City-scale analysis of water-related energy identifies more cost-effective solutions

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Abstract

Energy and greenhouse gas management in urban water systems typically focus on optimising within the direct system boundary of water utilities that covers the centralised water supply and wastewater treatment systems, despite a greater energy influence by the water end use. This work develops a cost curve of water-related energy management options from a city perspective for a hypothetical Australian city. It is compared with that from the water utility perspective. The curves are based on 18 water-related energy management options that have been implemented or evaluated in Australia. In the studied scenario, the cost-effective energy saving potential from a city perspective (292 GWh/year) is far more significant than that from a utility perspective (65 GWh/year). In some cases, for similar capital cost, if regional water planners invested in end use options instead of utility options, a greater energy saving potential at a greater cost-effectiveness could be achieved in urban water systems. For example, upgrading a wastewater treatment plant for biogas recovery at a capital cost of $27.2 million would save 31 GWh/year with a marginal cost saving of $63/MWh, while solar hot water system rebates at a cost of $28.6 million would save 67 GWh/year with a marginal cost saving of $111/MWh. Options related to hot water use such as water-efficient shower heads, water-efficient clothes washers and solar hot water system rebates are among the most cost-effective city-scale opportunities. This study demonstrates the use of cost curves to compare both utility and end use options in a consistent framework. It also illustrates that focusing solely on managing the energy use within the utility would miss out substantial non-utility water-related energy saving opportunities. There is a need to broaden the conventional scope of cost curve analysis to include water-related energy and greenhouse gas at the water end use, and to value their management from a city perspective. This would create opportunities where for the same capital investment, a greater amount of energy saving and carbon abatement could be achieved.

Keywords: urban water system, water utility, end use, cost curve, energy management, greenhouse gas management

1 Introduction

Energy is used in every stage of the urban water cycle, from water abstraction, treatment, distribution, to end use and wastewater treatment. In recent years, increasing energy consumption for providing water services, rising energy costs and the need for mitigating climate change have been drivers for better management of energy use and associated greenhouse gas (GHG) emissions in urban water systems. In the urban water context, a number of studies have shown that the water-related energy use in the water end use sector (i.e. residential, commercial and industrial) is far more substantial than that of water utilities (Kenway *et al.*, 2015; Plappally and Lienhard V, 2012).

Water utilities or regional water planners typically focus on optimising energy use and GHG emissions in their centralised water supply and wastewater treatment systems (including raw water abstraction and transfer, drinking water production, drinking water distribution, wastewater collection and wastewater treatment), despite a greater energy saving and carbon abatement benefit potentially present in the water end use. For instance, Cherchi *et al.* (2015), Conrad *et al.* (2010) and Frijns *et al.* (2013) showed cases in which cites focus on optimising the energy use of water utilities only. On the other hand, Zhou *et al.* (2013) acknowledged the energy saving potential of water conservation by considering a wider urban water system. Escriva-Bou *et al.* (2015) demonstrated the system-wide benefit of considering residential water-related energy use.

Marginal Abatement Cost Curves (MACC) have been used to support least cost planning for energy and GHG management in various disciplines. The approach illustrates graphically the relative cost-effectiveness and mitigation potential of different measures. Meier *et al.* (1982) is an early work of using the cost curve approach (i.e. called supply cost curves at that time) to populate energy saving options in the residential sector. MacLeod *et al.* (2010) developed MACCs for managing agricultural emissions in the U.K. In recent years, the cost curve approach has been applied in the water industry. Sydney Water Corporation (the water services provider for the Greater Sydney region) has developed a Cost of Carbon Abatement (CCA) tool for managing energy and GHG emissions based on the marginal abatement cost curve approach (WSAA, 2012) and licensed the tool to 19 water utilities across Australia as of 2014 (Sydney Water Corporation, 2014). Stokes *et al.* (2014) constructed a life-cycle carbon abatement cost curve for water utilities to account for pressure and leakage management strategy.

In the water sector, cost curves have been developed from the perspective of the utility, however, to the authors' knowledge, none have been published for a city perspective that considers and values options in both utility and water end use domains. Furthermore, water management options on the supply-side (i.e. within the system boundary of the water utility) and the demand-side (i.e. outside the system

boundary of the water utility) are not typically compared on the same basis. The development of a city cost curve for the water sector can provide a platform to compare options across the boundary between water suppliers and water consumers. It can also help overcome the norm that water end use is not included in the agenda for energy and greenhouse gas management in regional water strategy planning (i.e. an issue of sub-system optimisation).

An example of comparing cost curves from different perspectives is the Low Carbon Growth Plan for Australia (ClimateWorks Australia, 2010). It illustrates that the choice of perspective can have a profound impact on the interpretation of the abatement performance of different options. The work quantifies the emissions reduction opportunity and costs for society as a whole and compares with the same opportunity from the perspective of business sectors. It has shown that for a portfolio of carbon management options in Australia, the cost-effective abatement potential (i.e. the GHG emissions reduction from implementing projects with a positive net present value) for the investor cost curves is 24% less than that of the societal cost curves. This is because of a difference in the way investors and society value a project. For instance, investors generally consider a higher discount rate, and have a different energy prices considering account taxes and direct or indirect subsidies.

This work aims to develop and compare cost curves for water-related energy from the "water utility" and "city" perspectives (Figure 1), for a hypothetical city based on average Australian data. The water utility perspective refers to the point of view of water managers who consider purchased energy use, and financial performance within their entities. The city perspective considers the purchased energy use and financial performance of making water-related energy management investments in the whole urban water system, including water supply system, water end use, and wastewater treatment system. The curves are based on a list of water-related energy management options that have been implemented and/or analysed for their energy saving potentials and cost-effectiveness in Australia. The developed curves can reflect the difference between optimising the energy use of urban water systems from water utility and city perspectives. The implications of both the water utility and city perspectives for water policies are discussed.

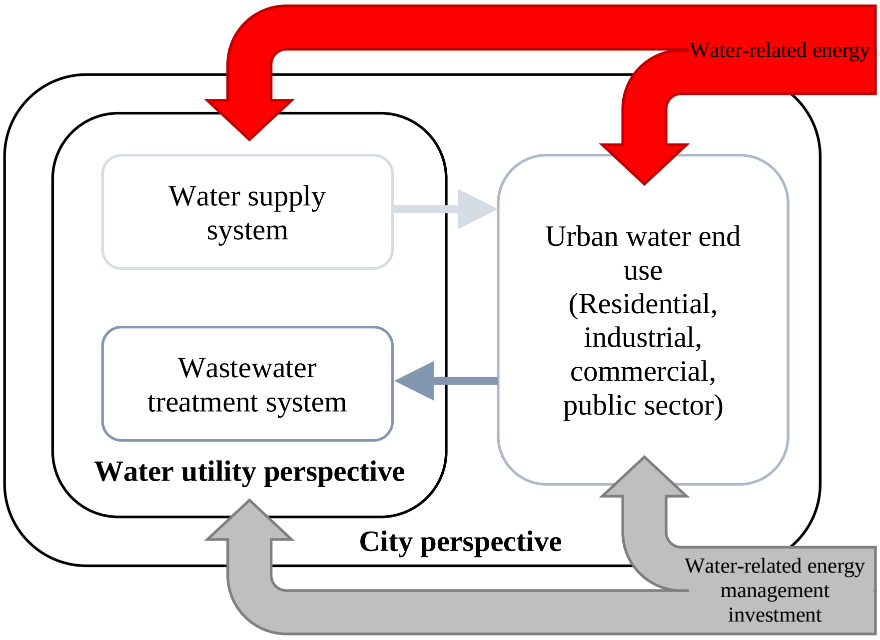

Figure 1 A system diagram showing the water utility perspective and the city perspective

2 Material and methods

2.1 Overall approach

This work developed cost curves for energy management of urban water systems following four major steps:

Step 1: Identifying options for improved energy management and efficiency in water utilities and water end use
Step 2: Defining scenario for implementation of the options in an urban water system
Step 3: Quantifying the energy saving potential and marginal cost of all the options from both the water utility and city perspectives
Step 4: Presenting the results in the form of cost curves

2.2 Identifying the options

The list of options (Table 1) for improved energy management and efficiency of urban water systems was compiled based on a review from academic literature and water utility reports. Most of these options have been studied or implemented, and their water and energy saving benefits have been demonstrated in some Australian cities (i.e. Adelaide, Brisbane, Gold Coast, Melbourne, Sydney). The list of options is not intended to be exhaustive. Instead, it aims to capture a range of options to show how these options are valued differently from the water utility and city perspectives. Ten of the options are utility options that can be applied to the potable water treatment plants, water distribution network and wastewater

treatment plants. Eight options relate to water end use. Further details of these options can be found in Table 1S in the Supplementary Material.

Table 1 Options related to water-related energy management

No.	Option	Scope [a]	City/ region implemented or studied	Nominal capital expenditure ($) [b]	Water saving from the mains (ML/yr)	Energy saving at utility (MWh/yr)	Energy saving at end use (MWh/yr)	Purpose	Source
1	Active leak detection and pressure management	DWD	Sydney	9,514,000	30,416	c	0	To reduce the frequency of leaks and the amount of water loss in the water distribution network	(Sydney Water Corporation, 2012b)
2	Scrubber ventilation efficiency	WWT	Sydney	203,464	0	1,044	0	To control the speed of ventilation fan based on the concentration of odour causing agents	(Sydney Water Corporation, 2013)
3	Sewage pumping efficiency	WWT	Sydney	58,500	0	562	0	To slow down the speed of some of the pumps to reduce frictional losses in the rising main	(Sydney Water Corporation, 2013)
4	Minimising the use of DAF	DWT	Sydney	78,700	0	500	0	To shift to the use of clarifier instead of dissolved air flotation (DAF) stage when raw water algae level is low	(Sydney Water Corporation, 2012a)
5	Most open valve aeration strategy	WWT	Sydney	220,000	0	2,000	0	To use control valves to optimise the pressure of aeration systems	(Sydney Water Corporation, 2012a)
6	Inverter speed control pump for bulk water transfer	BWT	Sydney	1,188,000	0	6,219	0	To control pumping by inverter speed control instead of by valves	(Sydney Catchment Authority, 2009)
7	Aeration optimisation	WWT	Melbourne	1,162,000	0	4,468	0	To reduce the continuous aeration for secondary treatment	(Melbourne Water, 2013)
8	Plant upgrade for biogas recovery and electricity generation	WWT	Adelaide	25,875,000	0	31,450	0	To upgrade the existing wastewater treatment to efficiently utilise all available biogas	(Public Works Committee, 2011)
9	Existing STP reuse and minor recycling	WWT	Sydney	7,670,000	2,160	c	0	To reuse and recycle the effluent from sewage treatment plant (STP)	(Sydney Water Corporation, 2009)
10	Stormwater harvesting	DWS	Sydney	31,181,800	1,000	c	0	To capture and use stormwater at community scale	(Bush, 2015)
11	Water-efficient clothes washer rebate	RWE	South East Queensland	46,968,485	1,465	c	111,740 [d]	To incentivise the uptake of water-efficient clothes washer	(Beal *et al.*, 2012; Walton and Holmes, 2009)
12	Water-efficient shower head rebate	RWE	South East Queensland	868,508	475	c	19,807 [d]	To incentivise the uptake of water-efficient showerhead	(Beal *et al.*, 2012; Walton and Holmes, 2009)
13	Dual flush toilet rebate	RWE	South East Queensland	6,309,339	755	c	0	To incentivise the uptake of dual flush toilet	(Walton and Holmes, 2009)
14	Solar hot water system rebate	RWE	Queensland	25,900,000	0	c	67,067 [d]	To incentivise the uptake of solar hot water system	(QLD Government Solar Hot Water Rebate, 2013; Beal *et al.*, 2012)
15	Alarming visual display monitors for shower	RWE	Gold Coast	7,500,000	1,491	c	60,200	To install alarming monitoring devices to induce a reduction in shower water use	(Willis *et al.*, 2010)
16	Plumber visit	RWE	Sydney	20,800,000	3,344	c	108,166 [d]	To have households visited by certified plumbers for offering services such as replacing inefficient showerheads, checking of leaks, and providing advice on water saving	(Turner *et al.*, 2005)
17	Cooling towers upgrade	IWE	Melbourne	4,430,000	220	c	4,400	To fund upgrading of cooling towers at manufacturing plants	(Lovell, 2013)
18	Irrigation and landscape efficiency program	OWE	Sydney	5,600,000	1,090	c	0	To improve water use efficiency for open space irrigation	(NSW Government, 2013)

Figures in the shaded boxes are based on the data sources.

[a] BWT: bulk water transfer, DWD: drinking water distribution network, DWS: decentralised water supply, DWT: drinking water treatment plant, IWE: industrial water end use, OWE: other water end use, RWE: residential water end use, WWT: wastewater treatment plant

[b] The figures were reported by the sources for the corresponding years in which the options were studied or implemented. They were the investment by governments or water agencies for implementing those options.

[c] It is a function of the energy intensity of the water systems and the volume of water saved from the mains.

[d] The energy saving at the end use was estimated based on a study of energy saving (i.e. electricity) from the use of water efficient devices and solar hot water system in Brisbane (Beal *et al.*, 2012).

2.3 The urban water system

A hypothetical Australian city was used in this work. The use of a synthesised hypothetical city enabled a more comprehensive list of water-related energy management options to be considered. The city was based on the water situation in four Australian capital cities - Brisbane, Melbourne, Sydney and Perth (collectively accounting for nearly 60% of the Australian population) (Table 2). The hypothetical city's water price, electricity prices, energy intensity for water services and characteristics were taken as the average of the four cities. All monetary terms are in Australian dollars.

The city has a population of nearly 3.4 million (population density of 360 people/km^2) with 70% of the dwellings being separate houses. It obtains water predominantly from dams (79%), supplemented with groundwater (9%), desalinated water (7%) and non-potable recycled water (5%). It has a humid subtropical climate with a mean temperature range of 16.3℃ to 26.5℃. Residential water use, commercial, municipal and industrial water use, and non-revenue water account for 65%, 24% and 11% of the total urban water demand respectively.

Table 2 Parameters used in the analysis pertaining to the hypothetical city

Context	Average value [1]	Remark [2]
Energy intensity of main water supply (kWh/kL)	0.57	Weighted-average of the energy intensity of centralised water supply systems of the greater capital city areas of Brisbane, Melbourne, Sydney and Perth in 2013-14. Water sources associated with this average energy intensity for water supply are 79% of surface water, 9% of groundwater, 7% of desalinated seawater and 5% of non-potable recycled water.
Energy intensity of wastewater treatment (kWh/kL)	0.83	Weighted-average of the energy intensity of wastewater treatment systems of the greater capital city areas of Brisbane, Melbourne, Sydney and Perth in 2013-14. 52% of the wastewater going through tertiary treatment, 30% for primary treatment and 18% for secondary treatment.
Water consumption charge ($/kL)	2.28	Average tier 1 water consumption charge of Brisbane, Melbourne, Sydney and Perth in 2013-14
Electricity price - Utility ($/MWh) (Industrial retail)	144	Average purchased electricity cost (including both the usage charge and the supply charge) of Yarra Valley Water (Melbourne), Queensland Urban Utility (Brisbane) and Sydney Water Corporation in 2013-14
Electricity price –End use ($/MWh) (Residential retail)	239	Average purchased electricity cost (the flat rate usage charge) of Victoria, Queensland and New South Wales as of 2016
GHG Emission factor of electricity generation (kg CO_2eq/kWh)	1.03	Average GHG emission factor of Victoria, Queensland, New South Wales and Western Australia in 2011-12. Considering the full fuel cycle (scope 2 and scope 3) emissions. Coal is the largest fuel source (61% as of 2013-14) for electricity generation in Australia, followed by natural gas (22%), renewable sources (15%) and oil (2%) (Department of Industry and Science, 2015).
Annual increase in water price	2%	Similar to the percentage increase in the consumer price index in Australia
Annual increase in electricity price	2%	Similar to the percentage increase in the consumer price index in Australia
Annual increase in energy intensity of water system	1%	Assuming an increasing trend of energy intensity as in major Australian cities in recent years
Emission factor annual change rate	0%	The emission factor of electricity generation in Australia has remained stable in recent years. (Department of the Environment, 2014)

Discount rate	5%	Based on the discount rates used for public utility or societal studies (ClimateWorks Australia, 2010; Stokes *et al.*, 2014)

[1] See Table 3S and 4S (Supplementary Material) for the values of the four Australian cities (Brisbane, Melbourne, Sydney and Perth) and the distribution shapes used

[2] See Table 3S for other contextual characteristics of the four cities and the hypothetical city

2.4 Quantifying the energy saving potential and marginal cost of options

Figure 2 shows the methodology for quantifying the total energy saving potential (GWh) and marginal cost ($/MWh) of an option over the assessment period. The quantification is based on the following general equations with some variations depending on the types of option (i.e. water saving, non-water saving, utility or end use).

For the water utility perspective,

$$EP_{Utility} = \sum_{t=1}^{t_{option}} \left(\left(EI_{WS,t} + EI_{WW,t} \right) \times V_{w,t} + E_{o,t} \right) \tag{1}$$

$$MC_{Utility} = \left(CAPEX_{Utility} - \sum_{t=1}^{t_{option}} \frac{\left(\left(EI_{WS,t} + EI_{WW,t} \right) \times V_{w,t} + E_{o,t} \right) \times EC_t - V_{w,t} \times WC_t}{(1+r)^t} \right) / EP \tag{2}$$

For the city perspective,

$$EP_{City} = \sum_{t=1}^{t_{option}} \left(\left(EI_{WS,t} + EI_{WW,t} + EI_{EU,t} \right) \times V_{w,t} + E_{o,t} \right) \tag{3}$$

$$MC_{City} = \left(CAPEX_{City} - \sum_{t=1}^{t_{option}} \frac{\left(\left(EI_{WS,t} + EI_{WW,t} + EI_{EU,t} \right) \times V_{w,t} + E_{o,t} \right) \times EC_t}{(1+r)^t} \right) / EP \tag{4}$$

where *EP* is the total energy saving potential (GWh), *t* is the year, t_{option} is the lifetime of the option (year), *EI* is the energy intensity of the associated activities in year *t* (MWh/ML) (i.e. water supply, wastewater treatment, hot water use), $V_{w,t}$ is the volume of water saved (ML/year), $E_{o,t}$ is other energy saving independent of water saving (MWh), *MC* is the marginal cost of an individual option ($/MWh), *CAPEX* is the capital expenditure of the option ($), EC_t is the energy cost ($/MWh) and *r* is the discount rate. In general, the energy saving potential of an option (equations 1 and 3) is quantified based on i) its water saving potential (if the option is a water saving one such as leakage prevention), ii) energy intensity for supplying drinking water and treating wastewater, and iii) other energy saving potential that is not water saving-related such as improving pump efficiency. The energy saving potential in the city perspective (equation 3) also includes energy intensity for water use activity such as hot water use. For each option, the marginal cost (equations 2 and 4) is its overall financial performance over its total energy saving throughout the assessment period. Utility perspective (equation 2) only account for the financial impacts (e.g. reducing energy expense, reducing revenue from water sales) experienced within the utility's organisation boundary.

Input parameters of the options include the lifetime, water saving potential, energy saving potential at water utility, unit energy saving potential at water end use and capital expenditure. Most of these parameters were based on the original data sources (Table 1). Several key assumptions were made to quantify the energy saving potential and marginal cost of all options:

1. All monetary terms of the options were adjusted to real terms in 2014 (reference year) based on the Australian Consumer Price Index (ABS, 2015) (Table 2S in the Supplementary Material).
2. All the options are technically feasible and they could achieve the same level of water and energy saving described in the original data sources.
3. A discount rate of 5% was used for all the options, over an assessment period of 20 years.
4. Potential interactions between options, marginal effect of energy use reduction, non-energy cost benefits and ongoing non-energy operating costs were not considered.

Other assumptions for quantifying the energy saving potential and marginal cost of each option are detailed in Table 1S in the supplementary material.

2.5 Constructing the cost curve

The quantified total energy saving potential (GWh) and marginal cost ($/MWh) for all the options were then used to construct the cost curve. The cost curve ranks the results from the most cost-effective option to the least cost-effective one from left to right based on the net cost per unit energy saved of each option. The height of the bar is the marginal cost of the option ($/MWh). Negative value means both monetary and energy saving (i.e. cost-effective), positive means energy saved in the expense of financial cost (i.e. not cost-effective). The width of the bar is the total amount of energy saved (GWh) over the assessment period, while the area of the bar is the net cost of the option.

Global input parameters

- Discount rate (r)
- Energy intensity – water supply ($EI_{WS,1}$)
- Energy intensity – wastewater treatment ($EI_{WW,1}$)
- Water price (WC_1)
- Electricity price – water utility ($EC_{WU,1}$)
- Electricity price – end use ($EC_{EU,1}$)
- Increase rates ($i_{EI,WS}$, $i_{EI,WW}$, $i_{EC,WU}$, $i_{EC,EU}$, i_{WC})

Input parameters (utility/ end use options)

- Lifetime (t_{option})
- Annual water saving potential (V_w)
- Annual energy saving in the utility ($E_{O,WU}$)
- Unit energy saving in the end use ($EI_{EU,1}$, E_{EU})
- Capital expenditure ($CAPEX_{Utility}$, $CAPEX_{City}$)

Computing the performance of options over the assessment period (T_{max}):

Year		***0***	***1*** ***st year***		**...**	***t*** ***th year***
Capital expenditure		*CAPEX*	-		...	-
Energy intensity – water supply	$EI_{WS,t}$	-	$EI_{WS,1}$		...	$EI_{WS,1} \times (1 + i_{EI,WS})^t$
Energy intensity – wastewater treatment	$EI_{WW,t}$	-	$EI_{WW,1}$		...	$EI_{WW,1} \times (1 + i_{EI,WW})^t$
Energy intensity – end use	EI_{EU}	-	EI_{EU}		...	EI_{EU}
Electricity price – water utility	$EC_{WU,t}$	-	$EC_{WU,1}$		...	$EC_{WU,1} \times (1 + i_{EC,WU})^t$
Electricity price – end use	$EC_{EU,t}$	-	$EC_{EU,1}$		...	$EC_{EU,1} \times (1 + i_{EC,EU})^t$
Water saving	V_w	-	V_w		...	V_w
Water price	WC_t	-	WC_1		...	$WC_1 \times (1 + i_{WC})^t$
Energy saving – water utility	$E_{WU,t}$	-	*Option no.2-8* *Option no.1, 9, 10* *Option no.11-13, 15-17* *Option no.18*	$E_{O,WU}$ $EI_{WS,1} \times V_w$ $(EI_{WS,1} + EI_{WW,1}) \times V_w$ $EI_{WS,1} \times V_w$	...	$E_{O,WU}$ $EI_{WS,t} \times V_w$ $(EI_{WS,t} + EI_{WW,t}) \times V_w$ $EI_{WS,t} \times V_w$
Energy cost saving – water utility	$ECS_{WU,t}$	-	$E_{WU,1} \times EC_{WU,1}$		...	$E_{WU,t} \times EC_{WU,t}$
Energy saving – end use	$E_{EU,t}$	-	*Option no.11, 12, 16* *Option no.14, 15, 17*	$EI_{EU,1} \times V_w$ E_{EU}	...	$EI_{EU,t} \times V_w$ E_{EU}
Energy cost saving – end use	$ECS_{EU,t}$	-	$E_{EU,1} \times EC_{EU,1}$		...	$E_{EU,t} \times EC_{EU,t}$

Quantifying the net cost:

For option no. 11-13, 15-17, $TC_{Utility} = CAPEX_{Utility} - \sum_{t=1}^{T_{max}} \frac{ECS_{WU,t} - (V_{w,t} \times WC_t)}{(1+r)^t}$

For all other options, $TC_{Utility} = CAPEX_{Utility} - \sum_{t=1}^{T_{max}} \frac{ECS_{WU,t}}{(1+r)^t}$

$TC_{City} = CAPEX_{City} - \sum_{t=1}^{T_{max}} \frac{ECS_{WU,t} + ECS_{EU,t}}{(1+r)^t}$

Quantifying the **energy saving potential**:

$$EP_{Utility} = \sum_{t=1}^{T_{max}} E_{WU,t}$$

$$EP_{City} = \sum_{t=1}^{T_{max}} (E_{WU,t} + E_{EU,t})$$

Quantifying the **marginal cost**:

$MC_{Utility} = TC_{Utility}/EP_{Utility}$

$MC_{City} = TC_{City}/EP_{City}$

Results for constructing the cost curves

Figure 2 Flow diagram showing the steps and equations for quantifying the energy saving potential and marginal cost

3 Results & discussion

3.1 Comparing the water utility cost curve and city cost curve

According to the utility curve (Figure 3(a)), the water utility in this hypothetical city can save approximately 1300 GWh over the 20 year period with respect to the baseline by implementing all the cost-effective options in its water supply and sewage systems (i.e. all the options with negative net cost). Improving pumping efficiency (no. 3) and aeration strategies (no. 4, 5) are relatively cost-effective, while active leak detection and repair (no. 1) is the most significant energy saving option.

The curve also shows that demand-side options (no. 9-13, 15-18) are highly unfavourable to the water utility in direct financial terms as a result of a loss of water sale revenue and relatively insignificant energy cost saving within utility. This is consistent with the GHG abatement cost curve developed by Sydney Water Corporation, which has indicated that none of the demand management options they evaluated are cost-effective to them (WSAA, 2012).

The city curve (Figure 3(b)) shows that approximately 5800 GWh can be saved cost-effectively through implementing most of the options studied. In particular, options related to hot water use (e.g. water-efficient shower head rebate (no. 12), plumber visit (no. 16)) are among the most favourable. It indicates that hot water use represents a significant portion of urban water-related energy use and is an important management opportunity. The most cost-effective option is water-efficient shower head rebate (no. 12) and solar hot water system rebate (no.14) saves the most amount of energy.

Comparing the two cost curves (Figure 3) illustrates the difference between optimising the water-related energy use in the urban water system from the water utility and the city perspectives. One distinct difference is the magnitude of energy savings. The cost-effective energy saving potential from the city perspective (~5800 GWh, ~292 GWh/year) is 4.5 times that of the utility (~1300 GWh, ~65 GWh/year). This is consistent with the earlier finding that a significant portion of water-related energy use is in the water end use (Kenway et al., 2015; Plappally and Lienhard V, 2012). This significant energy saving potential (from options no. 12, 15, 16, 14, 11) is not being captured by the utility curve as it only accounts for energy cost saving benefit within the utility.

For the city curve, some demand-side options (no. 12, 15, 16, 17, 14) can reduce energy use at lower cost than supply-side options (no. 1 – 7) which are very cost-effective in the utility curve. This illustrates that focusing solely on managing the energy use within the utility would miss out substantial non-utility water-related energy saving opportunities. The energy saving potential associated with the large-scale adoption of some of the demand-side options is clearly significantly greater than that of the supply-side

options. In Australia, rebate schemes have been a popular approach to incentivise the uptake of water-efficient or energy-related appliances (e.g. water-efficient devices, solar hot water system) (Beal *et al.*, 2012; Walton and Holmes, 2009). One of main reasons for the higher cost-effectiveness of demand-side options is that the purchased electricity unit price of residential end use (23.9¢/kWh) is nearly double that of the utility (14.4¢/kWh).

By comparing supply and demand-side options in a consistent framework, like the city cost curve (Figure 3(b)), it can be found that some demand-side options (i.e. with energy benefit beyond the system boundary of utilities) have greater energy saving potential than the other supply-side options with similar capital expenditure for policy implementation. For example, for a similar capital cost, investing in solar hot water system rebates (no. 14, at a capital cost of $28.6 million (adjusted to 2014 dollars)) would save more energy (67 GWh/year against 31 GWh/year) and offer a greater financial return ($111/MWh saved against $63/MWh saved) than upgrading a wastewater treatment plant for biogas recovery (no. 8, at a capital cost of $27.2 million (adjusted to 2014 dollars)).

Some of the options (no. 9, 10, 13, 18) are not cost-effective from either utility or city perspective as the developed cost curves have not accounted for any non-energy cost benefits (e.g. deferment of infrastructure augmentation, managing urban runoff, reducing treatment costs).

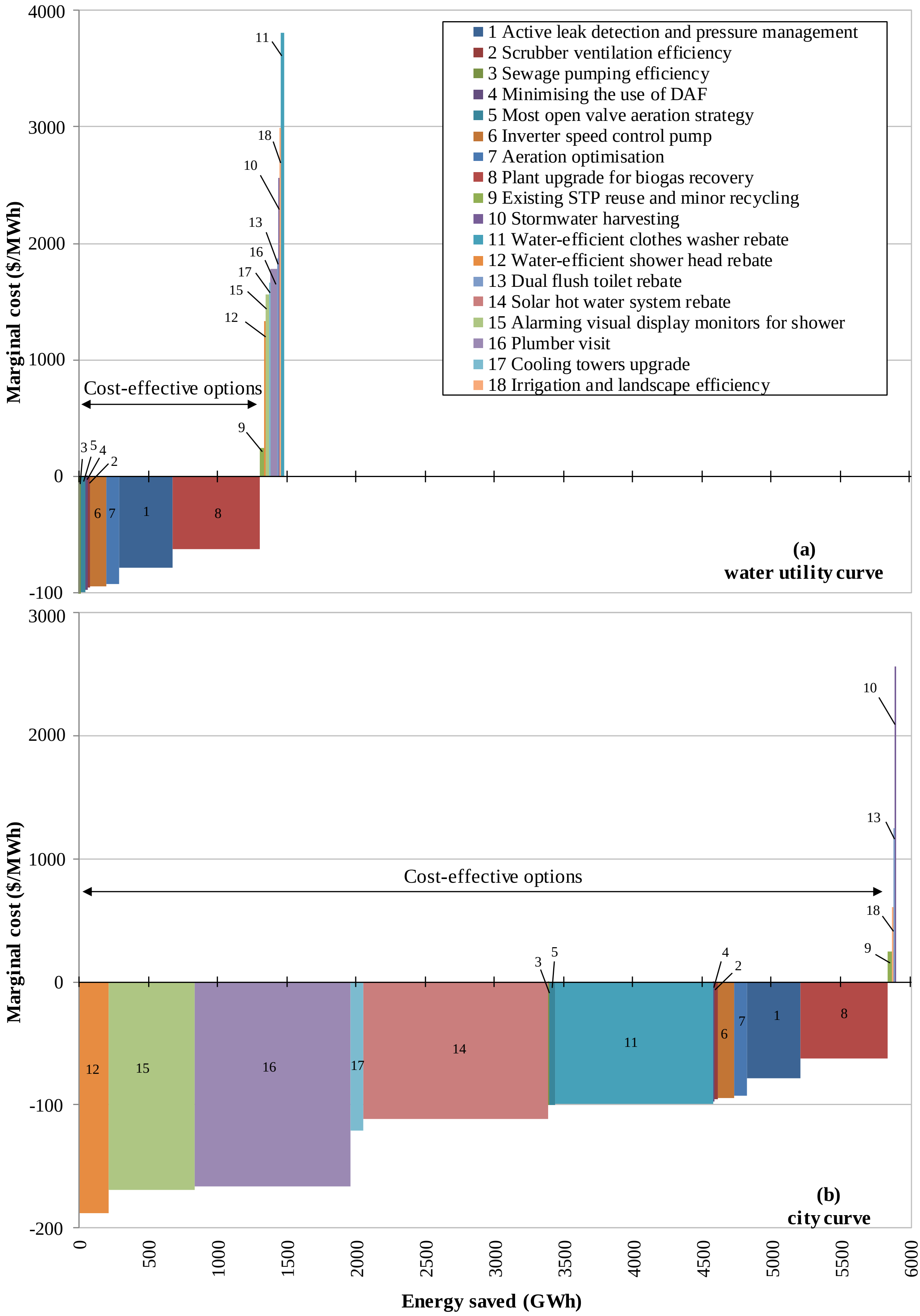

Figure 3 Cost curves for water-related energy management from (a) a water utility perspective and (b) a city perspective

3.2 Implications for setting water-related energy and GHG management policies

Energy use and GHG emissions of urban water systems are typically managed by utilities, but the water-related energy use and GHG emissions in the wider urban water system (which include residential water use, industrial water use, and decentralised water supply) are more loosely managed. Visions for managing water-related energy use and GHG emissions in urban water end use are scattered among different policy areas such as building efficiency, product energy efficiency, renewable energy targets, and water demand management programs. Water utilities are arguably the ideal agency for assisting end use water-related energy management because they have access to water use pattern data from water demand management programme (Turner *et al.*, 2005) and smart metering (Britton *et al.*, 2013). This information would enhance the quantification of the energy impacts of options and help customise the options based on the local context.

Based on the average GHG emission factor of electricity generation of the four Australian cities used for the hypothetical city, the corresponding marginal abatement cost curve for GHG emissions from the city perspective can be developed (Figure 4). Into the future, if the electricity mix becomes less carbon-intensive, the abatement potential (i.e. the width of the bar) will reduce and the magnitude of the marginal abatement cost (i.e. the height of the bar) will increase. Furthermore, if carbon is priced, the marginal abatement cost will become more negative.

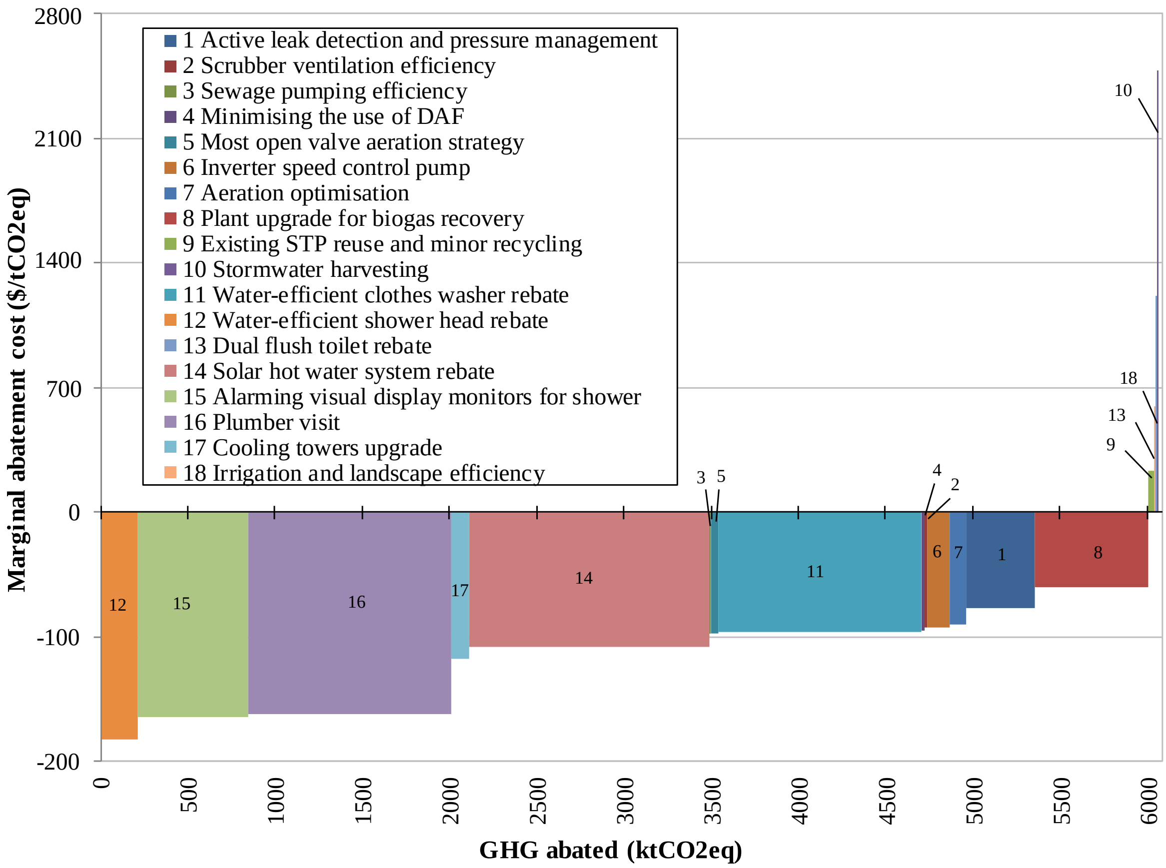

Figure 4 Marginal abatement cost curve from the city perspective

The utility curve (Figure 3(a)) has clearly shown that there is currently a lack of direct financial benefit for utilities to consider and support managing the water-related energy use and GHG emissions at the water end use. One way to overcome this barrier could be through some forms of carbon offset that creates a financial incentive. For instance, carbon management policy for water utilities could be designed to allow the purchase of non-utility water-related GHG emissions reduction to offset the emissions of the centralised systems. This would be similar to investing in external renewable energy generation to offset electricity use of desalination plants, or purchasing renewable energy credits (Cook *et al.*, 2012). As managing GHG emissions increasingly becomes a long-term goal for some water utilities, it would be a window of opportunity to include a wider range of water-related energy use management opportunities into the water agenda.

Some water utilities are aiming to make their systems "carbon-neutral" (Workman, 2015). They have encountered challenges to eliminate residual GHG emissions cost effectively. Taking a wider urban water system perspective would mean that instead of investing a significant amount of money for achieving carbon-neutrality within their organisation boundary, some of the budget would be allocated for options outside the utility, and would save more energy and abate more GHG for a city.

In recent years, water demand management has been one of the key elements in the water strategies of some utilities, especially regions encountering water stress. What they need to consider further is the energy consequence of their demand-side intervention and to include them in the energy and GHG management plan. Once these typically unaccounted for energy, GHG and cost benefits are included in cost-benefit analysis, this would provide policy makers a stronger incentive to promote wider-system options. This work demonstrates that the cost curve can be a decision support tool for water planners to prioritise options on both the water supply-side and the demand-side for long-term energy and GHG management of urban water cycle.

3.3 Sensitivity analysis

A sensitivity analysis was performed to determine how each input parameter influences the marginal cost and energy saving potential of each of the options. Percentage variations of -50% and +50% from the base values of input parameters were used. The sensitivity analysis results of the four most significant energy saving options in the city cost curve are presented in Figure 5 and all other results are included in the Supplementary Material. The sensitivity diagram shows the ranges of an output result (in Figure 5, it is the marginal cost) for the low (-50%) and high (+50%) values of all input parameters (Loucks et al., 2005). The analysis shows that the marginal cost is more sensitive to the changes in the electricity price, discount rate, and the water and energy saving potential of an option. For instance, the higher the electricity price, the more cost-effective the options would be.

The sensitivity analysis reflects the performance of energy saving options if these options are applied to other cities with different water systems (e.g. systems with different energy intensity of supply, water pricing, etc.) and energy systems (e.g. energy price, energy mix). In general, cities with higher energy prices would find the options more cost-effective than they are in the hypothetical city, providing that the capital costs of the options are similar. On the other hand, cities with higher energy intensity in the water supply system (i.e. having a different water supply mix such as more desalinated water or imported water) would not find any significant improvement in the marginal cost for most of the options, especially the end use options (Figures 5 and 3S). This is because the energy and cost saving occurred in the end use is several magnitudes greater than that in the water utilities.

A range of factors can influence the performance of individual options. While this level of detail is beyond the scope of this paper, some examples are worth clarifying. For example, the temperature of delivered mains water in cities with different climate would influence the relative energy impacts of different options. In particular, it would impact the energy saving potential of options which involve water heating (no. 11, 12, 14, 15, 16). Based on the sensitivity analysis (Figures 5 and 3S), this climatic

factor (determining “energy saving – end use”) is less influential on the marginal cost (i.e. the height of the bar in cost curve) than other factors such as electricity price and discount rate. On the other hand, the energy saving potential (i.e. the width of the bar in cost curve) is strongly influenced by such a climate difference (Figure 5S).

There are other behavioural, technological and environmental factors that are not directly captured by the sensitivity analysis can influence the cost curves in other cities. For example, shower duration, flow-rate, frequency and temperature all have significant impact on end use water-related energy (Kenway *et al*., 2016). Changes to these parameters in cities could have a marked impact on the relative size of options (e.g. options 11 (clothes washer rebate) and 12 (shower head rebate)). In addition, since some of the options used in this work are water conservation basis. Their saving potential would depend on the existing water-related household stock and water use behaviour (e.g. the efficiency of existing cloth washers, the average duration of showering time). For detailed sensitivity analysis of how technical, behavioural and environmental factors (including water temperature) influence household water-related energy use refer to Kenway *et al.* (2012; 2016).

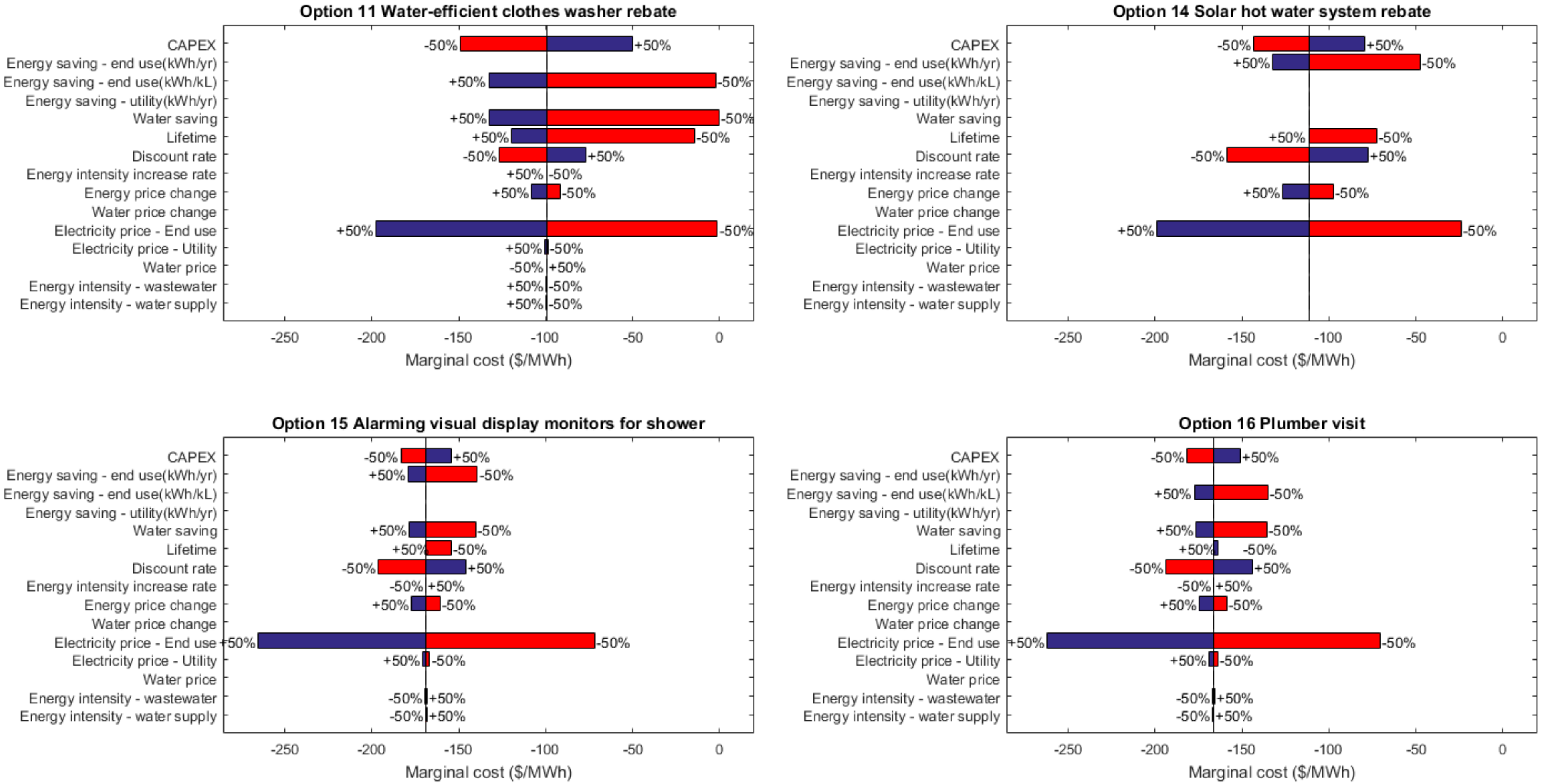

Figure 5 Sensitivity diagrams showing the ranges of the marginal costs of the top four significant options for low and high values of the input parameters

3.4 Uncertainty and limitations

In order to understand the uncertainty of the results, a Monte Carlo simulation using 10,000 runs was carried out (Figure 1S in Supplementary Material) based on an approach described in the literature (Stokes *et al.*, 2014). Probability distribution functions were assigned to all input parameters for the options and the hypothetical city. The distribution functions of input parameters used are listed in Table 4S and 5S (Supplementary material). The simulation generated the output distributions of the marginal cost ($/MWh) for each option. These distributions give indications of the uncertainty of the results. Figure 6 shows the median, 10^{th} percentile and 90^{th} percentile of the marginal cost of all the options in the city perspective curve. Considering the error bars, the 10^{th} percentile marginal costs of most of the significant cost-effective demand-side options (no. 12, 15, 16) are still lower than the 90^{th} percentile marginal costs of all the cost-effective utility options (no. 1 -8). Options that are not cost-effective (no. 9, 10, 13, 18) appear to have higher uncertainty in the marginal cost. However, since their energy saving potential is relatively insignificant (as shown in Figure 3(b)), their uncertainties have little effect on the overall result of the cost curve.

The major limitations of this work are the use of a hypothetical city and the reliance of published data rather than mechanistic modelling to develop the cost curves. This approach was adopted to overcome data limitations and focus on conceptual and methodological questions. Despite its hypothetical nature, the city was still based strongly on the characteristics of four Australian cities – Brisbane, Melbourne, Sydney and Perth. In addition, all the water-related energy management options used were based on implemented or evaluated actual options across Australia. The methodology outlined in this work can be used by water planners to construct the cost curves for water-related energy and GHG emissions management in their cities or regions based on their water balance models and detailed options analysis. Using local contextual data and models to conduct detailed analysis can potentially overcome some of the limitations of this work by for example, conducting detailed scenario analysis on the impacts of city characteristics, accounting for the interactions between options and conducting more comprehensive economic assessment.

Other limitations are on the cost curve approach itself and have been extensively discussed by Kesicki and Ekins (2012). To partially address some of these limitations (namely uncertainty and transparency), a probabilistic model was used in this work to perform an uncertainty analysis. In addition, the assumptions and the methodology used in this work are detailed in section 2 and the Supplementary Material.

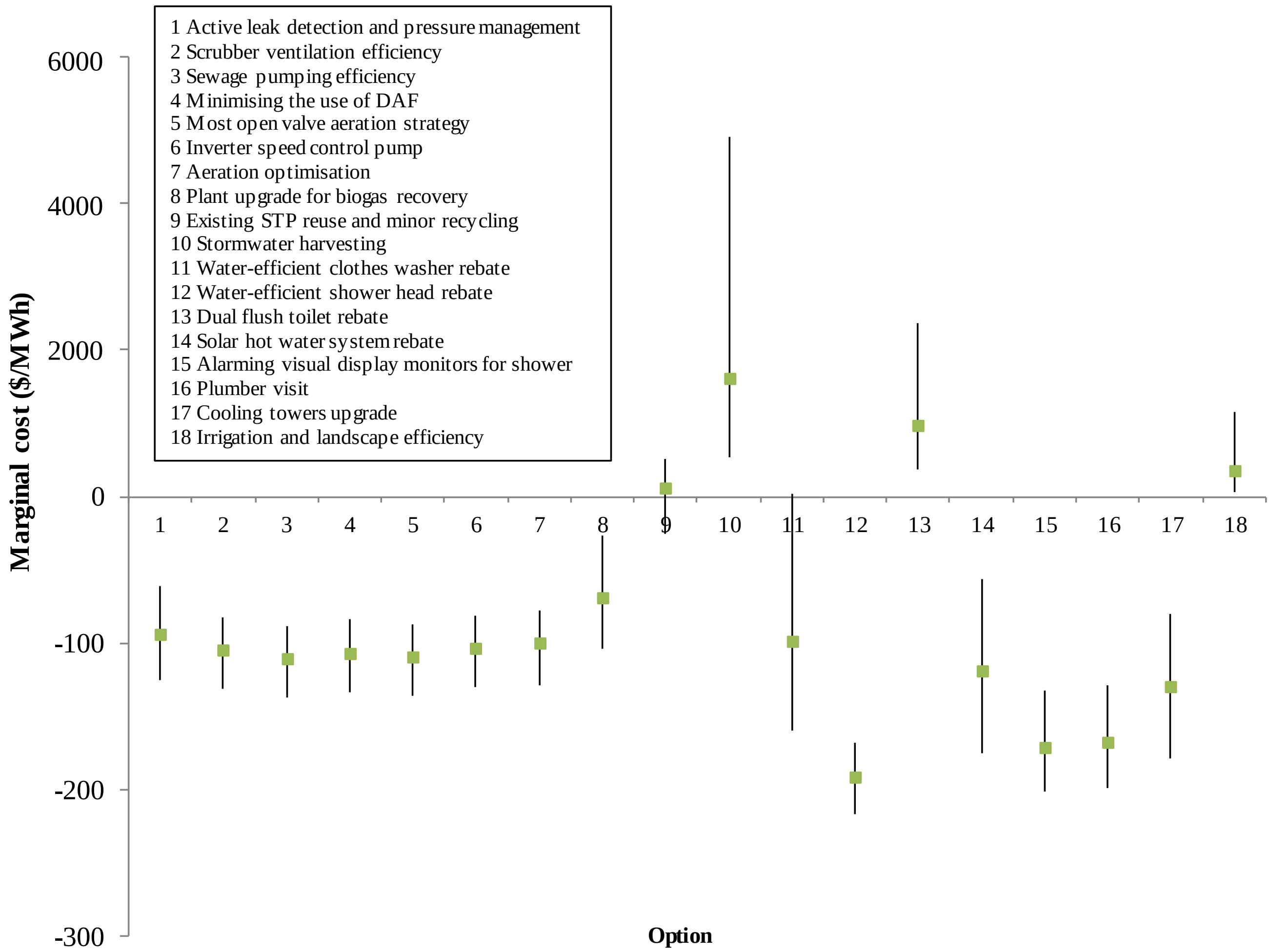

Figure 6 Median, 10th percentile and 90th percentile of the marginal cost of all the options in the city perspective curve from Monte Carlo simulation

4 Conclusions

The key contribution of this work is to develop and compare cost curves for water-related energy options in a hypothetical Australian city from two perspectives, namely the city and the water utility. The key insights are as follows.

- For the same set of water-related energy management options in the Australian context, the cost-effective energy saving potential experienced by the city is far more significant than that of the water utility. A significant portion of these additional energy saving comes from hot-water related energy use associated with water end use conservation.
- By broadening the current scope of cost curves beyond the system boundary of water utilities, some options with more significant energy saving potential and cost-effectiveness would stand out, instead of being neglected in the utility curve. This would create opportunities where for the same capital investment, a greater amount of energy saving and carbon abatement could be

achieved. On the other hand, focusing on the utility cost curve may result in energy saving and carbon abatement opportunities being overlooked.

- There is a need to create the right incentives for water utilities to look beyond their system boundaries so as to achieve greater energy saving and GHG abatement in urban water systems. Under the current cost-benefit analysis approach, water end use options do not offer direct financial incentive to water utilities. One way to overcome this barrier may be through some form of carbon offset scheme that allows water utilities to purchase non-utility water-related GHG emissions reductions to offset the emissions of the centralised systems operated by utilities.
- This work also demonstrates that the cost curve can be a useful decision support tool to compare and rank options across the interface of the utility and water end use.
- While this study is based on the Australian context and some of the local characteristics have been shown to strongly influence what the more cost-effective or greater energy saving options for a city can be, water planners in different cities can use the outlined approach to assess what the better energy saving opportunities in their wider urban water systems are.

Abbreviations

$CAPEX_{City}$	Capital expenditure from water utility/government and end users ($)
$CAPEX_{Utility}$	Capital expenditure from water utility ($)
E_{EU}	Energy saving at water end use as quantified by the data source (MWh/year)
$E_{EU,t}$	Energy saving at water end use in *t* th year (MWh)
$E_{EW,t}$	Energy saving at water utility in *t* th year (MWh)
$E_{O,WU}$	Energy saving at water utility (non-water saving related) (MWh/year)
$EC_{EU,t}$	Electricity price at water end use in the *t* th year ($/MWh)
$EC_{WU,t}$	Electricity price at water utility in the *t* th year ($/MWh)
$ECS_{EU,t}$	Energy cost saving at water end use in the *t* th year ($)
$ECS_{WU,t}$	Energy cost saving at water utility in the *t* th year ($)
EI_{EU}	Energy intensity for water end use activities (MWh/ML)
$EI_{WS,t}$	Energy intensity for water supply in the *t* th year (MWh/ML)
$EI_{WW,t}$	Energy intensity for wastewater treatment in the *t* th year (MWh/ML)
EP_{City}	Energy saving potential of an option from the city perspective (MWh)
$EP_{Utility}$	Energy saving potential of an option from the water utility perspective (MWh)
$i_{EC,EU}$	Electricity price annual change rate at water end use (%)
$i_{EC,WU}$	Electricity price annual change rate at water utility (%)
$i_{EI,WS}$	Energy intensity for water supply annual change rate (%)

$i_{EI,WW}$	Energy intensity for wastewater treatment annual change rate (%)
i_{WC}	Water price annual change rate (%)
MC_{City}	Marginal cost of an option from the city perspective ($/MWh)
$MC_{Utility}$	Marginal cost of an option from the water utility perspective ($/MWh)
t	Year
t_{option}	Lifetime of option
T_{max}	Number of assessment year
TC_{City}	Net cost of an option from the city perspective ($)
$TC_{Utility}$	Net cost of an option from the water utility perspective ($)
V_w	Water saving from the mains (ML/year)
WC_t	Water price ($/ML)

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