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Life Cycle Assessment of Seawater Desalinization in Western Australia

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***Abstract*—**Perth will run out of available sustainable natural water resources by 2015 if nothing is done to slow usage rates, according to a Western Australian study [1]. Alternative water technology options need to be considered for the long-term guaranteed supply of water for agricultural, commercial, domestic and industrial purposes. Seawater is an alternative source of water for human consumption, because seawater can be desalinated and supplied in large quantities to a very high quality.

While seawater desalination is a promising option, the technology requires a large amount of energy which is typically generated from fossil fuels. The combustion of fossil fuels emits greenhouse gases (GHG) and, is implicated in climate change. In addition to environmental emissions from electricity generation for desalination, greenhouse gases are emitted in the production of chemicals and membranes for water treatment. Since Australia is a signatory to the Kyoto Protocol, it is important to quantify greenhouse gas emissions from desalinated water production.

A life cycle assessment (LCA) has been carried out to determine the greenhouse gas emissions from the production of 1 gigalitre (GL) of water from the new plant. In this LCA analysis, a new desalination plant that will be installed in Bunbury, Western Australia, and known as Southern Seawater Desalinization Plant (SSDP), was taken as a case study. The system boundary of the LCA mainly consists of three stages: seawater extraction, treatment and delivery. The analysis found that the equivalent of 3,890 tonnes of CO_2 could be emitted from the production of 1 GL of desalinated water. This LCA analysis has also identified that the reverse osmosis process would cause the most significant greenhouse emissions as a result of the electricity used if this is generated from fossil fuels

***Keywords*—** Desalinization, Greenhouse gas emissions, life cycle assessment.

I. INTRODUCTION

ONE of the most important problems nowadays, which is becoming increasingly acute, is the scarcity of fresh water of adequate quality for human consumption and for industrial and agricultural use. Increasing world population, together with increasing industrial and agricultural activities, has led to excessive exploitation of available water resources and pollution of freshwater resources. Hence, the supply of fresh water is becoming more scarce.

In the south of Western Australia, drought has been severe since 2001 and this has reduced the average inflow of fresh water into Perth's metropolitan dams from 340 GL in 1975 to less than 90 GL currently [2]. As Perth's population grows, the demand for water continues to increase. In response to this changing condition, the Water Corporation is developing a range of alternatives to increase the supply of fresh water. Seawater, which can be desalinated and supplied in large quantities of high quality, is an alternative source of water for human consumption.

In November 2006, the Water Corporation commissioned the Perth Seawater Desalination Plant (PSDP), which is now delivering 17% of the Integrated Water Supply Scheme [3]. It has demonstrated that desalination is a reliable and climate independent source of water. However, the decline in rainfall has meant that an additional climate-independent water source will be required in the coming years to secure water supply for the population of Western Australia. This desalination technology requires a large amount of energy, and the overwhelming majority of the energy currently used for desalination is obtained from fossil fuels. In addition to environmental emissions due to electricity generation for desalination, greenhouse gases are emitted from the production of chemicals and membranes used in water treatment. Of these environmental impacts, Australia gives priority to the impact of global warming caused by the emission of greenhouse gases, such as CO_2, N_2O and CH_4 [4].

This paper determines the life cycle of greenhouse gas emissions due to the production of desalinated water using both non-renewable and renewable sources of energy. It also identifies the hotspots causing the most greenhouse gas emissions during the life cycle of the production of desalinated water, including the determination of the total carbon footprint of the production of 1 GL of desalinated water.

Firstly, this paper discusses the life cycle assessment methodology for determining the greenhouse emissions for desalinated water production from the SSDP. Secondly, an analysis is carried out to determine the hotspots for freshwater production and to determine the carbon footprints for different energy mixes for the SSDP.

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II. METHODOLOGY

The LCA approach used in this paper assessed the greenhouse emissions from the production of desalinated water from the SSDP powered by renewable energy technology, national grid electricity, and a mix of both.

This approach enabled the greenhouse gas emissions from the extraction, treatment and delivery of desalinated water to be calculated. The LCA follows the ISO14040-43 guidelines [5], and is divided into four steps: 1) goal and scope definition; 2) inventory analysis; 3) impact assessment; and 4) interpretation (as presented in the 'Results' section of this paper).

A. Goal and Scope Definition

The goal is to assess the life cycle greenhouse emissions of seawater desalination at the Southern Seawater Desalination Plant in Western Australia. This research uses a 'cradle to gate' approach, where the functional unit is defined as the global warming potential of 1 Gigalitre (GL) of desalinated water production.

The system boundary of LCA mainly consists of three stages: seawater extraction, treatment and post-treatment. The emissions from the production of capital equipment, including building, pipe infrastructure and machinery, are not included in the system boundary of the LCA analysis due to its long-term span [6]. Frequently consumed items such as chemicals, energy, short life-time components or components requiring frequent replacements, such as membranes, have been included in the system boundary [7].

The seawater extraction stage includes the greenhouse gas emissions from electricity generation for pumping seawater into the water treatment plant. The seawater treatment stage consists of three stages: pre-treatment, reverse osmosis system and post treatment. Each of these stages includes greenhouse gas emissions from the production and transportation of chemicals and membranes for water treatment and from the generation of electricity for pumping. Post-treatment includes greenhouse gas emissions from electricity generation for water delivery and waste handling. Greenhouse gas emissions (CH_4) from sludge and screenings disposal have also been included in the LCA analysis.

Once the greenhouse gas emissions for different stages have been calculated, the greenhouse emissions for desalinated water production will be determined for different energy mixes (for example, 50% renewable energy and 50% conventional fuel) in order to assess the implications of renewable energy technologies on reducing emissions. . This LCA analysis will also identify the stages causing the most significant greenhouse emissions and the inputs (energy or materials) creating the largest carbon footprints (measured as weight of CO_2-e). In addition, the greenhouse emissions from the production of fresh water from the SSDP will be compared with those from an existing plant, in this case the Perth Seawater Desalination Plant (PSDP) in Kwinana.

B. Inventory Analysis

A life cycle inventory considers the amount of each input and output for processes which occur during the life cycle of a product. Undertaking a life cycle inventory is a necessary initial step in carrying out an LCA analysis. Table 1 shows the inputs for five stages of the life cycle of 1 m^3 of water production, which were obtained from the Engineering Design Report to calculate the inputs for 1 GL of water for GHG emission calculations.

TABLE I
LIFE CYCLE INVENTORY OF 1 M^3 OF DESALINATED WATER PRODUCTION

Input	Amount	Unit	km	Locations
Extraction				
Sodium Hypochlorite	1.94E-03	l/m^3	220	CSBP, Kwinana
Pre-treatment				
Membrane	290.00	g/m^3	3,000	Sydney
Sodium Hypochlorite	1.63	g/m^3	220	CSBP, Kwinana
Sulfuric Acid	6.86E-01	g/m^3	220	CSBP, Kwinana
Citric Acid	2.82E-01	g/m^3	220	Redox Bibra Lake WA
Sodium Metabisulphite	7.39E-02	g/m^3	782	Orica Australia Pty Ltd Kalgoorlie WA
RO				
Nalco PC1020	3.06	g/m^3	220	Nalco, Kwinana
Citric Acid	6.55E-01	g/m^3	220	Redox Bibra Lake WA
Detergent	2.72E-03	l/m^3	220	Huntsman local agent Perth
DBNPA	6.79E-03	l/m^3	220	Nalco, Kwinana
Caustic Soda	3.60E-02	l/m^3	220	Coogee Chemicals Kwinana
Membrane (1st pass)	34.00	g/m^3	15,230	USA
Membrane (2nd pass)	2.00	g/m^3	15,230	USA
Post-treatment				
Lime	51.03	g/m^3	22 0	Cockburn cement WA
Carbondioxide	43.00	g/m^3	20	BOC Bunbury WA
Chlorine	1.200	g/m^3	220	CSBP, Kwinana
FSA (Fluorosilicic acid)	0.85	g/m^3	220	CSBP, Kwinana
Polyelectrolyte	0.03	g/m^3	220	Nalco, Kwinana
Waste treatment				
Flocculants	0.15	L/m^3	220	
Polyelectrolyte	0.19	g/m^3	220	Nalco, Kwinana
Waste	11.00	g/m^3	30	Dardanup

Electrical energy is used for pumping and delivery, and also for flowing seawater through the membranes in the micro-filtration and reverse osmosis processes for seawater treatment. Chemicals are used for shock disinfection, membrane cleaning, chlorine removal, mineralisation and potabilisation. Along with greenhouse gas emissions from electricity generation, greenhouse gas emissions due to the production and transportation of these inputs have been calculated in order to estimate life cycle greenhouse gas emissions from the production of 1 GL of water.

C. *Impact Analysis*

The greenhouse emissions assessment of producing 1 GL of desalinated water includes two steps. The first calculates the total gases produced in each process, and the second converts these gases to CO_2-equivalent (CO_2 –e).

Step1: The input and output data in the life cycle inventory were put into the Simapro 7 [8] software to ascertain the greenhouse emissions due to the production of desalinated water. The input and output data from the life cycle inventory were linked to relevant libraries in Simapro 7. The LCA Library is a database, which consists of energy consumption, emission and materials data for the production of one unit of a product. The units of input and output data from the life cycle inventory depend on the units of the relevant materials in Simapro or its libraries [8].

In order to make the LCA results more representative for Australia, local databases and libraries have been used. In the absence of Australian databases, European databases were included to carry out the analysis. When neither a local library nor a European library were available in the Simapro software database for a particular product, a new library was created by obtaining GHG emissions information from the literature.

The library for chemicals is the Australian LCA database [9], which was used to calculate greenhouse gas emissions from the production of chemical inputs, such as sulphuric acid, caustic soda, lime, chlorine, biocide and flocculant. The emission factor for sodium hypochlorite, carbon dioxide liquid, and fluorosilicic acid was obtained from the Eco-invent database [10], as other databases or libraries were unavailable [9].

Libraries for antiscalant, citric acid, detergent and sodium metabisulphite were not found in the Simapro database. Separate databases or libraries were therefore made for these chemicals. The emission factor of antiscalant has been obtained from Mrayed [11]. The emission factor for citric acid was not available in the literature, and the energy required to produce 1 kg of citric acid was obtained from Tongwen [12] and multiplied by the emission factor for Western Australian electricity generation. Emission factors for detergent were obtained from [13]. Neither emission factors nor energy consumption values for sodium metabisulphite were available in the literature. Therefore, emission factors from the Simapro database of the two main ingredients of sodium metabisulphite (caustic soda and sulphur dioxide) have been used [8] to determine the equivalent emission factor of sodium metabisulphite.

Libraries for membranes for both microfiltration and reverse osmosis were not found in the Simapro database. The article of Tangsubku [14] has been used to determine greenhouse gas emissions from the production of membrane for microfiltration and from Mrayed (Mrayed and Leslie 2009) for membranes used in reverse osmosis (RO) passes 1 and 2.

The library of the supply chain of chemicals and membranes to the point of use was incorporated in order to assess the greenhouse gas emissions from transportation. Table 1 shows the locations and distances for transportation of inputs to the SSDP. The locations for different chemicals were obtained from Table 9.2 of the Engineering Design Report (EDR) by Sothern Seawater Desalinization Plant (SSWA). For the desalination plant at Binningup, it is assumed that a 30-tonne articulated truck, which is widely used in rural Australia, travels 220 km to carry chemicals and membranes to the plant. In the case of waste disposal, the distance to transport sludge to landfill is about 30 km to Dardanup. The unit for the transport library is tonne-kilometre (tkm). For example, 0.00047 tkm is required to carry 0.0021 kg of sodium hypochlorite for 220 km (2.14×10^{-6} tonne x 220 km).

The library for Western Australian electricity generation was used to calculate the greenhouse gas emissions [9]. The emission factor for electricity generated by wind (i.e. 9.7 kg CO_2 –e/MWh) was obtained from Lund [16].

Although SSDP sludge is likely to be high percentage minerals, consideration has been given to include the greenhouse gas emissions from the likely organic content of sludge from SSDP. Sludge from the the SSDP is expected to be 1.5 tonnes per day of inorganic material from the clarifier, estimated by SSWA to be 3-4% lime. This will be recycled for agricultural or other use if possible or disposed of to landfill. Using IPCC default value of CO_2 emission from lime [17], CO_2 emissions from lime in the sludge for producing 1 m^3 of water was calculated. In addition, SSWA estimate I tonne per week of organic screened material (e.g. mussels, seaweeds etc.), which is likely to be disposed of to landfill since it will be unsuitable for compost. This will give rise to methane emissions if it goes to a conventional landfill. Following Department of Climate Change methodology [18], methane emissions from the organic waste generation for producing 1 m^3 of water was calculated.

Step 2: Simapro software calculated the greenhouse gas emissions once the inputs and outputs were linked to the relevant libraries. The program sorted greenhouse gas emissions from the selected libraries, and then converted each selected greenhouse gas to CO_2 equivalents. The Australian Greenhouse Gas method, developed by RMIT [9], was used to assess the greenhouse gas emissions.

III. LIMITATIONS OF THE STUDY

Although the approach used here has enabled the determination of life cycle greenhouse gas emissions, identification of the stage or input that contributes most greatly to greenhouse gas emissions, and allowed a comparison of the environmental performance of two desalinisation plants, some limitations are evident due to the lack of data.

Cartridges, which are an input for the filtration process, had to be excluded from the analysis due to the absence of information on the emission factors and energy consumption of cartridge production. Since the quantity of cartridges in terms of mass per cubic metre of fresh water produced is insignificant (10^{-6} g/m^3), exclusion of this input does not seem to affect the LCA result significantly.

Foreign databases and generic values for emission factors of some chemicals and membranes have been used due to the absence of libraries of these materials in the Simapro software. Emission factors for sodium hypochlorite, carbon dioxide liquid and fluorosilicic acid were obtained from the Eco-invent database, which is based on European production and energy mix, and these can affect the accuracy of the LCA analysis. The emission factor for the production of the membranes used in Southern Seawater Desalination Plant, known as MEMCOR CP960 filtration modules, was not available; therefore, the generic emission data was extrapolated from Mrayed [15] and Tangsubku [14].

The emission factor for citric acid production was not available in either the Simapro library or the literature, but the energy consumption data was available. It was assumed that citric acid would be manufactured in Western Australia and, therefore, the energy consumption value was multiplied by the Western Australian emission factors for the electricity mix in order to determine the emission factor of citric acid production.

Neither emission factors nor energy consumption values for sodium metabisulphite were available in the literature. Therefore, as noted above, the emission factors of the two main ingredients of sodium metabisulphite (caustic soda and sulphur dioxide) from the Simapro database [8] have been used to determine the equivalent emission factor of sodium metabisulphite. However, the energy required to convert these chemicals to sodium metabisulphite was not found in the literature and, hence, does not reflect the true emission factors of sodium metabisulphite production.

Despite these limitations, the LCA analytical framework is sufficiently sophisticated to enable the determination of probable hotspots requiring improvement and a reasonable comparison of the greenhouse emissions of two desalinisation plants.

IV. RESULTS AND DISCUSSIONS

A. Carbon Footprints and Identification of Hotspots

Fig. 1 shows the greenhouse gas emissions from different stages, including extraction, pre-treatment, reverse osmosis, post-treatment, water delivery and waste treatment, for 1 GL of water produced by the Southern Seawater Desalination Plant. The equivalent of 3,890 tonnes of CO_2 could be emitted from the production of 1 GL of desalinated water. A similar study carried out by Mrayed found that the total carbon emissions from seawater desalination is 5,400 tonne CO_2-e/GL [11]. Biswas (2009) [19] found that SSDP could produce about 22% less greenhouse gas emissions than the existing Perth Seawater Desalination Plant (PSDP) for two reasons. Firstly, the use of micro-filtration in the pre-treatment process would reduce the amount of chemicals needed for water treatment, which in turn reduces the greenhouse gas emissions. Secondly, SSDP would employ a split hybrid system in the first pass of the reverse osmosis system, which is another feature that could reduce the energy consumption and, therefore, mitigate greenhouse gas emissions.

The reverse osmosis stage contributes significantly higher greenhouse gas emissions than other stages during the production of desalinated water. Greenhouse gas emissions from the extraction, pre-treatment, reverse osmosis, post-treatment, and water delivery and waste treatment stages accounted for 6.2% (251 tonne CO_2-e), 1.5% (57 tonne CO_2-e), 75.1% (2,920 tonne CO_2-e), 1.2% (48 tonne CO_2-e) and 16% (613 tonne CO_2-e) of 1 GL of water production, respectively. Figure 1 also shows the total emissions of three greenhouse gases from different stages. These gases are the major greenhouse gases emitted by extraction, pre-treatment, reverse osmosis, post-treatment, water delivery and waste treatment. CO_2, CH_4 and N_2O account for 99%, 0.8% and 0.2% of the total greenhouse gas emissions from 1 GL of water production.

From this LCA analysis, it was estimated that the emissions from the generation of electricity for pumping, membrane operation and water delivery account for a large proportion (3,586 tonnes of CO_2-e or 92.1%) of the greenhouse gas emissions during the life cycle of 1 GL of water production. Other significant sources of greenhouse gas emissions include GHG emissions from chemicals production (7%). The emissions from transportation, membrane production and from sludge and screenings in landfill together account for less than 1% of the total life cycle greenhouse gas emissions. A similar study carried out by Mrayed found that the greenhouse gas emissions from the generation of electricity for the operation of seawater desalination plant accounted for a large proportion (95%) of the total greenhouse gas emissions, followed by chemicals production (4%) [15]. The GHG emissions from sludge were not taken into account in this study.

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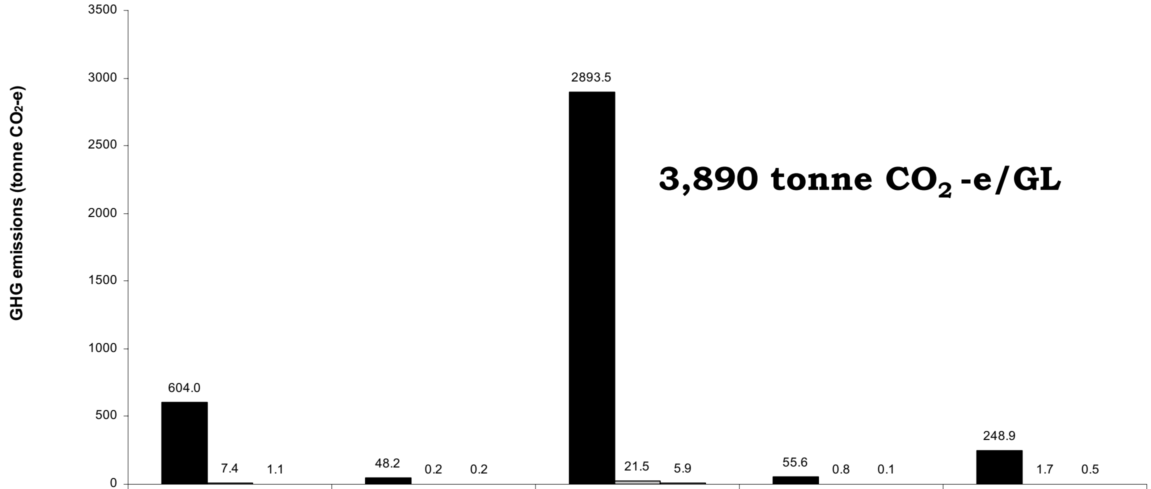
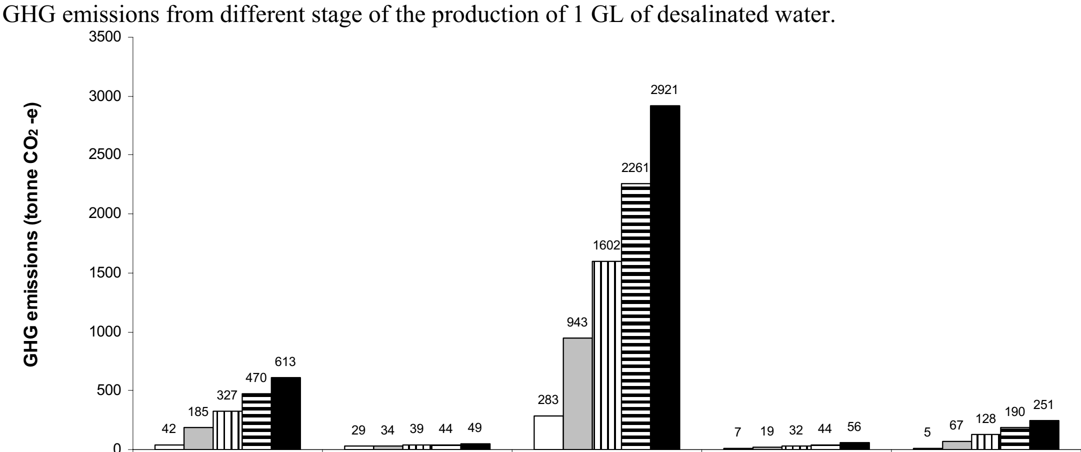


	Desal - SSWA - delivery and waste treatment	Desal - SSWA - Post-treatment	Desal - SSWA RO	Desal SSWA - Pre-treatment	Desal SSWA - Extraction
■ Carbon dioxide	603.99	48.18	2893.51	55.61	248.93
▨ Methane	7.44	0.20	21.50	0.77	1.67
□ Nitrous oxide	1.11	0.19	5.91	0.11	0.47

Fig 1 GHG emissions from different stage of the production of 1 GL of desalinated water.



	Desal - SSWA - delivery and w aste treatment	Desal - SSWA - Post-treatment	Desal - SSWA RO	Desal SSWA - Pre-treatment	Desal SSWA - Extraction
□ Wind 100% National Grid 0%	42	29	283	7	5
▨ Wind 75% National Grid 25%	185	34	943	19	67
▥ Wind 50% National Grid 50%	327	39	1602	32	128
▤ Wind 25% National Grid 75%	470	44	2261	44	190
■ Wind 0% National Grid 100%	613	49	2921	56	251

Fig 2 Effect of conventional and renewable energy mix on the life cycle greenhouse emissions for 1 GL of desalinated water production

A. Effect of Conventional and Renewable Energy mix on the Life Cycle Greenhouse Emissions

In the previous section, greenhouse gas emissions from electricity generation have been identified as the hotspot of 1 GL of desalinated water production from the Southern Seawater Desalination Plant. Therefore, electricity generation from wind turbines has been considered in the energy mix. Wind turbines on the seashore, which is close to the desalinisation plant, could be an appropriate type of renewable energy to supply electricity for the desalination plant. Since the development of wind turbines is not expected in the near future, a sensitivity analysis has been carried out for different energy mixes to supply electricity to the desalination plant.

Fig. 2 shows the effect of different energy source combinations of national grid and wind turbines on the life cycle greenhouse emissions for 1 GL of desalinated water production. Life cycle greenhouse gas emissions can be reduced from 3,894 tonnes CO_2-e to 367 tonnes CO_2-e if 100% of the total electricity comes from wind turbines. Another study, that considered the use of renewable energy for powering desalination plants, found that 920 to 1780 kg CO_2 -e of life cycle GHG missions can be emitted in the production of 1 GL of water [20]. Figure 3 also shows that there will be about 68%, 45% and 23% less greenhouse gas emissions with substitution of wind generated electricity by national grid electricity by 75%, 50% and 25%, respectively. There is a significant potential for mitigating greenhouse gas emissions in the reverse osmosis stage by substituting national grid electricity by wind energy. Life cycle greenhouse gas emissions can be reduced by 68% if electricity is generated from wind turbines to power the reverse osmosis system only.

V. CONCLUSIONS

The equivalent of 3,894 tonnes of CO_2 would be emitted from the production of 1 GL of desalinated water from the SSDP. Reverse osmosis contributes significantly higher greenhouse gas emissions than other stages during the life cycle of desalinated water production. The greenhouse gas emissions from the generation of electricity for pumping, membrane operation and water delivery account for a large proportion (3,586 tonne of CO_2-e or 92%) of the greenhouse gas emissions during the life cycle of 1 GL of water production. About 90% of the total greenhouse gas emissions from the national grid-powered desalination plant can be avoided by switching to wind energy. The use of micro-filtration and a split hybrid system has been found to provide significant environmental benefits.

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