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Assessing the Water Energy Nexus and Sustainability Benefits of a Closed Loop Water Treatment System in Qatar

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Qatar has very limited freshwater resources. This paper assesses the sustainability implications of using bore water and treated sewage effluent (TSE) for residential water supply (for non-drinking purposes) in a residential compound in Doha, Qatar. The treated bore water was considered for non-drinking domestic applications in kitchens and bathrooms, while the TSE was considered for use in air conditioning cooling systems. Excess TSE was also considered for irrigation use. Water quality from the aquifer in the Al Waab area of Doha was used to design a pre-treatment and desalination process to produce potable water for a local residential compound consisting of 113 villas. The wastewater from these villas consisted of both grey and black water and was proposed to be treated in a sewage treatment plant to produce TSE to operate the cooling systems in the compound. The reject brine from the desalination process was designed to be discharged to sea through the storm water network and the blowdown water from the cooling systems was considered for use in irrigation in surrounding areas. A lifecycle assessment of this closed loop water recycling system was conducted to assess the potential sustainability benefits of reduced greenhouse gas emissions, embodied energy consumption, and water consumption, together with cost savings and employment generation from these water recycling options.

1. Introduction

The Qatari Government is keen to implement technically sound, economically feasible and environmentally safe water recycling options. There are a number of technological solutions for addressing this increasing water demand, but these solutions warrant investigation in terms of economic and environmental impacts. The Qatari Government is currently looking for opportunities to expand both the collection and the distribution systems for recycled water (Jasim, 2018). By distributing recycled water to more consumers, the Government can decrease the demands on other better quality sources of water and reduce wastewater discharge. By extending its domestic wastewater collection and treatment network, the Government can gradually reduce dependence on septic tanks. Advanced tertiary technologies, like membrane filtration and ultraviolet disinfection, can potentially be considered for further processing the treated wastewater for reuse in domestic applications, reducing the pressure on existing MSF desalination resources. Renewable energy technologies can be used to operate these advanced wastewater treatment technologies in order to reduce associated environmental and economic costs. Recent studies which have been conducted in Australia and Europe mainly dealt with the use of recycled wastewater for irrigation purposes (Laurenson et al. 2012). This wastewater can potentially be used by other applications, such industrial cooling purposes (Jasim, 2018). The use of a decentralised closed loop residential water supply option, as opposed to a centralized system, could be an alternative option for a water scarce region such as Qatar. This is because the aggregation of services over this rapidly growing region through a centralised water supply network is likely to be expensive in accommodating future water demand. Secondly, it will require considerable pumping energy to transport water over longer distances. No decentralised water supply option to date has been developed in Qatar, where locally available bore water can be treated for non-drinking applications and wastewater coming out of the residential complex can potentially be recycled for cooling systems, and other suitable applications, such as irrigation and landscaping. Some research has already been carried out comparing the environmental performance of MSF and MED with seawater reverse osmosis

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desalination (Darwish et al., 2013), to assess the lifecycle environmental impact of renewable energy powered reverse osmosis systems for enhancing food security (Samanaseh et al. 2017), and to assess the economic viability of wind energy systems (Marafia et al. 2003) in Qatar. The economic and environmental implications of the treatment of bore water for non-drinking applications and the use of treated wastewater in cooling systems in the Gulf region have not yet been reported. This paper assesses techno-economic and environmental implications of the use of closed loop decentralised water recovery system.

2. Materials and methods

This section presents the steps to work out the amount of chemicals and energy of water treatment for environmental and economic assessment.

2.1 Water quality analysis

The water quality data of bore water that was extracted from the construction sites of underground train stations in Doha was reviewed to determine the minimum, maximum and average values of key water quality parameters (Table 1). On the basis of bore water quality, a water treatment system has been designed to supply potable water for non-drinking application and cooling system usage for a residential compound in Al Wabb area of Qatar. The treatment system consists of a pre-treatment and desalination for converting bore water to water for non-drinking applications. The water system design includes filtration through media filters followed by reverse osmosis. The specific energy consumption of the process is primarily dictated by the water salinity. Therefore an estimate of the salinity was obtained using analytical results from water obtained from Doha's underground station sites. The TDS for the 15 percentile, 50 percentile and 85 percentile were determined. For each percentage, the complete analyses for each percentile was considered in the range of calculated percentile ± 250 mg/L. The 50 percentile was then taken for each analyte. Both black and greywater from the residential compound are mixed together before going to a municipal sewage treatment plant. This wastewater is typically 85% of the volume of incoming treated bore water that was supplied to this compound. The salinity of TSE was assumed to be reduced to 50 mg/L using reverse osmosis and ultra-filtration systems. This is value is representative of permeate from a reverse osmosis system.

Table 1: Water quality data of bore waters

Parameters	Units	15 percentile	50 percentile	85 percentile
pH	mg/L	7.73	7.65	7.51
Total suspended solids	mg/L	5	7	4
Total dissolved solids	mg/L	3,605	4,798	10,352
Turbidity	NTU	4	6	4
COD	mg/L	14	17	12
BOD	mg/L	3.4	3.6	3.0
Calcium	mg/L	579	608	675
Magnesium	mg/L	126	164	272
Iron	mg/L	0.03	0.02	0.01
Chloride	mg/L	840	1,371	4,486
Sulphate	mg/L	1,375	1,550	1,650
Bicarbonate	mg/L	171	165	233
Total alkalinity	mg/L as $CaCO_3$	145	135	191
Silica	mg/L	27	29	19
Coliforms	(MPN/100mL)	122	30	4.15

2.2 Water treatment system design

The design of the reverse osmosis system was evaluated for each water quality using the proprietary membrane design software to predict membrane performance. Knowledge of the performance under the three water qualities enabled a polynomial trendline to be derived to calculate the parameters (i.e. Specific energy consumption, permeate salinity, sulphuric acid dose rate to feed stream, calcium hydroxide dose rate to permeate) with respect to any bore water salinity in the range of 3,000 mg/L to 9,000 mg/L. Sulphuric acid is used to condition the feed stream to overcome potential scaling within the reverse osmosis system. Calcium hydroxide is used to condition permeate to give a Langelier Saturation Index (LSI) between 0 and -0.5 at a pH of less than 8.2 for the potable water stream. Calcium hydroxide is not dosed into the cooling tower make up stream. The pre-treatment and desalination processes were together designed to produce water for a residential compound of 113 villas in the Al Waab area. It is estimated that about 413 m^3/d will be required for water supply for domestic applications which is far less than the maximum yield of this location (i.e. 11,994 m^3/d). Figure 1 shows the design of the following two decentralised domestic water supply systems to supply water for domestic application and cooling systems. Option 1: Open loop decentralised water supply system using treated bore water for both non-drinking domestic applications and cooling systems. Option 2: Closed loop decentralised water supply system using treated bore water for non-drinking domestic applications and the use of TSE for cooling systems. A comparison between Options 1 and 2 was conducted to assess the environmental benefits in using TSE in cooling systems. In the case of Option 1, treated bore water has been considered for both non-drinking domestic applications (i.e. kitchens, bathrooms and toilet) and cooling systems of a residential compound. The wastewater that is discharged from this compound is typically disposed of to the ocean through a local sewage network. In the case of Option 2, treated bore water was considered for non-drinking domestic uses, while the TSE was considered for use in the cooling system. The wastewater from these villas that consists of both grey and black water was initially treated in a sewage treatment plant (STP) and then further treated through an advanced treatment system for use in the cooling system of the compound. The reject brine from the desalination process is disposed of to sea through a stormwater network and the blowdown water from the cooling system is used for irrigation in surrounding areas. If the salinity level of brine is high, the stream is diluted before disposal through the stormwater network. The chemicals and energy used to treat this bore water and TSE for Options 1 and 2 are presented in Table 2. These inputs were used for calculating the environmental and economic performance of Options 1 and 2.

2.3 The lifecycle assessment

Following the LCA of water conducted by Biswas (2009), a lifecycle assessment tool has been used to estimate the GHG emissions and embodied energy consumption associated with the production of the daily water requirements of the housing complex in Qatar. This proposed Environmental Life Cycle Assessment (ELCA) followed the four steps of ISO 14040-44. i) Goal and scope: The goal is to determine the environmental benefits associated with the use of a closed loop water recycling system. The functional unit is the annual water requirements of this residential compound. This LCA research does not take into account capital equipment, including infrastructure and machinery. It only considers the inputs (i.e., chemicals, membranes and energy) used during the operational stages, including extraction, pre-treatment, reverse osmosis, post-treatment, brine discharge, sludge treatment and delivery of desalinated water.. The GHG emissions and embodied energy consumption from the manufacturing of capital equipment, including building, pipe infrastructure and machinery, are not included within the system boundary of the LCA analysis due to their long term spans following Biswas (2009). ii) Lifecycle inventory (LCI): The LCI is a prerequisite for LCA analysis. Table 2 in fact shows the LCIs of options 1 and 2. This LCI has been divided into two parts. The first part of the LCI includes inputs (energy and chemicals) of extraction, pre-treatment, reverse osmosis, brine disposal and post-treatment of water desalination, while the second part includes inputs for municipal activated sludge plant and municipal TSE treatment using UF/RO for cooling system. iii) Impact assessment: Once the inventory has been developed, input data from the inventory will be inserted into Simapro 8.4 LCA software to determine GHG emissions and embodied energy consumption. The input/output data of the LCI will be linked to relevant emission databases in Simapro 8.4. The amount of inputs has been multiplied by the corresponding emission factors to calculate the impacts. Ecoinvent 3 emission database has been used for estimating GHG emissions from chemical production. The emission factor of Qatari electricity was obtained from Biswas et al. (2017). According to the IPCC data on global warming potential factors, at 100 y, CO_2 has a factor of one, CH4 a factor of 28 and N_2O a factor of 265 (IPCC 2015). These factors must be considered when working out the CO_2 equivalent calculations. The cumulative energy demand method in the software was used to calculate embodied energy consumption. This embodied energy includes the energy consumed by processes, including mining, manufacturing, transport associated with the production and use of water. Interpretations: Once the lifecycle impact, in terms of GHG emissions and embodied energy consumption, has been calculated, a hotspot analysis will be conducted to determine the best mitigation options to reduce embodied energy consumption and GHG emissions. Using the same system boundary for ELCA, an economic analysis was conducted to determine the operation and maintenance (O&M) cost in terms of USD/m^3 of delivering water for non-drinking applications. Only the labour cost that was not within the system boundary was included to determine the overall O&M cost. The cost data was obtained from Gulf Organization for Research and Development (GORD), QSTP, Doha.

3. Results and discussion

The use of TSE for cooling applications could reduce the water footprint of the residential compound from 0.9 m^3/person/day (i.e. 413 m^3/d per building complex/113 villas per building complex/4 persons per villa) to 0.15 m^3/person/d, providing a significant water resource conservation strategy. However, the water energy nexus of this closed loop decentralised system requires the management of energy intensive water treatment processes and the challenge remains to manage the eco-efficient use of both resources.

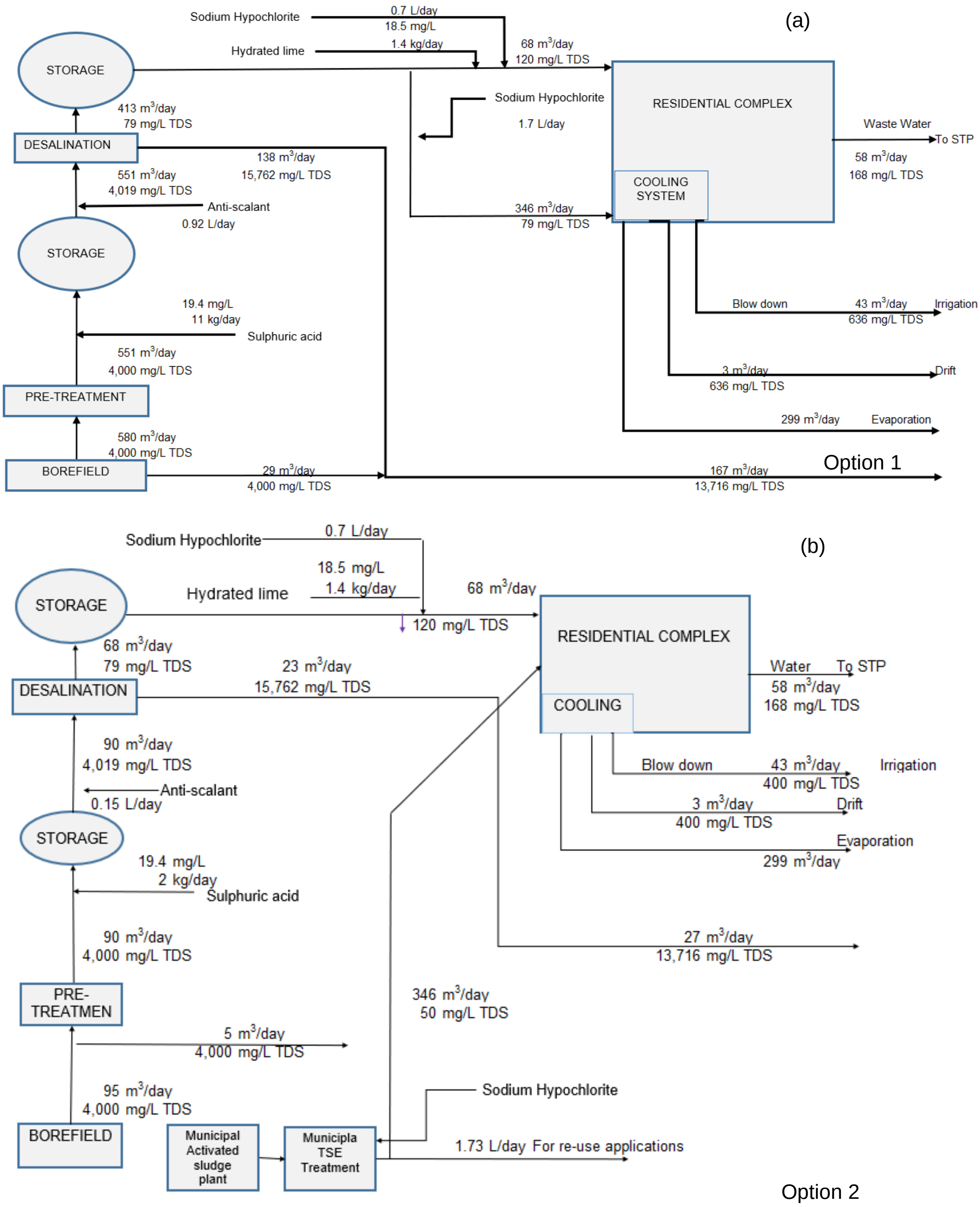

Figure 1: Water treatment systems for (a) Option 1 and (b) Option 2

Whilst the water footprint of this closed loop decentralised water supply system decreased by 83 % due to the use of TSE, the carbon footprint increased by 59 % due to the incorporation of energy intensive ultrafiltration and reverse osmosis processes to further treat the TSE for use in cooling systems (Table 3). The TSE treatment system alone accounted for 65 % of the total GHG emissions associated with the water generation for cooling system applications. The electricity required to power this treatment process accounted for 76 %-80 % of GHG emissions in term of kg CO_2 equivalent (or kg CO_2-eq) (30,453 – 45,982 kg CO_2-eq/y) of the total GHG emissions for this process, followed by membranes (14 %-16 %) and chemicals (5 %-8 %).

Table 2: Inputs of Options 1 and 2

		Environmental inputs		Economic inputs (USD)	
		Option 1	Option 2	Option 1	Option 2
RO Chemicals (as delivered)					
Anti-scalant	L	335	335	905	905
Sulphuric acid	kg	3,991	654	0	0
Hydrated lime	kg	509	509	0	0
Sodium hypochlorite in potable water	L	247	247	182	182
Sodium hypochlorite in cooling tower make up	L	631	631	465	465
SBS for chlorine neutralisation	L		600	0	329
UF Chemicals (as delivered)					
Sodium hypochlorite for biocontrol	L		1,752	0	1,290
Sodium hypochlorite for MW/CIP	L		673	0	495
SBS for chlorine neutralisation	L		256	0	140
Energy					
Local RO treatment	MWh	117	19	948	155
Local potable water distribution in complex	MWh	4	4	34	34
Cooling tower make up	MWh	16	32	128	256
TSE	MWh		151	0	1,226
RO membranes					
Type 8" spiral wound 400 ft^2 area					
Local RO		26	4	6,955	1,141
TSE RO			28	0	7,476
Replacement time	y	6	6		
UF Membranes for TSE					
Membrane area in m^2			480		2,628
Replacement time	y	6	6		

Option 3 used solar electricity as a replacement for conventional grid electricity to reduce the carbon footprint. Using Doha's annual solar radiation data, it was estimated that a photovoltaic (PV) system of 4.3 kW would be required to meet the energy demand of the entire water treatment process (i.e. bore water and TSE). The area that would be required to install these PV panels was estimated to be 23.65 m^2, which could be made easily available near the treatment area. It is assumed that the excess energy will be fed to grid and would cover the energy required during night time to run the treatment system, avoiding the need for a large size battery storage. The carbon footprint of Option 3 that treats TSE using solar electricity was estimated to be 30.73 t of CO_2-eq which is 65 % and 19 % less than Options 1 and 2. The GHG emissions associated with the use of solar electricity to power this TSE treatment process are largely associated with the manufacturing of the photovoltaic module. Similar to carbon footprint, the embodied energy demand of option 2 was found to be 56 % more than Option 1 for the residential compound. Option 3 was also found to produce higher embodied energy demand than Option 1 due to the manufacturing of PV cells for energy production. The environmental performance of Options 1, 2 and 3 was then compared with the existing water treatment options in the Gulf region in terms of 1 m^3 of water. Table 4 and 5 show that the decentralized options generate less carbon footprint (i.e. 0.20 – 0.40 kg CO_2/m^3) and consume less electricity (i.e. 0.91- 1.4 kWh/m^3) during the treatment process compared to existing options, which was largely due to the avoidance of the pumping energy that is required for distributing water in a centralized supply network. The inputs that were used for environmental assessment were then used to calculate the annual operation and maintenance cost of Options 1, 2 and 3. Option 1 has lower annual O&M cost (10,685 USD) than Option 3 (15,051 USD) and Option 2 (18,580 USD), mainly due to the requirement of additional chemicals and membranes for the TSE treatment. The O&M costs of water per m^3 basis of these three decentralised water supply options are lower than the O&M costs of the existing centralised water supply options in the Gulf region. The O&M cost of water treatment of Options 1, 2 and 3 are 0.07 USD/m^3, 0.11 USD/m^3 and 0.12 USD/m^3, while the O&M cost of existing options, such as MSF, SWRO, Hybrid MSF/MFD and hybrid SWRO are 0.26 USD/m^3, 0.35 USD/m^3, 0.5 USD/m^3, 0.23 USD/m^3 and 0.35 USD/m^3 (Almar water solution, 2016).

Table 3: Carbon footprints (kg CO_2-eq/y) of Options 1, 2 and 3 for a residential compound in Doha

Inputs	Option 1 without TSE		Option 2 using TSE		Option 3 using TSE and solar PV	
Chemical	2,033	5 %	5,092	8 %	5,092	17 %
Membranes	5,460	14 %	9,450	16 %	9,450	31 %
Electricity	30,543	80 %	45,982	76 %	16,183	53 %
Total	38,036	100 %	60,524	100 %	30,725	100 %

Table 4: Embodied energy consumption (MJ) of Options 1, 2 and 3 for a residential compound in Doha

Option 1 without TSE	Option 1 using TSE	Option 1 using TSE and solar PV
530,117	825,247	631,719

Table 5: Comparison of environmental performance between proposed and existing options

	Carbon footprint (kg CO_2-eq/m^3)	Total electrical energy (kWh/m^3)
Proposed options		
Option 1 without TSE	0.25	0.91
Option 2 using TSE	0.40	1.4
Option 3 using TSE and solar PV	0.20	1.4
Existing options (Cornejo et al. (2014))		
Multi-effect distillation (MED)	0.3 – 26.9	6.0 – 10
Multi-stage flash (MSF)	0.3 – 34.7	13.5 – 23.5
Seawater desalination - RO	0.08 – 4.3	4 - 4.5

4. Conclusions

The application of a decentralised closed loop water supply system could significantly reduce the water footprint of a residential compound in a water scarce region like Qatar. The water energy nexus of this closed loop decentralised system requires the management of an energy intensive treatment process to produce water resources and the challenge remains to manage the eco-efficient use of both water and energy resources. Whilst the water footprint of the residential compound reduced by 83 % due to use of TSE water, the carbon footprint and embodied energy consumption increased by 59 % and 56 %. The use of solar electricity for powering the closed loop decentralised water supply system reduces the carbon footprint of Options 1 and 2, by 56 % and 19 %. The closed loop decentralised water supply systems powered by both conventional and solar electricity were found to be more environmentally and economically competitive than the existing centralised water supply systems (MED, MSF and the seawater desalination system).

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