumbed to supply water for indoor use) (Walton and Holmes, 2009). The number of new rainwater tanks (at least 5,000 L) installed in response to the Queensland Development Code Mandatory Part 4.2 (in effect 2007 until late 2012) was estimated to be 37,800. The estimation was obtained by scaling the increase in the number of tanks between 2010 and 2013 in Brisbane to that of SEQ based on their population ratio (Australian Bureau of Statistics, 2013). For all the new rainwater tanks (294,894), it is assumed that the percentage of these tanks plumbed into dwellings was 31.7%, the figure for Brisbane in 2013 (Australian Bureau of Statistics, 2013). Among these new rainwater tanks, approximately 77% of them were still in use as of 2013 based on the percentage of household with installed rainwater tanks in Brisbane (40.2%) and the percentage of households still using rainwater tank as a source of water (31.0%) (Australian Bureau of Statistics, 2013). The water yield and pumping electricity intensity are based on a detailed residential rainwater tank study in SEQ (Siems and Sahin, 2016). The inventory is included in the Supplementary Material.

3.3. Scenario modelling

We utilised an optimisation model, namely the Decision Support System Optimiser (DSSO), to simulate long-term water balances of SEQ between 2014 and 2033 under different scenarios. The DSSO model is owned and used by Seqwater for long-term water security planning. The model operates through cost optimisation of the supply and demand configurations of the water supply system based on the defined scenarios of catchment inflow, water demand and system operation rules. It has been described and used in a previous study to quantify the historical time-series direct energy use of the SEQ water supply system (Lam et al., 2016). A similar bottom-up approach was used in this current study for future life-cycle energy quantification. It involves coupling the generated water balance (a monthly water balance of SEQ from 2014 to 2033) with the life-cycle energy intensities of key system components including 12 major water treatment plants, key water transfer and

distribution pipelines to 40 demand zones, the three bulk water transfer pipelines, the seawater desalination plant and the potable recycled water system. Rainwater tanks are not included in the DSSO model and were modelled separately. Further details of the DSSO model are provided in the Supplementary Material.

We evaluated the life-cycle energy impacts of four different scenarios, defined as “Normal”, “Dry”, “High water demand” and “Design capacity”, over a 20-year period.

- The “Normal” scenario continues the low utilisation status of the desalination system and the water recycling system observed in 2014. The scenario is based on a historical period with both wet and moderate dry hydrological years. It is also based on the most likely demand scenario forecasted by the water utility (Seqwater, 2014). The demand forecast considers population growth, commercial and industrial usage, water leakage, regional variation, seasonal variation and a long-term urban water demand of 285 L per person per day (Seqwater, 2014).
- The “Dry” scenario assumes an unlikely extended period of dry conditions (i.e., worse than the Millennium Drought) with all the catchments receiving just 25% of the inflows in the “Normal” scenario over the 20-year period. Based on the DSSO model simulation, the seawater desalination system and the potable water recycling system would have to operate on average at 62% and 49% of their design capacities, respectively. Urban water demand is assumed to reduce to 260 L per person per day (the Millennium Drought’s level) as a result of outdoor water restrictions and water conservation campaigns. The possibility of more extreme reductions in water demand is evaluated in a sensitivity analysis.
- The “High water demand” scenario is similar to the “Normal scenario”, but with a 20% higher urban water demand. This scenario aims to explore the marginal energy impacts of water demand changes, and compare the long-term energy impacts of increased water demand with that of the four alternative water strategies.
- The “Design capacity” scenario assumes that both the desalination system and the water recycling system would be operating at their design capacities, and all installed rainwater tanks would be in use. This would reduce the use of conventional surface water. This “upper bound” scenario is common in the literature.

A summary of the key assumptions and values used for the four scenarios is given in Table 2. Further details are in the

Table 3

Summary of key assumptions and values used for the four scenarios.

	“Normal” scenario	“Dry” scenario	“High water demand” scenario	“Design capacity” scenario
Catchment inflow	Default ^a	75% lower than default ^a	Default ^a	Default ^a
Average per capita water demand ^b	Increasing from 250 L/p/d to 285 L/p/d between 2014 and 2018, and maintaining at 285 L/p/d for the remaining years	Increasing from 250 L/p/d to 260 L/p/d between 2014 and 2018, and maintaining at 260 L/p/d for the remaining years	Increasing from 250 L/p/d to 340 L/p/d between 2014 and 2018, and maintaining at 340 L/p/d for the remaining years (20% higher than the “Normal” scenario)	Same as the “Normal” scenario
Average annual population growth rate	1.5%			
Desalination system operation rule ^c	Fixed minimum throughput to that of year 2014, maximising throughput if combined key storage capacity drops below 60%			Operating at its design capacity
Recycled water system operation rule ^c	Fixed minimum throughput to that of year 2014, maximising throughput if combined key storage capacity drops below 40%			Operating at its design capacity
Regional average water use from rainwater tanks ^d	27.4 kL/hh/yr	21.7 kL/hh/yr	32.8 kL/hh/yr	51.6 kL/hh/yr

^a The default catchment inflow scenario used in the DSSO model is a 20-year historical inflow covering both wet and moderate dry hydrological periods around the Federation Drought of 1902–03.

^b The DSSO model simulation shows that there would not be demand shortfall over the 20-year period for the four scenarios. Existing supply capacity would be sufficient to meet the demand, without the need of building new supply sources. Additional water mains are assumed to be constructed as the water demand grows.

^c Operation rules for the “Normal”, “Dry” and “High water demand” scenarios are based on that of Seqwater (2014).

^d The water yields of rainwater tanks for outdoor and indoor use are based on a SEQ study that modelled the average annual yield of rainwater tank over 20 years with both dry and wet periods (Siems and Sahin, 2016). For the “Dry” scenario, it is assumed that the water yield from rainwater tanks reduces. For both the “High water demand” and the “Design capacity” scenarios, it is assumed that the water use from rainwater tanks increases. See the Supplementary Material for details.

Supplementary Material.

3.4. Uncertainty analysis

A data quality assessment on the input parameters was conducted to provide transparency (Supplementary Material). The assessment criteria include data acquisition method, independence of data sources, representativeness of the data, data age, geographical correlation and technological correlation. The overall average data quality for this study was 4.2 (scale of 1–5 where 5 is highest quality). It should be noted that lower quality data was typically associated with the construction phase of centralised systems which generally did not contribute significantly to the results. To further quantify the uncertainty in the input parameters, Monte Carlo simulation using 10,000 runs was performed on each case - the current (2014) and the three future scenarios. The approach is based on earlier work (Lam et al., 2017; Stokes et al., 2014), in which probability distribution functions were defined for all input parameters. The definition of the distribution functions was guided by the data quality assessment. Details are provided in the Supplementary Material. In Section 4, the deterministic results

are presented with the 5th and 95th percentile results of the Monte Carlo simulation shown as error bars.

4. Results and discussion

4.1. Current (2014) life-cycle energy impact of alternative supply strategies

Upgrading SEQ's urban water supply system with four alternative supply strategies in response to the Millennium Drought increased its life-cycle energy use by approximately 24% (under 2014 low-utilisation conditions) compared to the pre-drought system (Fig. 1). Nearly half of this increased energy use was contributed by the rainwater tanks. For the local water utilities (one bulk water supplier and five water distributors), the three alternative supply strategies in the centralised system have increased the total direct operational energy use by approximately 16%. The low-utilisation operation status is a likely typical scenario for the SEQ system for the coming decade because of a relatively high expected water security based on stochastic modelling (Seqwater, 2015).

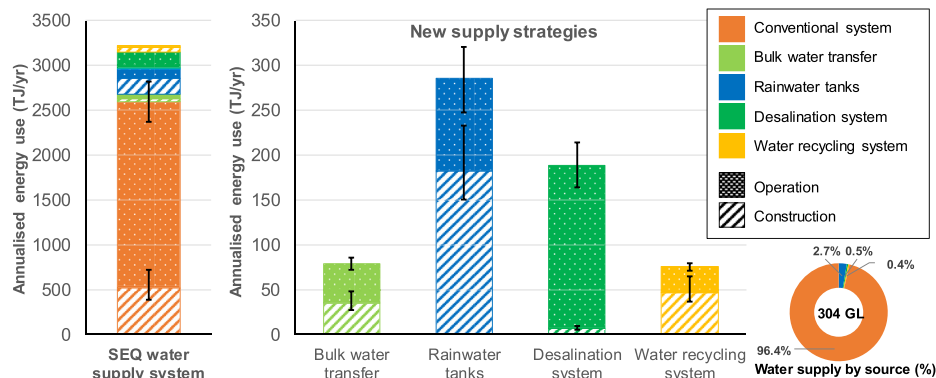


Fig. 1. Breakdown of annualised life-cycle energy use of SEQ water supply system, annual total water supply, and water supply by source in the current status (2014) with low utilisation of new supply infrastructure. Error bars shows the range of 5th to 95th percentile results for the annualised energy use from Monte Carlo simulation.

With low utilisation of new infrastructure in 2014, the construction phase of the four supply strategies constituted nearly half of the additional life-cycle energy use. It was contributed mostly by the manufacturing and installation of bulk water pipelines and rainwater tanks. The bulk water pipelines required nearly 400 km of mild steel cement lined pipeline (mostly larger than 1,000 mm in diameter). The more than 290,000 new rainwater tanks in the region are typically fabricated from polyethylene and have capacities between 3,000 and 5,000 L.

The two climate-independent sources – the seawater desalination and potable water recycling systems – collectively provided approximately 1% of the total water supply in 2014. Rainwater tanks only contributed an estimated 3% of regional water supply, but added over 10% to the life-cycle energy use.

The results also highlight that the energy use for the operation of seawater desalination system is high even under a minimum operating condition (less than 3% of its design capacity). The empirical operation data shows that the desalination system would have a higher energy efficiency (i.e., lower energy intensity [MJ/m³]) when operating with a higher throughput. This dynamic will be discussed further in the scenario modelling section.

Bulk water transfer pipelines have a relatively minor influence on the overall energy use of the whole system, even though they were utilised much more in terms of design capacity than the desalination and water recycling systems. These pipelines are much less energy intensive (MJ/m³) because some of the pipelines are gravity-fed under typical operating conditions.

4.2. Future life-cycle energy impact under different scenarios

Fig. 2 presents a comparison of the average annualised life-cycle energy use of the SEQ water supply system and the distribution of different water supply sources over a 20-year period (between 2014

and 2033) for four different future scenarios. “Conventional system (baseline demand in 2014)” is the baseline life-cycle energy use for the conventional system. In addition to that, the scenario analysis results include the “Conventional system (demand growth between 2014 and 2033)” which is the additional future life-cycle energy use (i.e., including treatment, pumping, chemicals, expanded distribution network) to meet the increased demand with conventional surface water sources. The current (2014) annualised energy use is approximately equal to that of the “Normal scenario” less the demand growth component.

The scenario analysis shows that in the “Dry” scenario, the annualised energy use of the overall water supply system would be 44% more than that of the most likely “Normal” scenario, despite assumed 9% decrease in demand. This additional energy consumption is mostly from the increased direct electricity use by desalination and water recycling processes. The annualised energy use in the “High water demand” scenario is between that of the “Normal” scenario and the “Dry” scenario. The modelled results in the “High demand” scenario also indicate the need for increasing production from the desalination system in some dry years to meet the increased demand. In Seqwater's latest water strategy (Seqwater, 2015), the desalination system is given a higher priority for operation than the water recycling system.

A “Dry” scenario with higher utilisation of the new supply infrastructure would almost double the life-cycle energy use compared to the 2014 conventional supply system. By contrast, alternative new supplies add less than 25% in the “Normal” scenario. Under the “Dry” scenario, the desalination system and the potable water recycling system supply 21% of total urban water demand. This type of high utilisation scenario is a common scenario in the literature (e.g., (Lane et al., 2015; Mo et al., 2014; Shrestha et al., 2011)). It clearly, though unconservatively, demonstrates the energy burden of operating some of these alternative water

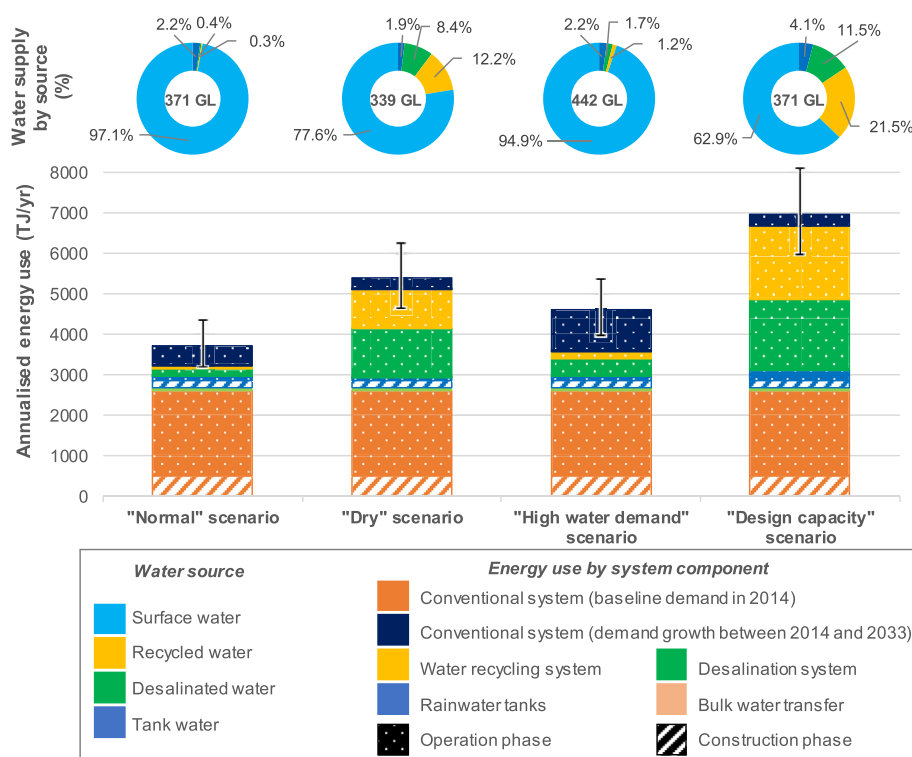


Fig. 2. Breakdown of average annualised life-cycle energy use of SEQ water supply system, annual average total water supply, and average water supply by source between 2014 and 2033 under different scenarios. Error bars shows the range of 5th to 95th percentile results for the total annualised energy use from Monte Carlo simulation. Source-specific uncertainties for each scenario are provided in the [Supplementary Material](#).

sources.

In the longer term, the life-cycle energy impact from future increased water demand in the “Normal” scenario would indeed be significant (approximately 75% of that of the four alternative supply strategies introduced in the Millennium Drought). In the case of “High water demand” scenario, 86%, 9% and 5% of the increased water demand (on a per capita water use basis, increased by 20%) would be supplied by conventional surface water, seawater desalination and water recycling, respectively. The associated increased energy use would even contribute more to the total life-cycle energy use of the system than that of the alternative sources in the “Normal” scenario. This clearly illustrates the important role of demand management on long-term water-related energy management. The important role of conserving water as a means of conserving energy should be recognised and evaluated in decision-making, just as the energy intensity of new supplies is considered.

In the “Design capacity” scenario, the combined annualised life-cycle energy use for the desalination system and the water recycling system is similar to that of the rest of the water supply system. Under this scenario, the total annualised life-cycle energy use of the whole water supply system would become 87% higher than that of the “Normal” scenario. The increased contribution by the three alternative water sources – desalinated water, recycled water and tank water would lead to a reduction in the water demand from surface water sources.

The scenario analysis results also can be presented in term of energy intensity (MJ/m^3) (Fig. 3). Energy consumption per unit volume of water supplied is commonly reported in life-cycle energy assessments of urban water systems (Loubet et al., 2014). For each water supply type, the life-cycle energy intensities for the construction phase and operation phase are shown.

The results show that the life-cycle energy intensities of the four alternative water strategies strongly depend on operational conditions over their design lifespan (i.e., the lifetime throughput of a water supply strategy). For the construction phase, this influence of the volumetric throughput is most significant for the water recycling system (i.e., comparing the construction energy intensity of WR across the four scenarios). In addition, the seawater desalination system is far more energy efficient when it operates closer to its design capacity as opposed to far from its designed operating point. In the “Dry” scenario, the average annual water yield of rainwater tanks would decrease, causing a relatively higher energy

intensity attributed to the construction phase. If alternative water sources are compared based on their energy intensity, this case study highlights that defining an appropriate long-term average water supply rate and realistic lifespans for the infrastructure is critical.

4.3. Sensitivity analysis

A sensitivity analysis was conducted for all input parameters impacting the annualised life-cycle energy use and the life-cycle energy intensity of the current (2014) water supply system. Percentage variations of -50% and $+50\%$ from the base values of input parameters were used. For each of the five system components, the sensitivity diagram (Fig. 4) shows the ranges of annualised life-cycle energy use and life-cycle energy intensity for the low (-50%) and high ($+50\%$) values of the five most sensitive input parameters. The detailed sensitivity analysis is provided in the [Supplementary Material](#).

The sensitivity analysis shows that the life-cycle energy use result is most sensitive to the life-cycle energy intensity for electricity generation and the lifespan of the component. This work uses the life-cycle energy intensity for electricity supply in eastern Australian result from the Australasian LCI database (lifecycles, 2015), which is a life-cycle inventory adapted to the Australian context. This would arguably help manage the sensitivity issue of this parameter. Lifespan has an inverse, non-linear effect on both the annualised energy use and the energy intensity. The lifespan of the component is important if there is significant infrastructure construction compared to operational energy use. For some other sensitive parameters (e.g., electricity intensity of water treatment plant, electricity intensity of desalination, number of new rainwater tank through the rebate scheme), this study uses data obtained directly from water utilities or government agency publications, which helps minimise the uncertainties (detailed in the data quality assessment in the [Supplementary Material](#)).

The sensitivity analysis also complements with the scenario analysis to give indication of how certain future changes in the water supply system would influence the life-cycle energy use and energy intensity. For instance, a reduction in the life-cycle energy intensity for electricity generation through shifting to a less coal-dependent energy mix would reduce the annualised energy use and energy intensity for all system components. While improving

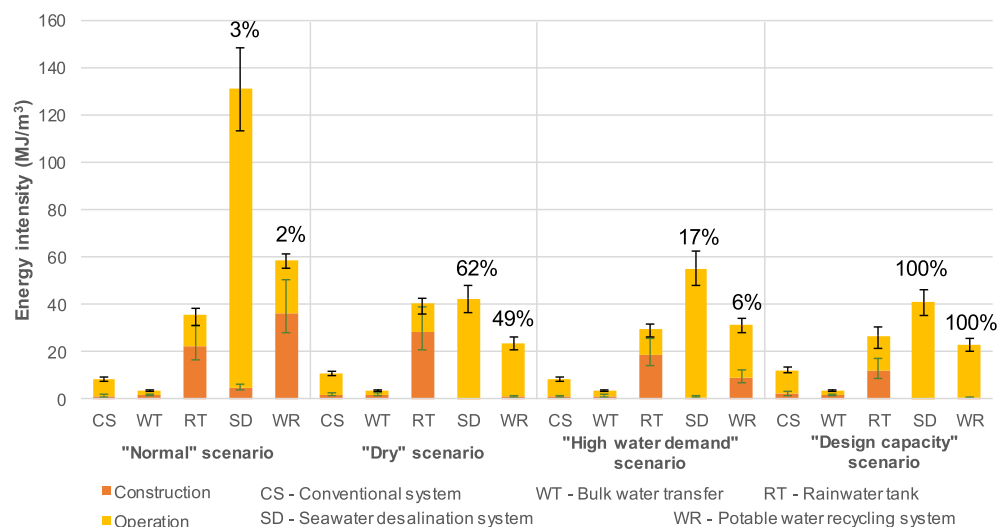


Fig. 3. Energy intensity of SEQ conventional water supply and the four water strategies under different scenarios. The percentage indicates the proportion of source's design capacity that is utilised in the scenario.

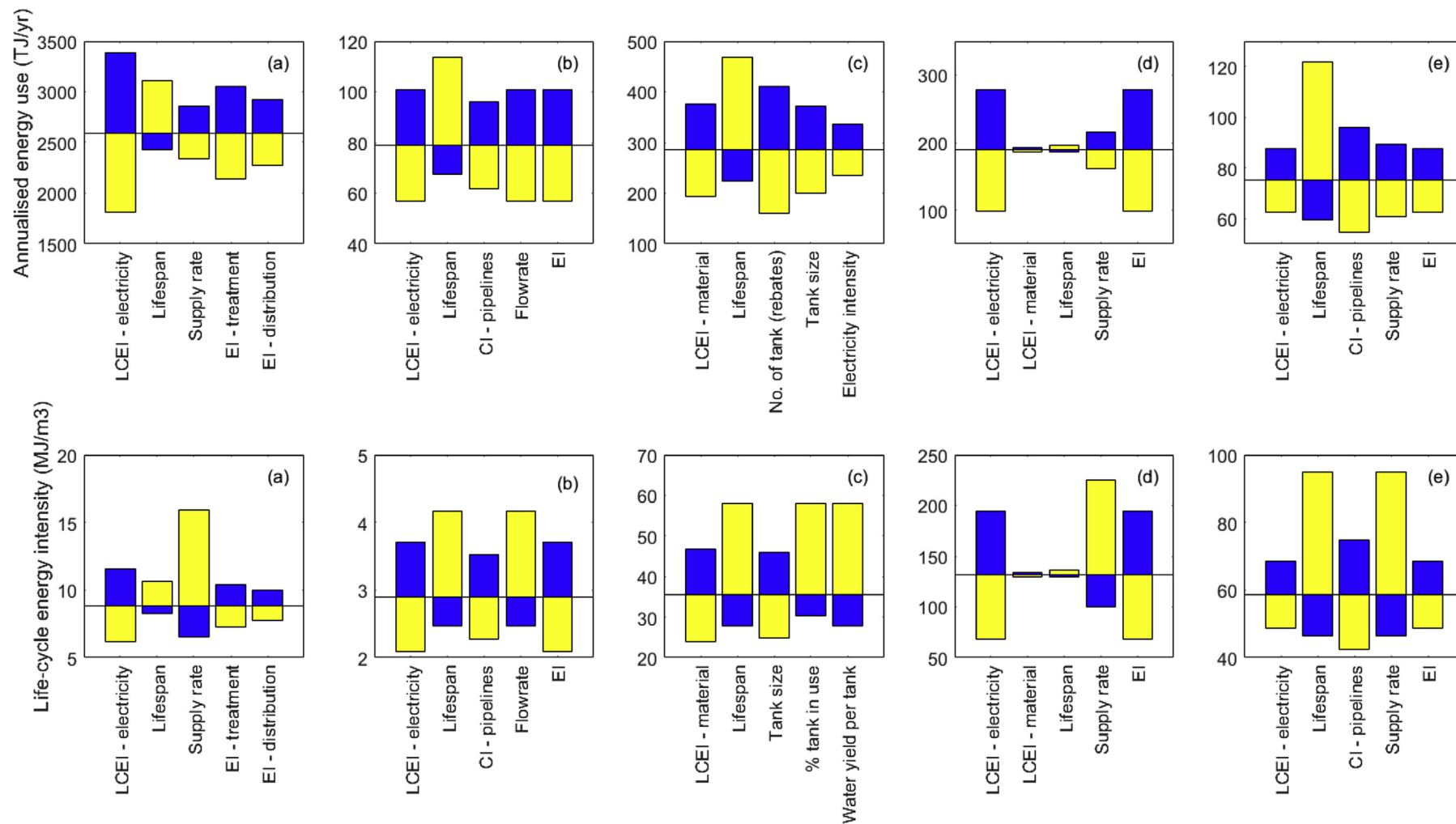


Fig. 4. Sensitivity diagrams showing the ranges of annualised life-cycle energy use and life-cycle energy intensity for each system component in the current status ((a) conventional system, (b) bulk water transfer, (c) rainwater tank, (d) desalination system, (e) water recycling system) for low (−50%, yellow) and high (+50%, blue) values of the five most sensitive categories of parameters. The full sensitivity diagrams are provided in the [Supplementary Material](#). (LCEI: life-cycle energy intensity, EI: electricity intensity, CI: construction inventory). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

the pump efficiency can help reduce the overall energy use of rainwater tank systems, ongoing maintenance of these systems (to preserve and even extend their lifespans) seems to be also important to reduce the annualised energy use. A significant reduction of water demand would moderately reduce the annualised energy use of the conventional system, but significantly increase its life-cycle energy intensity.

4.4. The regional energy implications of rainwater tanks

From an energy intensity perspective, rainwater tanks are far more energy intensive than conventional water supply sources in SEQ. On a life-cycle energy intensity basis (MJ/m^3), high regional uptake of rainwater tanks, estimated to be 40% of SEQ households (Australian Bureau of Statistics, 2013), would be as energy intensive as seawater desalination, if a considerable portion of the tanks are under-utilised and/or their water yield reduces due to droughts (i.e., comparing RT and SD in the “Dry” scenario in Fig. 3). Under-utilisation of rainwater tanks is expected in normal conditions. As previously stated, a post-drought survey on water use and conservation in Brisbane and Queensland has shown that an estimated 77% of these tanks were still in use as of 2013 (Australian Bureau of Statistics, 2013). The survey has also shown similar under-utilisation situation (less than 90%) in other major Australian cities.

In addition, a large portion of the new tanks (68%) were not internally-plumbed as of 2013 and, therefore, their usage is limited to outdoor water use. This can undermine their contribution to reducing total water demand. A detailed rainwater tank study in SEQ has suggested that 72% of water usage from internally-plumbed water tanks is for indoor water use (Siems and Sahin, 2016). Intuitively, if rainwater tanks can only be used outdoors, they are more likely to support optional uses, such as watering thirsty plants and topping up swimming pools, than to offset basic water use from major activities such as shower, toilet and clothes washer. It can also mean that a large portion of the tanks which are limited to outdoor water use may not be optimised for size (i.e., they are too large for outdoor water demand). This SEQ case shows that whether rainwater tanks are under-utilised and internally-plumbed are important factors and should be included in any regional assessment of this type of alternative water source. Neither factor has been explored in previous single tank studies.

This scenario study was based on the latest available rainwater tanks usage data in 2013 (i.e., 5–7 years after most tanks were installed) to quantify their long-term regional life-cycle energy impact. It does not account for possible further reduction in the utilisation of the tanks (e.g., because of pump problems, usage pattern change). Therefore, the regional life-cycle energy intensity of these tanks can potentially be even higher than modelled in this study. Retrofitting a large portion of the 68% of non-internally-plumbed rainwater tanks for indoor water use and optimising the pumping configuration (Vieira et al., 2014) may help lower the overall life-cycle energy intensity but is likely to be costly.

4.5. The implications for scenario building of water supply systems

This work illustrates that the choice of long-term operational scenario has a significant impact on evaluating the life-cycle energy impact of any alternative supply strategy and affecting the prioritisation of new supply sources based on their energy use or energy intensity (which subsequently influences the evaluation of GHG emissions or other environmental factors). This has implications for scenario building of life-cycle assessments of water supply systems.

For alternative water sources used for drought adaptation in regions with high climate variability, choosing a design capacity or high utilisation scenario for life-cycle energy impact evaluation

could result in significantly higher evaluated impacts than using more realistic average long-term operational scenarios (i.e., in this SEQ case (Fig. 2), the annualised life-cycle energy use in the “Design capacity” scenario is 87%, 29% and 51% higher than that of the “Normal”, “Dry” and “High water demand” scenarios respectively). In the literature, Lundie et al. (2004) is one of the early studies that quantified the life-cycle energy impacts of urban water systems under different scenarios. Their study defined scenarios in which alternative supply sources in Sydney would be in high utilisation (e.g., building and continuous operation of a seawater desalination plant providing 6% of water supplied). In reality, Sydney built a seawater desalination plant in response to the Millennium Drought. The plant came online in 2011 (after the drought ended in 2010), but it ceased operation in 2013. Many other studies after Lundie et al. (2004) defined similar high utilisation of alternative water sources in their scenario analysis (Hall et al., 2011; Lane et al., 2015; Mo et al., 2014; Shrestha et al., 2011).

Another critical aspect to be considered in scenario building is how much the regional long-term average performance of decentralised systems could deviate from that of an individual decentralised system. Decentralised systems are not always operational and functional (Moglia et al., 2016). The uncertainties of under-utilisation and operational issues should be accounted for when developing long-term scenarios to compare decentralised supply options with centralised supply options. Individual decentralised system studies (e.g., Racoviceanu and Karney (2010), Devkota et al. (2013), Rygaard et al. (2014), Hendrickson et al. (2015)) are unlikely to capture this uncertainty when comparing their decentralised systems with centralised options, especially in studies that include energy as the metric of interest. Taking this uncertainty into consideration, decentralised systems on an average regional basis can be more energy intensive than their designed individual systems (e.g., in Fig. 3, the energy intensities of RT in the “Normal”, “Dry” and “High water demand” scenarios are higher than that of the “Design capacity” scenario).

4.6. The implications for other water-stressed regions

Centralised alternative water sources such as desalination, potable water recycling and inter-basin water transfers are often labelled as “energy intensive” (Plappally and V Lienhard, 2012; Wakeel et al., 2016). The SEQ case and similar emerging cases in Spain (March et al., 2014) and other Australian cities (Barnett and O'Neill, 2010; Turner et al., 2016) show that for water-stressed regions with high climate variability, alternative water sources only have higher utilisation in extended droughts. Climate change is likely to make dry areas drier overall and cause precipitation variability to intensify for the large portion of the world with weather patterns influenced by the El Niño-Southern Oscillation (IPCC, 2014). Therefore, the number of utilities that may consider alternative supplies to supplement supply in dry periods is likely to increase over time. Evaluating the energy use and intensity of these centralised supply sources without considering their long-term likely operating scenarios can potentially distort and over-emphasise their energy implications relative to the whole urban water system. In fact, as in the case of SEQ, it is worth paying more attention to other parts of an urban water system for water-related energy management. For example, low-hanging fruit for energy minimisation can come from decentralised sources through optimising pumping configuration (discussed in Section 4.4), wastewater systems (Lane et al., 2015) or even water end use (with high water-related energy and cost saving potential in Australia found by Lam et al. (2017)).

For other water-stressed regions considering new supply sources, they should carefully assess whether the new supply sources

are mostly for drought adaptation (i.e., only operating in dry years) or for wider or more regular use. As shown in this work, this classification would affect how the new supply sources are evaluated for their long-term life-cycle energy impacts and compared against other strategies. While alternative water sources can diversify the supply portfolio and increase system flexibility during future droughts, a continuous operation of the desalination system under minimum production rate has shown to be highly energy inefficient in SEQ (i.e., three times more energy intensive than if it is operating at its design capacity). This inefficiency can be attributed to the need for a significant amount of internal bypass of seawater to reach the necessary discharge velocity for better mixing of the brine effluents (Poussade et al., 2011). This likely applies to other conventional desalination systems. Water systems that experience, or expect to experience, climate variability should explicitly consider operational flexibility across the range of possible operating conditions for their desalination system in their design process to avoid sacrificing energy efficiency when desalinated water is not needed.

This work highlights that, while desalination often dominates the water-related energy story, there is also a significant life-cycle energy consumption for the use of rainwater tanks (half of the energy use is in the construction phase for the plastic rainwater tanks in SEQ). Future energy evaluation of projected large-scale adoption of decentralised sources (e.g., rainwater harvesting, greywater recycling) in water-stressed regions should consider embodied energy use and scenarios of under-utilisation and operational issues. This would give a better quantification of energy use when comparing with other alternative water sources. Any scheme for promoting decentralised sources should also be carefully designed to find the optimum design capacities and to maximise utilisation through ongoing monitoring and maintenance.

5. Conclusions

Life-cycle energy impacts of alternative water supply strategies were studied. We focused on the current post-drought (2014) and future life-cycle energy impacts of four alternative water supply strategies introduced during the Millennium Drought in SEQ compared to conventional sources. The key insights are as follows.

- Our work highlights the energy burden of alternative water supply strategies compared to the conventional urban water supply systems. In SEQ, adapting its water supply system to the Millennium Drought with four alternative supply strategies has increased its annualised life-cycle energy use by approximately 24% under post-drought conditions, when two of the centralised strategies (seawater desalination and water recycling) were in minimum operation. Over half of this additional life-cycle energy use was from the centralised alternative supply strategies. Rainwater tanks only contributed an estimated 3% to regional water supply, but added over 10% life-cycle energy use to the existing system.
- Our work demonstrates the important role of defining more realistic long-term operating scenarios for life-cycle energy assessment of alternative supply strategies. More specifically, strategies used for drought adaptation (only operating in dry years) should be evaluated with consideration of climate variability over a long period. In addition, when evaluating decentralised sources, under-utilisation should be taken into account (e.g., in SEQ in 2013, only 77% of rainwater tanks were still in use and 68% of tanks were not internally-plumbed).
- The life-cycle energy intensity (MJ/m^3) of an alternative supply strategy can differ significantly under various scenarios (depending on the utilisation rate of the strategy). This can have

implications for comparing and selecting alternative water supply strategies based on energy intensity (MJ/m^3), a commonly reported unit for life cycle energy assessment of urban water systems. For instance, a desalination system has a potential “energy penalty” when it operates at a low output. Based on empirical data, the results show that the SEQ desalination plant at low utilisation ($126 \text{ MJ}/\text{m}^3$ for 3% capacity) is three times more energy intensive on a per unit volume basis than if it is operating closer to its design capacity ($42 \text{ MJ}/\text{m}^3$ for 62% capacity). In addition, regional uptake of rainwater tanks can be more energy intensive than seawater desalination if a significant portion of the tanks are under-utilised (i.e., not internally-plumbed or reduced collection or usage).

- The life-cycle energy burden for increasing per capita water use can be as significant as introducing alternative water supply strategies. This work demonstrates that focusing on managing long-term urban water demand is also important, in addition to acknowledging the energy-intensive nature of alternative water sources. The scenario analysis shows that a 20% increase in per capita water use from 285 L/p/d to 342 L/p/d ($864 \text{ TJ}/\text{yr}$) would “consume” more energy than the four alternative water supply strategies in the “Normal” scenario ($625 \text{ TJ}/\text{yr}$).
- While centralised alternative water sources still have considerable energy impacts, this research demonstrates that long-term low utilisation of some of these sources has greatly reduced their total energy burden (adding only 13% in the “Normal” scenario). In an age of climate change, the number of utilities that may consider alternative supplies to supplement supply in dry periods is likely to increase over time. Evaluating the energy implications of these supply sources without considering their long-term more realistic operating scenario can potentially distort and overemphasise their energy implications relative to the whole urban water system. It may be worth placing more policy focus for water-related energy management on other parts of urban water systems such as decentralised sources, wastewater systems or even water end use.

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Appendix A. Supplementary data

Supplementary data related to this article can be found at <https://doi.org/10.1016/j.watres.2017.10.016>.

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