CHEMICAL ENGINEERING TRANSACTIONS
VOL. 72, 2019

A publication of AIDIC
The Italian Association of Chemical Engineering
Online at www.aidic.it/cet

Guest Editors: Jeng Shiun Lim, Azizul Azri Mustaffa, Nur Nabila Abdul Hamid, Jiří Jaromír Klemeš
Copyright © 2019, AIDIC Servizi S.r.l.
ISBN 978-88-95608-69-3; **ISSN** 2283-9216
DOI: 10.3303/CET1972035

Techno-economic and Environmental Implications of the Use of a Closed Loop Water Recycling System in Qatar

Wahidul K. Biswas[a,*], Yousef Al Horr[b], Cynthia A. Joll[c], Michele Rosano[a]

[a]Sustainable Engineering Group, School of Civil and Mechanical Engineering, Curtin University, Western Australia
[b]Gulf Organization for Research and Development, Qatar Science and Technology Park, Doha
[c]Curtin Water Quality Research Centre, School of Molecular and Life Sciences, Curtin University, Western Australia
w.biswas@curtin.edu.au

This paper presents the environmental and economic benefits from the use of potable water from a desalination plant, and treated sewage effluent (TSE) for non-potable reuse, in Lusail, Doha. This newly built city plans to use TSE for a large portion (98 %) of its non-domestic applications instead of discharging TSE to the ocean. It was estimated that about 140,112 m^3/d desalinated water will be produced for potable water supply and 93,236 m^3/day of TSE will be produced from a sewage treatment plant (STP) for use in district cooling systems and in the irrigation of local landscapes, lawns, and pocket gardens. Less than 2.5 % of water demand for non-domestic applications (i.e. irrigation of lawns for water features) will need to be met by potable water. There are significant sustainability benefits associated with the use of TSE in a water scarce and fast growing region like Qatar. A life cycle assessment analysis has been carried out to determine the greenhouse gas emissions, embodied energy consumption and cost savings associated with the recycling of wastewater in Lusail.

1. Introduction

Per capita, Qatar is among the highest water consumers in the world, however, fresh water resources are limited (Ismail, 2015). The nation is currently experiencing significant challenges in meeting the demand for water, as a result of its population growth, rapid urban development, dwindling natural resources, increasing industrial development and climate change issues. The current water consumption per capita is 500 L/d, which is the highest in the world (Baalousha and Ouda, 2017). Desalinated seawater is the main source of potable water (99 %) in Qatar. Interestingly, Qatar has an abundance of energy reserves, but it has limited water resources. In the future, Qatar's water demand will increase energy consumption significantly (Malki, 2015), along with increasing GHG emissions. Total water production in Qatar from desalination, fresh groundwater abstraction and the re-use of treated sewage effluent (TSE) rose from 220 Mm^3 in 1990 to 841 Mm^3 in 2014 (Ministry of Development Planning and Statistics, 2015). TSE has been used in landscaping and irrigation applications for many years. This effluent is now considered for use in Qatar's district cooling systems. The Qatari Water Resources Committee (PWRC) in 2014 banned the usage of potable water for cooling purposes. It is estimated that these industries will consume nearly 73 Mm^3 of TSE which represents 17 % of total TSE demand by 2020 (Jasim et al., 2016). Using TSE as an alternative to potable water in district cooling plants (DCP) will serve nearly 39 Mm^3/y of potable water by 2023 (Jasim et al., 2016).
DCPs in Lusail city have been designed to use TSE water and potable water. Lusail is a city of 38 km^2, and is able to accommodate 200,000 residents, 170,000 employees and 80,000 visitors (Industry ME, 2016).Some recent studies which were conducted in Australia and Europe focused on the use of recycled wastewater (Laurenson et al. 2012), where this wastewater can potentially be used by other applications such as industrial cooling and landscape irrigation purpose (Grant et al. 2012). Lusail city has been considered as a case study in this research project as it is a new city with potential to develop innovative and environmentally friendly water supply options. Lusail city is also close to the ocean allowing desalination of water for domestic purposes. Both TSE and seawater treatment are energy intensive, resulting in a large amount of greenhouse gas (GHG) emissions and other environmental impacts (Samanaseh et al. 2017). Therefore, in the current paper, a LCA analysis has been done to determine the impact on global warming (or GHG emissions) of both energy-intensive

Paper Received: 30 March 2018; Revised: 26 August 2018; Accepted: 15 December 2018

Please cite this article as: Biswas W.K., Horr Y.A., Joll C., Rosano M., 2019, Techno-economic and environmental implications of the use of a closed loop water recycling system in qatar, Chemical Engineering Transactions, 72, 205-210 DOI:10.3303/CET1972035

wastewater treatment systems. The environmental performance of MSF and MED was compared with seawater reverse osmosis desalination (Darwish et al., 2013), to assess the lifecycle environmental impact of renewable-powered reverse osmosis systems for enhancing food security (Al-Ansari et al., 2014), and to assess the economic viability of wind energy systems (Marafia et al., 2003) in Qatar. This paper reports an assessment of the environmental and economic implications of two water treatment technologies, where potable water is sourced from an on-site desalination plant and TSE is used in DCPs.

2. Methodology

2.1 Water quality

Since seawater quality data from the Lusail area was not available, water quality data from the desalination plants at Ras Abu Fontas, Qatar has been considered for designing the desalination plant to produce potable water. According to Abdel-Wahab (pers. comm. Chemical Engineering Program, Texas A & M University at Qatar), seawater quality does not vary much across Doha. Table 1 shows the water quality data from Ras Abu Fontas, Qatar, provided by the Gulf Organization for Research and Development (GORD).

Table 1: Seawater analysis of Ras Abu Fontas Desalination plants RAF B and RAF A1 in Qatar

Parameter	RAF B	RAF A 1
pH	8.17	8.19
Conductivity (mS cm^{-1})	63,200	63,300
TDS (mg L^{-1})	44,750	44,945
Total hardness (mg L^{-1})	7,880	7,900
Calcium hardness (mg L^{-1})	1,150	1,160
Magnesium hardness (mg L^{-1})	6,730	6,740
Calcium (mg L^{-1})	460	464
Magnesium (mg L^{-1})	1,615	1,618
Total alkalinity (mg L^{-1})	125	126
Sulphate (mg L^{-1})	3,200	3,220
Sodium (mg L^{-1})	12,200	12,300
Ammonia (mg L^{-1})	0.40	0.40
Bromide (mg L^{-1})	74	75
Chloride (mg L^{-1})	24,800	24,900
Copper (mg L^{-1})	5.0	5.0
Iron (mg L^{-1})	20	22
Silica (mg L^{-1})	0.8	0.8
Turbidity (NTU)	2.5	3.0
Suspended solids (mg L^{-1})	8.0	8.5
Bicarbonate (mg L^{-1})	153	154

2.2 Water treatment options

The cost elements for the desalination process are based upon a pre-treatment system using dissolved air flotation and media filtration. Filtrate from this process is subjected to desalination by a seawater reverse osmosis system. The permeate is then remineralised using lime and carbon dioxide. The energy of the reverse osmosis process was derived from standard membrane design software using the seawater analysis given in Table 1. The chemical consumption is based upon the quantities given in Table 3 on the basis of producing 1000 m^3 of potable water. The chemicals and energy consumption for wastewater treatment was based on Jasim et al. (2016) and the consultation with a local expert (Hazim Qiblawey, Qatar University). The cost elements for the wastewater treatment process utilising activated sludge, ultrafiltration and reverse osmosis were based upon standard operating values for treatment of secondary effluent by membrane processes. The chemical consumption is based upon the quantities given in Table 3 on the basis of producing 1000 m^3 of recycled water. Figure 1 shows the current water balance in Lusail, Qatar. About 140.1 kL/d of potable water will be supplied to the city for domestic drinking and non-drinking applications and to public places. The volume of wastewater that is generated from these end uses accounts for 75 % of the amount of potable water supply. This wastewater will be treated to produce TSE for landscape irrigation and district cooling system applications. DCP will use 50 % of this TSE as cooling water. In an additional scenario, 100 % of the water in the DCPs is TSE and the remaining TSE (17,338 m^3/d) is considered for landscape irrigation applications. Qatar Cool (a Qatari DCP) suggested that a reverse osmosis system has to be designed along with the DCP to maintain the TSE supply quality and to meet the authorities' compliance discharge requirements. The TSE has to go through an advanced water treatment system (i.e. using ultrafiltration and reverse osmosis) to reduce the concentration of TSE, to increase the cycle of concentration and to avoid the use of makeup water coming from the desalination plant (Figure 2). The reject brine is then directly discharged to ocean. These two options are now considered as Options 1 and 2 as shown in Table 2.

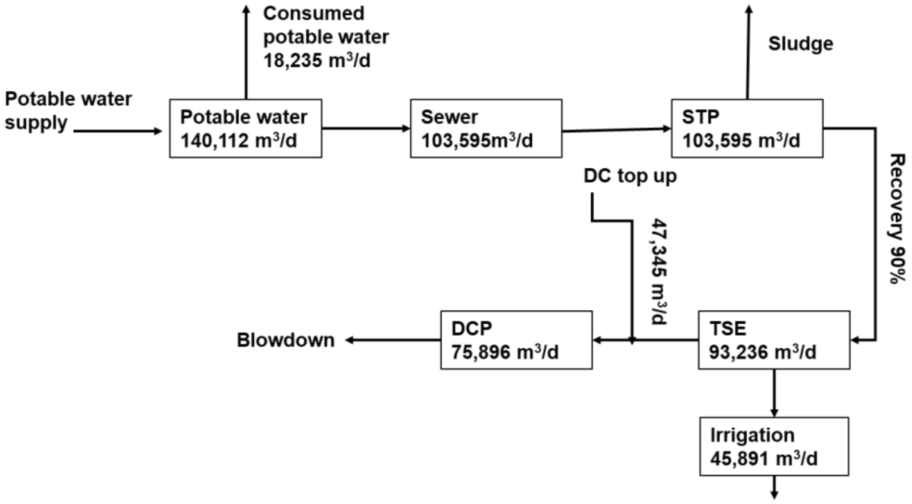

Figure 1: Water balance of Lusail city, Qatar (Al-Ishaq, 2018)

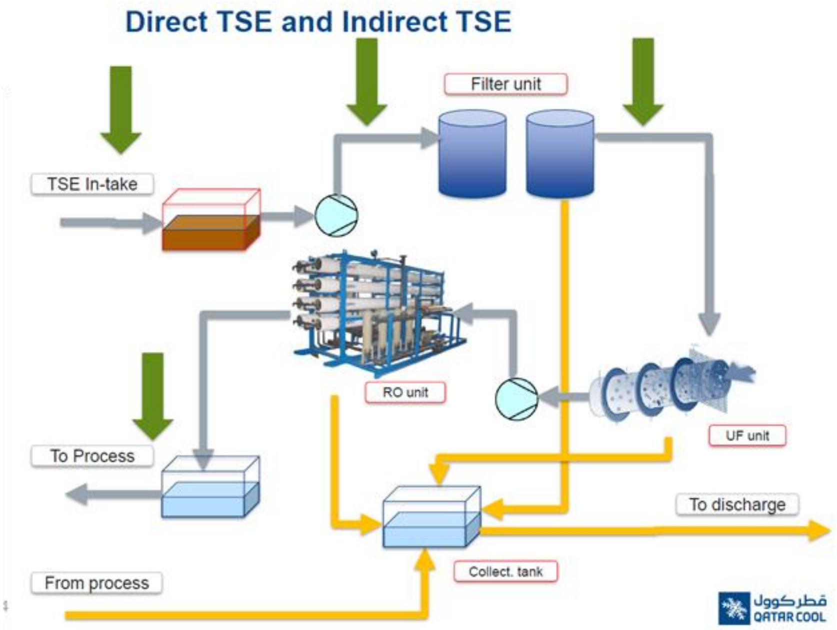

Figure 2: Treatment of TSE for cooling system application (Al-Mutawah, 2015)

Table 2: Design considerations for Options 1 and 2

Option 1	Option 2
97.5 % potable water supplied from a desalination plant for domestic purposes	97.5 % potable water supplied from a desalination plant for domestic purposes
2.5 % potable water for water features and lawns	2.5 % potable water for water features and lawns
50 % of DCP water is TSE	100 % of DCP water is TSE
50 % of TSE is used for landscape irrigation	20 % of TSE will be used for landscape irrigation
	Blowdown water will be used for landscape irrigation

2.3 Carbon footprint assessment

The inputs required for producing 1000 m^3 desalinated water per day and treating 1000 m^3 wastewater per day have been presented in Table 2 as a life cycle inventory (LCI). LCI is a pre-requisite in determining the carbon footprint of any product or service. The input data is then incorporated into LCA software to calculate both the carbon footprint of 1000 m^3 potable water per day and to calculate the carbon footprint associated with the treatment of 1000 m^3 wastewater per day. In order to calculate these carbon footprints, the input/output data of the LCI will be linked to relevant emission databases in Simapro 8.4. The inputs are then multiplied by the corresponding emission factors to calculate the impacts. The values for the impact of global warming can be calculated over time horizons of 20, 100 and 500 y, in order to make relevant climate change decisions. In this current research, the 100 y horizon has been considered in the carbon footprint calculation, as it is typically a reference point for policy makers. According to the IPCC data on global warming potential factors, at 100 y, CO_2 has a factor of one, CH_4 a factor of 28 and N_2O a factor of 265 (IPCC 2007).

Table 3: Life cycle inventory of desalination and wastewater treatment

	Values	Units	USD
DESALINATION			
Chemicals			
Anti-scalant	2.4	L/d	12.9
98 % Sulphuric Acid	79.28	kg/d	82.8
42 % ferric chloride	47.74	kg/d	23.9
Polyelectrolyte	1.25	kg/d	3.8
Lime*	40	kg/d	4.8
Carbon dioxide	10	kg/d	50.0
Chlorine	2	kg/d	7.8
Specific Energy Consumption			
Desalination plant	3.4	kWh/m^3	28.0
Drinking water pumping	0.3	kWh/m^3	2.5
RO membranes			
Number	86	elements	63.6
Life	6	y	0.0
WASTEWATER TREATMENT			
Production	1000	m^3/d TSE	
Chemicals			
Anti-scalant	2.2	L/d	11.8
10% Sodium hypochlorite	7.3	L/d	6.6
40% sodium bisulphite	2.7	L/d	0.9
Specific Energy Consumption			
Overall plant	1.2	kWh/m^3 of TSE	9.9
TSE pumping	0.3	kWh/m^3	2.5
RO membranes			
Number	80	elements	59.2
Life	6	y	0.0
UF Membranes for TSE			
Membrane area in m^2	1389	m^2	20.8
Replacement time	6	y	

Based on the estimated carbon footprint of 1000 m^3/d of potable water and TSE 1000 m^3/d of treated wastewater, the carbon footprint of these two options was then estimated.

2.4 Operation and maintenance costs

Using the same LCI of LCA, the operation and maintenance (O&M) costs of delivering water for domestic and cooling applications in USD/m^3 are then determined. The capital costs for treatment technologies have been excluded from the analysis. Only the labour costs associated with the water delivery are included.

3. Results and discussion

Options 1 and 2 were compared from environmental and economic perspectives. 50 and 100 % of the TSE are used as cooling water for DCP in Options 1 and 2. The use of TSE not only reduces the water footprint from 220 to 143 kL/d, it also reduces the carbon footprint in terms of t CO_2/d. Option 2 produces less carbon footprint (162 t of CO_2/d) than Option 1 (178 t of CO_2/d) due to the fact that the former used TSE as make up water instead of potable water produced in a desalination plant (Table 4). If potable water would have been considered for both domestic and cooling applications, it is estimated that 268 t of CO_2/d would have been emitted. However, the use of TSE in the cooling system of Options 1 and 2 further reduces GHG emissions by 34 % and 40 %.

Table 4: Carbon footprint (t CO_2/d) analysis of Options 1 and 2

	Chemicals	Membranes	Electricity	Total
Option 1				
Potable Water	9	7	118	134
Treated TSE for DCP	0	1	16	17
Make up water for DCP	2	1	24	27
Total	11	9	158	178
	(6 %)	(5 %)	(89 %)	(100 %)
Option 2				
Potable water	9	7	118	134
TSE for DCP	1	2	25	27
Total	9	9	144	162
	(6 %)	(5 %)	(89 %)	(100 %)

For both Options 1 and 2, electricity use accounted for a significant portion of the total GHG emissions or carbon footprint (i.e. 89 %) mainly due to the fact that the electricity is generated from a natural gas fired combined cycle power plant. In coastal Doha, the use of photovoltaic technologies and wind energy can be considered as a replacement for fossil fuel generated electricity. Additional mitigation strategies can also be considered to reduce the overall carbon footprint of water production. Firstly, instead of sending brine to the sea, it can be used to remove moisture from the air in the first stage of a desiccant cooling process, thereby decreasing the use of carbon intensive refrigerants (Lychnos et al., 2012). Secondly, brine can also potentially be used in the cement industry (Fattah et al., 2015).

Table 5: Comparison of carbon footprint and total electrical energy consumption between proposed and existing options

	Carbon footprint (kg CO_2/m^3)	Total electrical energy (kWh/m^3)
Proposed options		
Option 1	0.82	3.5
Option 2	0.74	2.9
Existing options (*)		
Multi-effect distillation (MED)	0.3 – 26.9	6.0 – 10
Multi-stage flash (MSF) distillation	0.3 – 34.7	13.5 – 23.5
Seawater desalination - RO	0.08 – 4.3	4 - 4.5

(*) These options are currently used in Doha for water treatment purposes.

The environmental performance of closed loop water supply Options 1 and 2 was compared with existing water treatment options in the Gulf region. Table 5 shows that Option 2 generates less carbon footprint, as well as consumes less electricity, during the treatment process compared to existing treatment options. This is due to the avoidance of pumping energy that is required for distributing water in a centralized water distribution network. In the case of Lusail, desalination is performed onsite, reducing the pumping energy required for distribution. The desalination options in the current research and other studies consume less electricity than MED and MSF plants. The same inputs that were used to calculate the carbon footprint were used in calculations of the daily operation and maintenance cost of Options 1 and 2. Option 2 was found to have lower operation and maintenance (O&M) cost (USD 5,068 per day) than Option 2 (8,483 USD/d).

In order to compare with the currently available options, the units O&M costs are converted from per day to per m^3. Interestingly, the O&M costs of water per m^3 for these two options is almost the same as the O&M costs of the existing water treatment options in the Gulf region. The O&M cost per m^3 of water treatment of Options 1 and 2 are 0.24 USD and 0.22 USD, while the O&M costs of existing options, such as MSF, SWRO, Hybrid MSF/MFD and hybrid SWRO are 0.26 USD, 0.35 USD, 0.5 USD, 0.23 USD and 0.35 USD (Almar water solution, 2016). Efforts to improve water productivity through wastewater reuse will still need to overcome economic, planning, regulatory, institutional, and public acceptance challenges (Grant et al. 2012).

4. Conclusions

The use of TSE as a replacement for potable water in a district cooling plant could significantly reduce the overall carbon footprint (34-40 %) of this closed loop decentralised water supply system. Further carbon footprint reduction could be possible by using electricity sourced from renewable energy technologies like solar and wind. Option 1 utilising 50 % of TSE in DCP and Option 2 utilising 100 % of TSE in DCP have both been found to be more environmentally friendly and more cost-competitive than the existing MED and MSF plants. In order to respond to Qatar's growing water demand pressures, Options 1 and 2 could deliver water at more competitive prices with less environmental impact. These options could also reduce electricity consumption significantly, conserving Qatar's natural gas resources whilst reducing GHG emissions.

Acknowledgments

This research was proudly supported by the Qatar National Research Foundation NPRP9-418-2-168. We acknowledge Mr. Abdulrahman A. Al Ishaq (Qatari Diar Real Estate Investment Company, Lusail), Prof. Hazim Qiblawey (Department of Chemical Engineering, Qatar University), Mr. Tanveer A. Tarapathi (Qatar Cool), Dr. Ammar Elhoweris and Ms. Reem Hayek (GORD) and Dr. Altaf Hussain (Conoco Phillips Global Water Sustainability Centre, Qatar), for providing information. Dr. Gavin Broom is thanked for his contribution in treatment system design.

References

Al-Ansari T., Korre A., Shah N., 2016, Integrated Modelling of the energy, water and food nexus to enhance the environmental performance of food production systems, 9th International Conference LCA of Food, 8-10 October, San Francisco, United States.

Al-Ishaq, 2018, TSE production and use, Qatari Diar Real Estate Investment Company, Lusail, Doha, Qatar

Al-Mutawah N., 2015, Qatar District Cooling Company TSE Migration, Qatar Cool, Doha, Qatar

Baalousha S.M., Ouda O.K.M., 2017, Domestic water demand challenges in Qatar, Arabian Journal of Geosciences, 10(537), 1-12.

Oraby W., 2012, Arid Nation the Qatar Water Industries' Strategic Plan, The Edge, 62-66. <metito.com/news/cnbc-interview-with-omar-zoubi/> accessed 01.09.2016

Darwish M., Hassabou A.K., Shomar B., 2016, using seawater reverse osmosis (SWRO) desalting system for less environmental impacts in Qatar, Desalination, 609, 116-126

Grant S.B., Saphores J.D., Feldman D.L., Hamilton A.J., Fletcher T.D., Cook P.L., Stewardson M., Sanders B.F., Levin L.A., Ambrose R.F., Deletic A., Brown R., Jiang S.C., Rosso D., Cooper W.J., Marusic I., 2012, Taking the "waste" out of "wastewater" for human water security and ecosystem sustainability, Science, 337(6095), 681-686.

Industry ME, 2016, Lusail city: bringing Qatari imagination to life, <industry-me.com/features/infrastructure/lusail-city-bringing-qatari-imagination-life/> accessed 6.06.2018.

IPCC (Intergovernment Panel on Climate Change) 2007, Direct Global Warming Potentials. IPCC Switzerland. <ipcc.ch/publications_and_data/ar4/wg1/en/ch2s2-10-2.html> accessed 30.05.2018.

Ismail H., 2015, Food and Water Security in Qatar: Part 2 – Water Resources, Future Directions International Pty Ltd, Dalkeith WA, Australia.

Jasim S.Y., Saththasivam J., Loganathan K., Ogunbiyi O., Sarp S., 2016, Reuse of Treated Sewage Effluent (TSE), Qatar Journal of Water Process Engineering, 11, 174-182.

Laurenson S., Bolan N.S., Smith E., McCarthy M., 2012, Review: Use of recycled wastewater for irrigating grapevines, Australian Journal of Grape and Wine Research, 18, 1–10.

Malki A S. A, 2015, Business Opportunities in Water Industry in Qatar, Qatar General Electricity and Water Corporation (KARAMA), Ministry of Development Planning and Statistics, Doha, Qatar.

Samanaseh V., Noor Z.Z., Hassan C.H.C., Sabeen A.H., 2017, Water-energy-nexus in water supply: a case study on greenhouse gases emissions trends of a water utility company in Johor, Malaysia, Chemical Engineering Transactions, 56, 1711-1716.

Jasim S.Y., Saththasivam J., Loganathan K., Ogunbiyi O.O., Sarp S., 2016, Reuse of Treated Sewage Effluent (TSE) in Qatar, Journal of Water Process Engineering, 11, 174–182.