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Water-Energy-GHG emissions accounting for urban water supply: A case study on an urban redevelopment in Melbourne

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Abstract: This paper presents a conceptual accounting framework to quantify the life cycle energy use and GHG emissions of alternative urban water supply strategies. The framework enables the comparative analysis of alternative strategies to design a fit-for-purpose water supply system that takes into account water supply, energy use and GHG emissions and has been tested on the Fisherman's Bend development site in Melbourne Metropolitan region and results are presented. This study does not include the environmental and social benefits incurred from deploying multiple water sources, which must be considered before making strategic decision about implementation of alternative sources of water supply.

Key Words: Urban water; Energy use; Greenhouse Gases (GHG's)

1. INTRODUCTION

Water scarcity and climate change are the key defining challenges of this century. Population growth, intense agricultural development, urbanisation and industrial growth are all leading to increased demand for water. At the same time, the environmental impacts of current water systems are being increasingly scrutinised. As many nations are now exploring alternative water supply and wastewater treatment options including rainwater tanks, recycling, reuse and desalination among others to provide future water security, it is critical to carefully examine the energy intensity and associated GHG emissions of these alternative strategies. This is especially significant since most of these alternative water supply options were found to have greater energy intensity than traditional sources (Aye *et al*., 2012; Cohen *et al*., 2004; Marsh and Sharma, 2007). Energy used to source, treat and distribute water, and collect and treat wastewater has been estimated to account for 7% of the total global energy use in 2001 (James *et al*., 2002). The nexus between energy and water cycle is increasingly important due to increasing water scarcity in many regions of the world which drives new strategies towards reusing water, and the urgent need to mitigate GHG emissions (Rocheta and Peirson, 2011). Climate change adds further complexity in some regions by reducing water availability and therefore increasing the energy intensity and associated GHG emissions needed to access and treat water (Kenway *et al*., 2011). As cities expand and existing areas are redeveloped, energy consumption associated with water distribution also increases. Understanding the water-energy nexus will enable the water industry to reduce its operational energy and reduce GHG emissions, and as a result, facilitate the design of water supply and wastewater treatment systems capable of realising more synergistic benefits (Sattenspiel, 2009).

In 2006, the total energy used (to source, treat and distribute water and collect & treat wastewater) by water utilities in Sydney, Melbourne, Perth, Brisbane, Gold Coast and Adelaide was 7.1 PJ (Kenway *et al*., 2008). Melbourne Water was among the top 15 electricity users in Victoria and the top 150 in Australia using 1.64 PJ of energy in 2009-10 (1.416 PJ in 2008-09) at a cost of \$20.2 million compared with \$17 million in 2008-09. Operational GHG emissions were 351 kt of carbon dioxide equivalent ($CO_{2\text{-}e}$) (Melbourne Water, 2010). Additionally, the recently constructed desalination plant with a capacity to deliver up to 150 GL a year, would consume 2,160 MWh of electricity daily and produce 1.4 Mt CO_{2-e} during construction with an additional 1.2 Mt CO_{2-e} annually.

True energy neutrality or better performance of alternative water supply and wastewater treatment strategies is clearly an important aim. In recent years, significant efforts have been made to reduce water consumption and GHG emissions. These efforts, however, have largely been carried out separately for water resource management and energy-GHG emissions due to lack of tools capable of analysing the nexus between water supply and energy/GHG in an integrated way. This has resulted in lack of coherence generally reflected in planning and management of water and energy resource in isolation of each other.

Several studies have dealt with various aspects of water supply and energy use. Wilkinson (2007) investigated the energy usage for urban water supply but the study did not focus on GHG emissions and possible solutions. Lundie *et al*. (2004) evaluated the water and wastewater services projected for 2021 in Sydney and concluded that demand management and energy efficiency provide the best opportunities in terms of water and energy savings respectively. Kenway *et al*. (2008a) studied the energy usage in the provision and consumption of urban water in Australian and New Zealand cities at the system level, object level (household level) and total urban energy use. The study provided a first estimate of energy use for water provision in Australia, but does not offer an in depth analysis of the interactions between the water and energy use and GHG emissions under various scenarios.

Detailed assessment and understanding of the Water-Energy-GHG nexus is crucial to enable the water and energy systems to ascertain where gains can be made more effectively (Rocheta and Peirson, 2011) and to ensure that the adaptation strategies in urban water supply systems do not contribute to increased GHG emissions. Understanding the water-energy-GHG nexus and having the ability to quantify life cycle energy use and GHG emissions associated with urban water provision and wastewater treatment can reduce its operational energy costs and associated GHG emissions.

Much of the research described above focuses on specific aspects of the water-energy nexus. There is, however, at present a lack of a comprehensive accounting framework capable of analyzing the water supply potential, energy use and associated GHG emissions in an integrated way. The main objective of this research is to enable the comprehensive quantification of water-energy-GHG nexus within the entire urban water cycle by development of a conceptual framework for the evaluation and comparison of various water supply options. This integrated approach will help the government and water and energy planners to make informed decisions to achieve synergistic benefits in water saving, energy saving and GHG mitigation. The framework can assist in developing and evaluating various alternative water supply and wastewater treatment strategies and quantify water and energy efficiency relationships.

2. THE MAIN ATTRIBUTES OF THE FRAMEWORK

The following key life cycle stages of the urban water cycle are considered in the proposed framework:

1. Extraction of surface or groundwater and transport to the water treatment plant,
2. Treatment of water to the desired quality,
3. Distribution of water to users,
4. Wastewater collection and transport to the treatment plant,
5. Treatment of wastewater to meet the required quality of discharge and final disposal.

At a sub-system level, complexity may vary to include internal processes and interactions between subsystems, which may include internal recycling processes such as:

- Use of rain water tanks to collect rainwater from rooftops. This study assumes that all the households and commercial buildings are equipped with rainwater tanks. A maximum tank size of 2.5 ML has been used.

- Storm water harvesting, which includes rainwater collected from pavements, roads and open spaces. This water can be collected by using various water sensitive urban design (WSUD) structures such as swales, bio filters, retention ponds and wetlands and subjected to various levels of treatment appropriate for further use.
- Decentralised water treatment, which includes grey water treatment and sewer mining.

Urban water supply and wastewater systems are highly complex. The number of subsystems and in particular the various interactions between these subsystems determine the complexity of the system. In conceptualising this framework, we have adopted a universally applicable methodology to account for the water demand, supply sources and the energy intensity at each step of urban water supply and wastewater treatment. The framework identifies all the linkages between various life cycle stages of urban water cycle and associated energy use and GHG emissions (Figure 1). In the following, we provide a description of the key underlying concepts and mathematical formulation associated with the proposed framework.

The total water demand in ML/year is estimated by:

$$W_D = W_r + W_c + W_i \tag{1}$$

where W_D is the total water demand (ML/year), W_r, W_c and W_i are the residential water demand (ML/year), commercial water demand (ML/year) and irrigation water demand (ML/year), respectively.

Residential water demand in ML/year is calculated as:

$$W_r = n w_r 365 \times 10^{-6} \tag{2}$$

where n = total number of occupants, w_r = average daily residential water use (L $person^{-1}$).

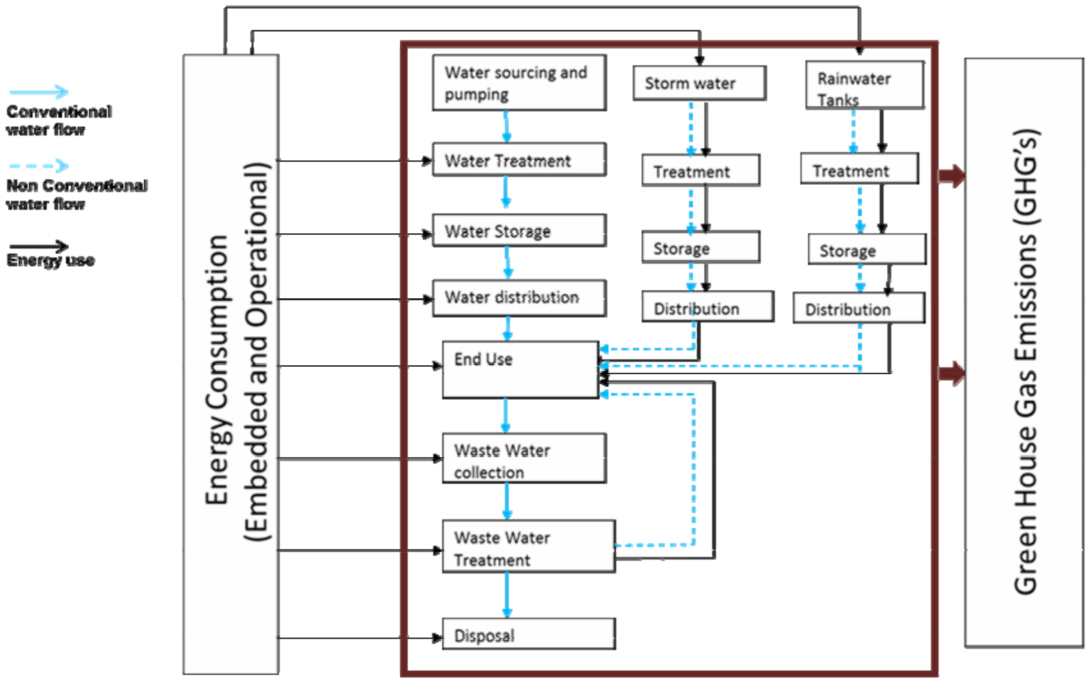

Fig. 1: The conceptual framework of components contributing GHG emissions and energy use in urban water cycle.

Commercial water demand in ML/year is calculated as:

$$W_c = A_c w_c 365\times10^{-6} \quad (3)$$

where, A_c = total area (m^2), w_c = average daily commercial water use (L m^{-2}).

Irrigation water demand in ML/year is calculated as:

$$W_i = A_i w_i 365\times10^{-6} \quad (4)$$

where A_i =total irrigated open area (m^2), w_i =average daily irrigation water use (Lm^{-2}).

The total available on site water supply potential (W_s) includes the recycling potential, rainwater harvesting potential and storm water runoff. In this paper, it was assumed these water sources will be utilized for irrigation, toilet flushing, laundry and other non-potable outdoor uses with or without treatment. None of these sources feed into the drinking water supply system which is supplied from conventional water resources (surface reservoirs in case of Melbourne) after treatment to potable standard. The total potential water sources available on site can be expressed as:

$$W_S = W_R + W_{RW} + W_{SW} \quad (5)$$

where $W_{R,}$ W_{RW} and W_{SW} are the recycling potential, rainwater harvesting potential and stormwater runoff potential, respectively.

Total recycling potential in ML/year is expressed as:

$$W_R = (W_r + W_c)g\,c_g + (W_r + W_c)b\,c_b \quad (6)$$

where g = grey water coefficient (L of grey water/L of water supplied), b = black water coefficient (L of black water/L of water supplied), c_g = capture rate for grey water (0.65) and c_b = capture rate for black water (0.65).

The rainfall-runoff generation model, SIMHYD (Chiew *et al*., 2002) was used to calculate the rainwater harvesting potential (W_{RW}) and storm water potential (W_{SW}) of the site. Historical daily rainfall data and potential evapo-transpiration data for the region for last 151 years (1860-2010) was collected from the Bureau of Meteorology to simulate daily rainwater and stormwater runoff potential. The provision of rainwater and stormwater will require additional plumbing, pumps and storage tanks.

The total imported water required (W_I) in ML/year can be calculated as:

$$W_I = W_D - W_S \quad (7)$$

where W_D and W_S are the total water demand and total on-site water supply potential, respectively.

A detailed calculation of the embodied as well as the transport and operational energy use for each stage of the urban water cycle is performed using a life cycle analysis (LCA) approach. The LCA of an urban system entails defining the geographical boundaries of the system including upstream and downstream cut offs, and includes the entire water supply chain extending from the diversion of water from surface or groundwater sources to the discharge of treated and untreated wastewater and storm water as specified in the proposed framework.

Conveyance of water and wastewater, treatment and disposal of sewage sludge determine the amount of energy use and GHG emissions throughout the life cycle stages. To estimate the life cycle GHG emissions, all GHG emissions in each stage must be quantified (Aye *et al.*, 2007). For this purpose, the energy use and greenhouse gas emissions are divided into three categories:

- Embodied energy and embodied GHG emissions (subscript e)
- Energy use and GHG emissions for transport (subscript t)
- Operational energy use and operation GHG emissions (subscript o)

Embodied greenhouse gas emissions are the cumulative greenhouse emissions associated with the production of materials used in the fabrication of the equipment used. This can be estimated by:

$$G_{s,e} = \sum (a_i W_i) \quad (8)$$

where a_i = embodied GHG emissions per unit of each material (kg CO_2-e/kg) and W_i = weight of each material (kg)

Transport GHG emissions is defined by:

$$G_{s,t} = \sum (b_i D_i W_i) \quad (9)$$

where b_i = transport GHG emissions per distance per unit weight of each equipment (kg CO_2-e/km per unit weight) and D_i = distance of transport (km)

Operational greenhouse gas emission is defined by:

$$G_{s,o} = \sum (c_j E_j) + \sum (G_r) \quad (10)$$

where c_j = full fuel cycle emission factor of each type of energy used (kg CO_2-e/MJ), Types of energy use include electricity, gas, oil and other forms of intermediate fuels, E_j = annual operational primary energy consumption (MJ), G_r = annual greenhouse gas emissions from solid, liquid or gaseous residues from operation (kg CO_2-e).

The total life cycle energy use can be expressed as:

$$E = \sum_{s=1}^{6} E_{s,e} + \sum_{s=1}^{6} E_{s,t} + \sum_{s=1}^{6} E_{s,o} = \sum_{s=1}^{6} E_s \quad (11)$$

where ‘*s*’ is the life cycle stage and E is the total life cycle energy use for stage ‘s’.

The total life cycle GHG emissions can be expressed as:

$$G = \sum_{s=1}^{6} G_{s,e} + \sum_{s=1}^{6} G_{s,t} + \sum_{s=1}^{6} G_{s,o} = \sum_{s=1}^{6} G_s \quad (12)$$

where *s* is the life cycle stage and G is the total life cycle greenhouse gas emissions for stage ‘s’.

3. CASE STUDY: FISHERMAN’S BEND DEVELOPMENT

In 2012, the Victorian State Government announced plans to redevelop the light-industrial

Fishermen's Bend district in Port Melbourne into a modern mixed-residential area. The site is approximately 240 hectares in size and is intended to house roughly 50,000 residents and provide 25,000 jobs. The Fishermans Bend Urban Renewal Area (FBURA) is divided into four precincts: Lorimer, Montague, Sandridge, and Wirraway as shown in Figure 2. The project will be developed in four phases. This case study presents an evaluation of water demand and supply and the associated energy use and GHG emissions for one of the precincts: Wirraway. The total area of the site is 89 hectares. The site consists of 500 detached houses and 6300 four-story apartments to cater for a total population of 13,900. It has a supermarket, an age care facility and an aquatic facility (combined commercial floor area 10,800 m^2) within the precinct. Three main sources of water are available locally in addition to imported water -roof rainwater, stormwater and recycled wastewater.

Figure 2: Locational map of the Fisherman's development project.

4. HYDROLOGIC ANALYSIS

The State Government has placed great importance on the sustainability and liveability of the new community. The existing Fishermans Bend water supply infrastructure is insufficient to cope with the future increase in population associated with the FBURA development project. Both water supply and wastewater management infrastructure require significant augmentation, which provides an opportunity to apply the proposed framework. These two types of water infrastructure are linked by the potential for wastewater recycling.

The first step in improving the water infrastructure is to determine the water supply requirements of the development followed by identification of water sources including mains water, rainwater and recycled water that are capable of meeting the water supply requirements and meet additional sustainability criteria including energy use and greenhouse gas emissions. Equations 1 to 12 were applied to estimate the water demand and supply potential, energy use and associated GHG emissions as presented in Tables 3 and 4.

End use water data (wr =155 Lpd, wc = 70 Lm^{-2}, wi = 0.21 Lm^{-2}) provided by Yarra Valley Water was used to calculate the water demand (Roberts, 2005). The volume of grey water and black water were calculated by applying a grey water coefficient (g=0.65) and a black water coefficient (b=0.35). The capture coefficient was estimated at cg=cb=0.65. The SIMHYD model was used to calculate the rainwater and stormwater potential of the site. Out of the total area of 0.89 km^2, 0.22 km2 is the roof top area, 0.33 km^2 is impervious area and the remaining 0.34 km^2 is pervious area.

An impervious runoff coefficient of 0.9 has been utilised in this study with 0.1 runoff loss coefficient. Table 1 shows a summary of the rainwater, stormwater and recycled water potential for the site. The results suggest that 85.5% of total demand for 13,900 residents can be met from on site sources if all the locally available sources of water are utilized.

Rainwater and storm water harvesting potential on the site was calculated by the rainfall-runoff generation model, SIMHYD (Chiew et al., 2002) using the historical daily rainfall data and potential evapotranspiration data for the region for last 151 years (1860-2010). Table 2 presents the rainwater potential of the site and the level of water security for various storage sizes. The optimal size of the storage needs to consider site specific requirements (e.g. the total water demand to be met from rain water tanks) and the cost and feasibility of selected storage size in terms of its placement. For example, with a 2.5 ML storage tank for rainwater collection, full demand at a rate of 40 L/d for toilet flushing and garden irrigation can be met for 143 days with 40% reliability and partial demand (less than 40 L/d) can be met for 220 days and 33.9% of total water will be spilled. On average, the water will spill for 18 days in any given year. A tank smaller than 2.5 ML will reduce reliability of water supply and increase the rainwater spillage. On the other hand, a larger storage tank may provide greater reliability of water supply but may incur significantly higher cost and space with little additional benefit in terms of water saving. These factors need to be considered while making management decision.

Table 1: Water demand and Supply potential for a population of 13,900 inhabitants.

Water Demand (ML/year)				**Water Supply potential of the site (ML/year)**				**Imported water needed (ML/year)**
Residential	**Commercial**	**Irrigation**	**Total**	**Rain water tanks**	**Storm water**	**Recycle d water**	**Total**	
786	276	27	1089	96	146	690	932	157
72.2%	25.3%	2.5%	100%	8.8%	13.4%	63.4%	85.5%	14.4%

Table 2: Rainwater potential of the site and the level of water security for various storage sizes.

Tank size (ML)	**Water captured (ML/Year)**	**Full demand met (days)**	**Reliability (%)**	**Partial demand met (days)**	**Spill days**	**Water spilled (%)**
1.5	86	119	32.6	204	26	50.58
2	92	132.6	36	213	21	40.76
2.5	96.7	143	40	220	18	33.92
3	100	151	41.3	225	16	29.50
4	106	162	44.6	233	12	22.17
5	110	171	47	238	9.9	17.73
8	118	187	51	248	5.7	9.75
10	121	193	53	253	4	7.02
12	123	197	54	256	3	5.28
15	125	201	55	258	1.9	3.60

Storm water harvesting can provide additional 146 ML/year of supply. Both rainwater and stormwater are weather dependent sources, whereas recycled water presents a huge opportunity in terms of volume of water available and can be extracted regardless of climatic conditions.

5. ENERGY ANALYSIS

Kenway *et al*. (2008) investigated and reported the life cycle energy use in the provision and consumption of urban portable water in several cities in Australia. Cook *et al*. (2012) later updated the data set. The energy use figures for various water supply sources applied in this case study are shown in Table 3. It should be noted that the available data is in the form of aggregated figures for combined embodied, transport and operation energy.

Table 3: Energy use for various water supply sources (Kenway et al., 2008; Cook et al., 2012; Tjandraatmadja et al., 2011, Grant and Opray, 2005).

Life cycle stage		**Energy use (E), MWh/ML**				
		Conventional	**Rain**	**Storm**	**Recycled**	**Desalination**
Extraction of water	E_1	-	-	0.41	-	-
Treatment of water	E_2	0.17	0.93	0.93	0.97	5.33
Distribution of water	E_3	0.29	1.3	0.29	0.29	0.29
Wastewater collection	E_4	0.52	0.52	0.52	0.52	0.52
Wastewater treatment & disposal	$E_{5\ \&6}$	0.64	0.64	0.64	0.64	0.64
Total energy use	E	1.63	3.39	2.80	2.42	6.78

The energy use mix for centralised water services in Melbourne are electricity 55.8%, self-generated purchased renewable energy 26.2%, natural gas 3.8%, Diesel oil 7.5%, LPG 0.6% and fuel oil 3.8% (Cook *et al*., 2012). The AGO (2012) estimated the weighted average GHG emission factor for Melbourne water services at 0.823 kg CO_2-e/kWh based on the energy use mix and the emission factors of these fuels for Victoria. The form of energy used by decentralised systems - rainwater tanks, storm water harvesting, and recycled water is assumed to be electricity with a GHG emission factor of 1.35 kg CO_2-e/kWh. This factor was also applied for all other decentralised water supply options. The derived GHG emission factors are presented in Table 4. The total energy use and GHG emissions associated with water services on the site are presented in Tables 5 and 6.

6. DISCUSSION

The energy use and GHG emissions of a water supply option can vary depending upon the method of water extraction, treatment process and end use. The framework presented herein is designed provide an assessment of the amount of energy use and GHG emissions associated with various source options for water supply. It should be noted that this study does not include the environmental and social benefits incurred from deploying multiple water sources, which under certain conditions may overweigh the detrimental impact of increased energy use and GHG emissions that arise from using alternative sources of supply. For example, recycling wastewater for non-potable uses can enhance water supply in dry seasons, better cope with extreme droughts and support urban green spaces and irrigation. However, a number of other social and environmental criteria may affect the decision to adopt these measures such as capital and operational expenditure, chemical use, land use for each system.

Water demand increases with increasing population growth, which in turns leads to an increase in the amount of recycled water available on the site. It is important to note that roof rainwater and storm water available on site are finite as these are determined by climatic factors. It was estimated that the Fisherman's Bend study site selected for this study is capable of providing water if population density exceeds 11,815 residents in an average rainfall year, however, it will require additional imported water is population density exceeds. Also, as rainwater and storm water are weather dependent sources, their availability might vary spatially and temporally and therefore require storage. The size of storage available can also influence the usable rainwater and storm water available on site.

The results from the case study reveal that annual energy use and GHG emissions are higher than the BAU scenario that employs only conventional water treated to potable standard for all end uses

(Tables 5 & 6). Rainwater requires the highest energy input followed by stormwater and recycled water. The use of conventional water sources entails the lowest amount of energy and associated GHG emissions. Water sourced from desalination requires more energy than all the other alternative sources.

Table 4: GHG emission factors (AGO, 2012).

Life cycle stage		GHG emission (*G*), Mg/ML				
		Conventional	**Rain**	**Storm**	**Recycled**	**Desalination**
Extraction of water	G_1	-	-	0.56	-	-
Treatment of water	G_2	0.142	1.25	1.25	1.30	4.38
Distribution of water	G_3	0.24	1.75	0.40	0.40	0.23
Wastewater collection	G_4	0.42	0.42	0.42	0.42	0.42
Wastewater treatment & disposal	$G_{5\ \&\ 6}$	0.52	0.52	0.52	0.52	0.52
Total energy use	G	1.34	3.96	3.17	2.66	5.57

Table 5: Energy use for the water services to 13,900 residents.

	Energy use for each water source (MWh)				**Total Energy use (MWh)**
	Conventional	**Rainwater**	**Storm water**	**Recycled Water**	
Integrated Water Supply	254.89	325.44	409.38	1677.26	2666.98
Business as Usual Scenario	1776.76	-	-	-	1776.76
Desalinated water replacing rain water, stormwater and recycled water	6322.46	-	-	-	6322.46

Table 6: GHG Emissions for the water services to 13,900 residents.

	GHG emissions (t CO) $_{2\text{-e}}$				**Total GHG emissions (t CO) $_{2\text{-e}}$**
	Conventional	**Rainwater**	**Storm water**	**Recycled Water**	
Integrated Water Supply	209.78	439.34	552.67	2264.31	3466.09
Business as Usual Scenario	1462.27	-	-	-	1462.27
Desalinated water replacing rain, storm and recycled water	5203.38	-	-	-	5203.38

Under a scenario where alternative water supply sources are fully utilized before resorting to importing potable water, the amount of energy input to the system is 35% greater than under a BAU scenario based on the full supply requirement met from conventional water source (Table 5). These results confirm the importance of considering the tradeoffs that exist between water services and energy use when a fit-for-purpose approach is used to meet water demand. These tradeoffs vary depending on the hydrologic and physical configuration of each system. The water-energy evaluation framework presented in this study can be used to evaluate these trade offs and allow the choice of the appropriate design to meet the sustainability objectives of the system concern.

7. CONCLUSIONS

This paper presents a framework for accounting and estimating water demand, potential available water from non-coventional sources, life cycle energy use and life cycle GHG emissions in the urban water cycle. The framework includes the identification of water supply options used, methods for water extraction and treatment, embodied energy and operational energy use. The assessment framework was applied to the Fisherman's Bend study site in Melbourne, Australia. The key findings of this study drawn from the application the framework and analysis of the case study show that at a local scale, the use of rainwater capture entails the highest use of energy (3.39 MWh/ML) while the use of conventional water resources consume the lowest amount of energy (1.63 MWh/ML). The higher energy intensity of distributed systems are generally due to the processes involved, technological advances, inappropriate scale of operation and poor maintenance of these systems. The provision of water to the Fisherman's Bend study site making maximum use of alternative non-conventional sources requires 2667 MWh of energy and 3466 t CO_2-e of GHG emissions compared with 1777 MWh of energy and 1462 t CO_2-e of GHG emissions when the full supply is sourced from conventional water sources. The results also show that the total energy requirement (6322.46 MWh) and the GHG emissions (5203.38 t CO_2-e) for replacing the rain water and storm water with desalinated water presents the worst case. This study does not include the environmental and social benefits incurred from deploying multiple water sources, which under certain conditions may overweigh the detrimental impact of increased energy use and GHG. To address these questions, we recommend conducting an integrated social, environmental and economic assessment of such systems before making strategic decisions about implementation of these systems.

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