Carbon footprint assessment of Western Australian Groundwater Recycling Scheme

Andrew Simms[1], **Stacey Hamilton**[2], **Wahidul K. Biswas**[3]

Corresponding author: Wahidul K. Biswas

w.biswas@curtin.edu.au

Abstract This research has determined the carbon footprint or the carbon dioxide equivalent (CO_2eq) of potable water production from a groundwater recycling scheme, consisting of the Beenyup wastewater treatment plant (WWTP), the Beenyup groundwater replenishment trial plant (GWRT) and the Wanneroo groundwater treatment plant (GWTP) in Western Australia (WA), using a life cycle assessment (LCA) approach. It was found that the scheme produces 1,300 tonnes of CO_2eq per gigalitre (GL) of water produced, which is 933 tonnes of CO_2eq higher than the desalination plant at Binningup in WA powered by 100% renewable energy generated electricity. A Monte Carlo Simulation uncertainty analysis calculated a Coefficient of Variation value of 5.4%, thus confirming the accuracy of the simulation. Electricity input accounts for 83% of the carbon dioxide equivalent produced during the production of potable water. The chosen mitigation strategy was to consider the use of renewable energy to generate electricity for carbon intensive GWRT. Depending on the local situation, a maximum of 93% and a minimum of 21% GHG saving from electricity use can be attained at GWRT by replacing grid electricity with renewable electricity. In addition, the consideration of vibrational

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[1] Department of Chemical Engineering, Curtin University, Perth, Australia
[2] Water Corporation, Perth, Australia
[3] Sustainable Engineering Group, Curtin University, Perth, Australia

separation (V-Sep) that helps reduce wastes generation and chemical use resulted in a 4.03 tonne of CO_2 eq saving per GL of water produced by the plant.

Keywords Groundwater recycling, carbon footprint, Western Australia

1 Introduction

In Western Australia, it has been observed that the freshwater run off into the dams, which has traditionally been the main source of water for the Perth metropolitan area, reached an all-time low of 11.4GL in the year 2015. When compared to the streamflow of 394GL as a pre-1975 average or 189GL as a post-1975 average, the current level is significantly low (i.e. about one third of post-1975) (Water Corporation, 2016a). Due to this scarcity of supply, the Water Corporation has sought out alternate sources of fresh water, including desalination and groundwater bores. Direct water recycling has also been considered, however, due to lack of community acceptance it is not yet in place within Western Australia (Kemp et al. 2012).

Desalination is seen as a climate independent source of water (Biswas 2009), whilst the use of groundwater is both climate and environmentally sensitive due to drought and low rainfall in a semi-arid region of WA (DPI 2016). In addition, desalination is seen as a more costly endeavour, both in monetary and environmental terms (Stokes and Horvath (2009); Siddiqi and Anadon 2011). This is because the removal of salts requires the use of a more energy intensive process (and is therefore costlier), than the removal of organic particulates seen in the groundwater system. Taking into account the high salinity of water and the comparatively large waste streams associated with desalination, groundwater recycling is favourable (Lyon et al. 2009).

In 2014–15, 17% of water supplied into the Integrated Water Supply Scheme (IWSS) came from surface water (dams), 42% from groundwater and 41% from desalinated seawater (Water Corporation 2015; Shahabi et al. 2014). The use of groundwater replenishment within Western Australia, could help Water Corporation to supply water with a lower impact on the environment in comparison with desalination (DoE 2016). It will also allow for the greater extraction of water in the future as the aquifers may not become depleted in the near future (Department of Water 2011). It was estimated that this water source could potentially provide up to 20% of Perth's drinking water supplies by 2060 (Water Corporation 2016). Groundwater replenishment has been successfully implemented in other parts of the world, including Singapore’s Newater initiative and the Orange County Water District Groundwater Replenishment System (Newater 2015). All of these systems are based on similar technologies, including pre-purification (traditional wastewater management), microfiltration, and reverse osmosis (RO) and UV light treatment before water distribution (NeWater 2015; Orange County Water District, 2016). Orange County also treats the water with hydrogen peroxide (a disinfectant) to further purify the water (Newater 2015). The Newater plant in Singapore adds chemicals to the water to make it drinkable or usable to industry. It is then pumped either back into the Singapore water supply or to factories (majorly wafer fabrication plants due to their requirement for high quality water), where it is reused (NeWater 2015). Orange County uses the water it produces for two main things: one third of the water produced is pumped in the ‘seawater intrusion barrier’, which is designed to stop seawater from entering the groundwater table due to its extremely low level in relation to the sea, whilst the other two thirds is pumped into recharge bores with the plan being that it can be removed many years later (Orange County Water District, 2016). The Perth groundwater replenishment trial acted on the same principle, however, all of the water from the Perth groundwater trial project was recharged into underground aquifers (Water Corporation 2011). The main reason for the water being recharged into aquifers instead of being used directly is to remove the societal stigma associated with drinking recycled water (Kemp et al. 2012).

In 2009 the Water Corporation began the construction of a trial groundwater replenishment plant next to the Beenyup wastewater treatment plant and this plant was operational for 4 years before being decommissioned to construct a full scale plant, due to become operational in 2017 (Water Corporation 2016b and 2016c). The full-scale groundwater replenishment scheme cannot only address WA's water scarcity issue, but there may be CO_2 emission saving opportunity associated with the production of recycled water.

Desalination plants accounting for Western Australia's largest water supply in the metropolitan area have been found to be a more carbon intensive water supply option compared to other existing options. For example, a local WA study found that to produce 1 GL of desalinated water, 3,890 tonnes of CO_2 equivalent emissions would be evolved when grid electricity is the main source of energy, which is extremely high compared to other water supply options (Biswas and Yek 2016). This is also similar to a study in Denmark that found that groundwater was the least polluting in terms of greenhouse effect while desalination was the greatest polluting source (Godskeseen et al. 2011). In another study, desalination technologies were compared with Memstill that involves the use of an external thermal energy resource to reduce chemical requirements. It was identified that due to the lower energy requirement of the Memstill unit it had a lower environmental impact than a similar sized reverse osmosis unit (Tarnacki et al. 2011).

The extraction, treatment and distribution of water has a significant energy footprint. The severe water scarcity that has been experienced in Australia over the last few decades have driven water utilities to consider and implement a range of energy intensive sources of water such as desalination and advanced water treatment. The energy intensity for water production is the highest for desalination through reverse osmosis (i.e. 3.64 – 5 MWh/ML), followed by groundwater extraction (0.13 – 0.6 MWh/ML), recycled water through advanced treatment (i.e. 0.08 – 0.32 MWh/ML), and surface water pumping (i.e. 0.04 – 0.30 MWh/ML) (Stanford University 2013; ISF 2013). If energy is generated predominantly from fossil fuels, then the increase in energy intensity of water production will increase the intensity of GHG emissions.

The groundwater recycling scheme that includes three stages: wastewater treatment, groundwater pre-treatment through advance treatment and groundwater extraction and treatment, is expected to increase both energy intensity and carbon footprints.

Carbon footprint assessment has been done in the research as it is one of the most important indicator for Australia. Prime Minister has reaffirmed during the Climate Change conference in December 2015 that the Australia would “meet and beat” its 2020 emissions reduction goal which is the reduction of 5 per cent compared with 2000 levels (Tom Arup, 2015).

A life cycle assessment (LCA) that followed the ISO 14040-44 guideline has been used to estimate the carbon footprints of water supply and wastewater treatment options. The use of LCAs within the wastewater treatment industry is relatively common and was first seen in the 1990s (Newater 2015).

Whilst LCA of other components of water supply and treatment have been conducted, the advanced water recycling has not been covered in a large amount of detail in the existing LCA analyses. Wastewater treatment initiatives have been covered by many LCA’s, as it allows for differing technology types to be compared and contrasted with each other on another level (Orange County Water District 2016). Groundwater treatment plants have had various LCA’s done on them so as to compare them to other potable water sources. Generally water treatment plants are decided on price and capacity constraints, however, it is now common for emissions to need to be considered due to the environmental authorities within each country (Bontonne et al. 2012). This gives rise to the need for LCA’s to be used to compare plants around the world in an emissions basis.

LCA has been used to determine that chemical treatment processes that would deliver required water quality with reduced level of GHG emissions (Foley et al. 2010). The changing of the conventional electrical energy source (coal to wind power) could significantly reduce the environmental impacts (Li et al. 2013). The comparative LCA also found that the enhanced conventional plant causes far greater amounts of environmental damage than the nanofiltration plant when both plants are powered via hydroelectricity (Bonton et al. 2012).

There is however one comparative LCA which compares three pathways for water supply for Scottsdale, USA: importation, advanced water recycling and desalination (Lyons et al. 2009). The report found that desalination was the largest emitter of greenhouse gas emissions, with water transportation the second and water recycling the lowest emitter. Also, it was found that when comparing desalination to advanced water recycling, the environmental impacts associated with the use of chemicals in advanced water recycling was higher than that of the desalination.

This research assesses the current groundwater recycling scheme in terms of its greenhouse gas (GHG) emissions. The carbon footprint of the scheme was chosen as it is the most commonly recognised (Racoviceanu et al. 2007). This means that the scheme can be easily compared and contrasted to other schemes and processes.

The analysis undertook a cradle to gate approach, with the cradle being the inlet at the Beenyup wastewater plant and the gate being the outlet into the Water Corporation’s Wanneroo reservoir. In the analysis of the scheme, four main discussion points will be covered; distribution of emissions within the plant, mitigation of emissions via the use of renewable energies, comparison to desalination as a climate dependant supply and the effect of the vibrational separation system on the greenhouse gas emissions.

From this point on in the research, scheme refers to the overall process (wastewater inlet to reservoir outlet), plant refers to individual plants within the scheme and stage refers to individual stages within each of the plants.

2 Groundwater cycle scheme components

There are three main plants within the groundwater recycling scheme. These are the Beenyup wastewater treatment plant, the Beenyup groundwater recycling plant (groundwater pre-treatment plant) and the Wanneroo groundwater treatment plant. Figure 1 shows a visual representation of these plants and stages.

The overview of the stages of these three plants has been completed via the information given during a tour of the Water Corporation's facilities, as well as the virtual tours which the Water Corporation has created to show the public where water comes from in Western Australia. [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016](Water Corporation 2016b, 2016c and 2016d).

Wastewater Treatment Plant: Overall electricity usage within the plant is 2189 kWh per GL [Hamilton S, Water Corporation, Perth, personal communication, April 29, 2016].

Pre-screening: Pre-screening is used to remove the bulk of the large objects. This can include rags, plastic and rubbish. The rubbish that is removed from this stage is taken away and disposed of at a landfill site. This is done as larger objects can damage equipment used within the process, which would be costly to repair or replace. From this section the removed waste is the only output. Odours from here are taken to the odour control section.

Grit Tanks and Washing: Grit tanks are used to allow inorganic materials to settle out of the process fluid. The water and organic materials are then drained to the next part of the process and the grit is washed to remove any final organic material and then sent to landfill to be disposed of. The output from this section is the grit, as it contains no organic material, it is assumed to be inert and therefore has no emissions.

Primary Sedimentation: Primary Sedimentation is where the bulk of the organic materials are removed from the water. The water is allowed to sit and the ‘sludge’ is allowed to settle to the bottom. Scrapers are then used to push the sludge to one end of the tank, from here it is then pumped to the sludge treatment area. Odours from this section are contained and sent to the odour control section. As such the sludge is the only output.

Sludge Treatment and Digestion: Sludge from the primary sedimentation area is pumped into heated digestion tanks, where it is broken down by bacteria. The broken down sludge is then dehydrated and sent to an offsite facility which converts it into fertiliser. During the breaking down of the sludge a large amount of methane is produced. This methane is used to heat and power mixers in the sludge digestion tanks as well as for heating and electrical generation within the plant. This is a major reason why the power usage within the plant is so low. The output from this stage is the dehydrated sludge.

Aeration: The water from the primary sedimentation tanks is then aerated in order to promote microbes to consume the last of the remaining organic matter and nutrients within the water. At this point the water is nearly clean enough to be returned to the environment (Water Corporation 2016b). These tanks are covered in order to limit the amount of odour and gas which is released to the environment. As the odour is contained there is no outputs from this stage.

Odour Control: Odour control is a major factor within the plant to maintain community support and meet government guidelines on odours and chemical emissions (Water Corporation 2016b). Odour control is managed by using chemical scrubbers, which then vent to high stacks which means that any remaining odour is dissipated to the atmosphere.

Secondary Sedimentation: Secondary sedimentation tanks are not covered as the water is already quite clean and odourless. This is used as a polishing step to remove any particles which may have been carried over by the process before it is either sent back to the ocean or pumped to the groundwater replenishment circuit.

Pumping to Replenishment: Water from the wastewater treatment plant is then pumped to the groundwater replenishment trial plant. This water must meet strict guidelines to be accepted, and as such surge tanks are used so that the flow to the groundwater replenishment plant can be established at a designated level of 5975 m^3/day (Water Corporation 2008). Water that is not suitable as it is outside the specifications set by the groundwater replenishment team is simply diverted back to the ocean outlet. [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016]

Groundwater Pre-Treatment Plant (Groundwater Replenishment): The groundwater pre-treatment plant requires a proportionally large amount of energy (1019669 kWh) due to the high pressures required by the reverse osmosis (RO) units. [Hamilton S, Water Corporation, Perth, personal communication, May 12, 2016]

Ultrafiltration: Water from the wastewater plant first undergoes ultrafiltration. This is done as a primary clean to stop any larger particles from entering the reverse osmosis (RO) unit. This prolongs the life of the RO membranes. When the pressure differential becomes too high they are backwashed, and the water from the backwash is returned to the beginning of the wastewater treatment plant.

Reverse Osmosis: Similar to the RO units used for seawater filtration, the RO units within the groundwater replenishment are used to remove any particles which may have made it past the ultrafiltration units. These run at a pressure up to 4136.80 kPa (Lenntech 2016).

UV Light: Ultraviolet disinfection is used to kill any viruses and bacteria which are left in the water after the RO system.

Recharge/Injection: The water is then recharged into bores. The bores for the groundwater trial were relatively shallow bores (150 – 220m (MWH 2010)), with the bores drilled for the full-scale project at a mixture of shallow and deep depths. The water from the bores is expected to remain underground for decades before being drawn up by the current water extraction bores.

Groundwater Treatment Plant: The groundwater treatment plant requires 2,19,205 kWh of power to operate. A lot of this power can be associated with the MIEX® system as it was a recent treatment addition to the plant, and as such requires large amounts of pumping.

Extraction: Water is extracted from several bores at varying depths in the northern suburbs of Perth to be used at the groundwater treatment plant site. Currently no water from the storage dams is being used for drinking water purposes due to their low level [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016]. The water for the Wanneroo groundwater treatment plant comes from several bores, which allows the plant to create a blended water type for a more constant feedstock to the plant. It can be assumed that the quantity of water being injected is equal to the quantity of water being extracted. This is because the Water Corporation currently has a credit system associated with their license, which allows for an equal amount of water to be extracted as is injected. [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016]

Aeration: Water which has come from the ground is often high in H_2S and iron, and as such must be treated to remove them. Aeration involves spraying the water into the air which oxidises contaminates such as hydrogen sulfide and iron sulfide. This is the cheapest and most effective way of removing these particles.

MIEX® (Magnetic Ion Exchange): MIEX® resin is used to remove the organic matter from the water. The MIEX® resin particles bind to the organic matter and due to its magnetic properties, make it heavier so it sinks to the bottom faster than conventional resin. This bottom stream is then taken away for regeneration, whilst the top stream is the relatively clean water which then goes to clarification.

MIEX® regeneration involves mixing the MIEX® resin loaded with organics with a saturated salt solution. The salt solution displaces the organics, meaning the MIEX® resin is ready to be used again. (Hamilton 2015) The salt and organic solution is sent to another location to be blended for ocean disposal. [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016]

Clarification: At the clarifiers two chemicals called aluminium sulfate (alum) and polyelectrolyte are added. Alum aids in binding the particles, making them larger and heavier so they will settle out of the solution and the poly electrolyte acts as a flocculent, coagulating the particles together. The clean water spills over at the top into spillways, whilst the larger particles at the bottom are scraped away and sent for drying. This dried sludge is the main output from the groundwater plant and is used for fire breaks.

At this point the clean water has any pH adjustments required made to it through the use of lime.

Filtration: Filtration is used as a final polishing step to remove any particles which may have made it through the clarification process. The filters used are bed filters, which are designed to use a variety of media in shrinking sizes. This media is layered on top of each other, in such a way that the water must pass through the media in order of decreasing size. This means that large particles can be caught before they get to the smallest media which would cause a blockage.

Filters are cleaned using backwashing, with the water from the backwash again being returned to the aeration step.

Disinfection: Finally the water has fluoride and chlorine added to the water. This is used to keep the water clear, bacteria free and the fluoride is added as it is a government requirement. (Department of Health 2016).

3 Methodology

The LCA was conducted following the guidelines outlined in ISO14040-44 (ISO 2010) and can be divided into four basic steps. These are; goal and scope, inventory analysis, impact assessment and interpretation. The interpretation part has been performed in the results and discussion section of this report.

Goal and Scope Definition: The goal of this report is to determine the emissions of various parts of the three plants used within the groundwater system. This research takes a cradle to gate (wastewater inlet to outlet into reservoir) approach to data collection and uses a functional unit of 1 GL. This allowed to carry out a mass balance to determine the amount of inputs and outputs in all processes of product life cycle to produce 1 GL of recycle water.

The carbon footprint (CO_2 equivalent or CO_2 eq) of the scheme was chosen not only because Australia had committed to reduce GHG emissions but also this indicator is the most commonly recognised and referenced GHG emissions (Worldwatch Institute 2011). This means that the scheme can be easily compared and contrasted to other schemes and processes (Worldwatch Institute 2011). From data generated on the carbon footprint both a hotspot analysis, as well as a comparison to other ‘climate independent’ water sources can be completed.

The LCA of the groundwater recycling scheme consists of three main plants, wastewater treatment, groundwater pre-injection treatment and groundwater treatment. Each of these plants are then broken into stages as shown in Figure 1. Emissions from equipment and capital that has a long life span is not included in the system boundary (Sharrad 2008), however short lifespan items or operational items have been considered.

Inventory Analysis: An initial inventory analysis was completed using data provided by the Water Corporation. In this inventory analysis the inputs and outputs of each stage in the process are considered. Where real-time average data were not available, data set points and average design flows were considered. These inputs and outputs are used to create the life cycle inventory (LCI) for the water treatment plants. Table 1 shows the LCI which was a pre-requisite to carry out a life cycle impact analysis. All raw data are converted into a single unit which allows for to be compared to each other. The unit of water which has been chosen to be used is 1 GL of output water (water outputted to the reservoir at the end of the process). This means that a considerable amount of extra water would need to be used in the beginning to account for water leaving the system through other mediums.

Energy and chemicals used within the system for pumping, transport, control, disinfection, cleaning, regeneration and making the water potable must be considered in the process (Table 1). The transport required for the chemicals and waste also needs to be considered (Table 2). The unit of tkm (tonnekilometers) will be used in calculation of the transport emissions.

Impact Assessment: The values for the impact of global warming are expressed over time horizons of 20, 100 and 500 years respectively to allow relevant climate change decisions to be made. As such, GHG emissions from around the scheme must be converted to their CO_2 equivalent values using established conversion factors (IPCC 2007). In this research, the 100 year horizon has been considered, as it is usually a reference point by policy makers. According to the IPCC data on global warming potential factors, at 100 years, CO_2 has a factor of one, CH_4 a factor of 25 and N_2O a factor of 298 (IPCC 2007).These factors must be considered when working out the CO_2 equivalent calculations.

Once the inventory data was collected, they were entered into SimaPro program to calculate the GHG emissions for each LCI item. This LCA software program contains libraries (i.e. emission databases) for the GHG emissions for various chemical and energy inputs. A library in Simapro is an emission database of chemicals and processes which give GHG (CO_2, N_2O, CH_4) values associated with their production. This value was then converted within SimaPro, using the global warming potential factors to the CO_2 equivalent value. These values were then totalled up to give the total CO_2 eq value.

Table 3 shows the different inputs and outputs, the libraries used and their associated CO_2 equivalent values as well as the totals for each stage of the overall scheme. The unit of the data required from the inventory is dependent on what value each database requires. Where possible local databases i.e. AusLCI (Australian Life Cycle Inventory) has been used, however in the event where a local value has not been available (Life Cycle Strategy Pty Ltd. 2015), a new database has been created representing the local situation (Table 3). The value for the CO_2 of the salt used at the GWTP was found from the WA Salt Group which produces it (Lake Deborah 2016). Where chemicals were required to be transported by truck, it was assumed that a 28 tonne articulated truck was used.

4 Limitations of the Study

There was a lack of emission database of following chemicals used within the various processes [Hamilton S, Water Corporation, Perth, personal communication, April 29, 2016]:

BASF ZETag 8165 (11082.75 kg per GL used)

BASF ZETag 7563 (674.2 kg per GL used)

IXOM MIEX® Resin (1481.48 L per GL used)

Nalco PC 191-T (171371.23 L per GL used)

Hydrex 4703 (38 L used per week)

Hydrex 4705 (38 L used per week)

A second limitation is that membranes and cartridges have not been considered due to the inability to gather significant data on their life and construction and also due to the trial nature of this GWRT project [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016]. Also negated in this LCA is the cleaning chemicals used (i.e. NaOH, Antiscalant (PC 191-T), Citric Acid) within the RO units as they are inaccurate due to the trial nature of the system. The emission factors of two important chemicals MIEX® Resin, Dissolved Air Flotation Thickener and Centrifuge Polyelectrolyte (STF) are unavailable and their impacts have been excluded in the assessment.

Exclusion of aforementioned chemicals and membrane will not affect the results significantly. This is because all chemicals and membrane together account for very small portion of GHG emission (<5%) of energy intensive water treatment processes (Biswas 2009).

The emissions factor of organic content of the sludge was a negative emission due to the collection of landfill gases for energy production (Pré Consultants 2016). It was chosen to omit these figures due to the uncertainty of landfill gas collection being utilised at the landfill sites.

5 Results and Discussion

5.1 Monte Carlo Simulation (Uncertainty Analysis)

There are uncertainties associated with the data that is used for estimating carbon footprint. This data includes; the quality of the inputs and output and the emission factors. In order to model these uncertainties a stochastic modelling approach was taken (Clavreul et al. 2012). A Monte Carlo Simulation (MCS) was performed in order to estimate the uncertainty of each of these data points and predict the influence that variable has on the environmental impacts (Goedkoop et al. 2013). The MCS is an iterative approach which uses an input from a probability distribution and produces a distribution of all possible values for in this case 1000 iterations (Goedkoop et al. 2013).

MCS was performed using a confidence interval of 95% and 1000 iterations using the SimaPro software. It was done using a single score method. The mean value of carbon footprint of the overall scheme has been estimated to be 1,300 tonnes of CO_2 eq per GL of water production (Figure 2). The uncertainty analysis through MCS simulation proves the validity of LCA results. This is shown as the standard deviation is only 5.4% of the mean value, meaning that the data is of good quality (Goedkoop et al. 2013). This value is also known as the coefficient of variation (CV).

5.2 Breakdown of Western Australia’s groundwater recycling scheme’s GHG emissions

Figure 3 shows the distribution of GHGs over the overall groundwater recycling scheme in terms of 1 GL of water produced. The groundwater replenishment section produces the greatest amount of greenhouse gases (i.e. 1,027 tonnes CO_2 eq/GL, 79%). This is mainly due to the large amount of energy which is required for the RO pumps in order to get the water pressure up high enough for the RO membranes to operate as required.

Other sections of the scheme keep their power usage low via the use of novel ideas such as using gravity to reduce pumping costs and not requiring high pressures to operate [Hamilton

S, Water Corporation, Perth, personal communication, March 31, 2016]. The wastewater treatment plant is an example of this as they only require 2,189 kWh electricity/GL on site due to gravity pumping and heating via methane from digestion.

At the groundwater treatment plant (GWTP) the power usage is higher than the WWTP due to two main reasons. These are that they must operate pumps to draw the water from the underground aquifers and because of the added available MIEX® treatment option . The original plant was designed to use mainly gravity to flow the water from one end of the plant to the other, however, the added MIEX® treatment section requires pumps to move the water throughout the GWTP (Water Corporation 2016c).

This breakdown of emissions compares favourably to the data presented by Godskesen in 'Life cycle assessment of three water systems in Copenhagen – a management tool for the future' (Godskeseen et al. 2011). The research conducted found that for comparable groundwater replenishment and groundwater extraction plants the carbon footprint associated with groundwater extraction was around 5.2 times lower than that of groundwater replenishment.

Figure 4 shows the breakdown of these emissions in terms of key inputs. Electricity accounts for the majority (83%) of the greenhouse gas emissions from the parts of the scheme. As can be demonstrated in Figure 4, the emissions associated with transport account for only 0.5% of the total greenhouse gas emissions. This is because the majority of the transport occurs on a local basis. The final section being chemicals and waste accounts for 16.5 % of the overall emissions. This can also be regarded as a significant source of emissions for the project.

5.3 GHG Mitigation potential

The major reduction potential for GHG emissions in the WA groundwater recycling scheme life cycle revolve around the production and usage of power for plant operation. As most of the scheme already relies on gravity for water transfer between sections of the plants, there is no real way to reduce energy consumption via changes to the pumping within the plants. However, through the use of lower pressure differential RO membranes the pumping energy within the groundwater replenishment plant could possibly be reduced, however, has not been considered in this research. Secondly, energy efficiency improvement could be another option to reduce the combustion of fossil fuels for electricity generation, but most of Water Corporation's energy efficiency improvements have already resulted from incremental changes to asset designs, maintenance and operating practices, as well as staff awareness of energy use after the implementation of energy efficiency program in 2008. Third mitigation would be to consider the use of more renewable energy within the plant.

Renewable energy was chosen as power generation was identified as a hotspot, and because renewable energy has currently being considered for use within the Water Corporation at their Southern Seawater Desalination Plant (SSDP) as all of its energy needs are met by the 10 Megawatt Greenough River solar farm and 55 Megawatt Mumbida wind farm (Water Corporation 2016e). It was found that there is a reasonably direct relationship between the amount of renewable energy used and the reduction in carbon dioxide equivalent emissions. Should a similar initiative be introduced to the groundwater recycling scheme, there would be a significant reduction in emissions.

Small portion of renewable energy already exist within the Western Australian grid system. In the current WA power mix wind accounts for 4.5%, solar accounts for 0.04% and biomass accounts for 0.1% of energy production (Grant 2015). However there is still a huge potential to generate 37% of Western Australia's electricity from renewable energy sources by

2030 (Clean Energy Council 2011). About 43% and 39% of this projected renewable energy supply will come from wind and solar respectively.

The location of GWRT does not allow wind or solar to meet 100% of electricity demand. This is due to the proximity to a residential area meaning wind alone would be inappropriate to meet the electricity demand, due to noise pollution and landscape changes and the lack of space meaning there is an inadequate amount of land to install solar panels for electricity generation. Due to these reasons, both wind and solar together are to be considered for use as a mitigation strategy for replacing at least some portion of carbon intensive grid electricity.

Considering these social and resource constraints and as no renewable energy plant has been designed for these particular locations in Beenyup and Wanneroo, a scenario analysis has been considered for grid and renewable energy mix for wind and solar for providing electricity for GWRT and it will help the Corporation in the decision making process. For each grid and renewable mix, different mixes of solar and wind have been considered further for finding the less carbon intensive energy mix under locally available renewable resources and socio-economic constraints.

The maximum GHG emissions from the generation of electricity from wind turbines and PV are 9.7 and 217 tons CO_2 -eq per GWh energy generated, respectively (Lund and Biswas 2008). These emission factors have been considered when estimating GHG emissions from GWRT using renewable energy as a partial replacement of grid electricity. Figure 5 shows that GHG mitigation from electricity use at GWRT can be ranged from 21% (i.e. 1,080 – 858 = 222 tonne CO_2 eq) for replacing 25% grid electricity with renewable electricity (i.e. 75% solar and 25% wind) to 93% (i.e. 1,080 – 73 = 1007 tonne of CO_2 eq.) for replacing 100% grid electricity with that produced from 25% solar and 75% wind.

This research correlates strongly with the life cycle assessment of a municipal wastewater treatment plant in Suzhou, China. The researchers found that by increasing the reliance of a wastewater plant on renewable energy technologies, a seven-fold decrease in the global warming impact was achieved (Li et al. 2013).

The key driving force to make it happen would be Western Australia's Low Emissions Energy Development (LEED) Fund program that assists in the promotion of renewable energy technologies. LEED has already invested more than $30million dollars over four years into clean and renewable energy technologies (Government of WA YEAR). In addition, there are a number of renewable energy incentive programs at the national level, known as the expanded national RET scheme, which will continue until 2030, driving renewable energy investment. These may be some of the key reasons that the share of renewable energy sources in the energy mix increased from 5% in 2007 to 9% in 2013 in WA (IMO 2014). It can thus be concluded that there is a favourable situation to harness the potential of renewable energy resources to address WAs energy water nexus in an environmentally friendly manner to secure long term water supply. This current research equally applies to other water scarce region around the globe with high renewable energy potential to operate groundwater replenishment systems using renewable energy technologies to deliver long term water supply with a minimum level of environmental impacts.

5.4 Comparison of Groundwater recycling scheme with existing SSDP

The groundwater recycling scheme compares favourably to desalination for several reasons. Whilst the main reason is because of reduced cost, there are also several major environmental considerations that need to be considered. Using a similar plant as described in LCA of SSDP in WA, a desalination plant would produce 3,890 tonnes CO_2 equivalent per GL with no renewable energy considered and 367 tonnes CO_2 when renewable energy is considered (Biswas 2009). Interestingly, this desalination plant is now using all of its energy from renewable sources. In comparison the groundwater recycle plant produces 1,300 tonnes CO_2 equ as grid electricity is the main source of power. However, this water supply option can only be environmentally competitive with SSDP if 100% of the electricity used is generated from renewable energy for energy mixes of wind and solar between (50%W+50%S) and (75%W+25%S) (Table 4). The GHG emissions can be reduced to 353 tonnes of CO_2 and 293 tonnes of CO_2 per GL of water produced for energy mixes of 50%W+50%S and 75%W+25%S, respectively. Also Figure 5 shows the level of GHG emissions that can be mitigated due to other energy mixes. These results would help Perth's full scale groundwater replenishment plant which is due to operational in 2017 to consider the optimum energy mix for delivering water with the lowest possible amount of GHG emissions.

It was also found in the case of life cycle assessment of three water systems in Copenhagen that there is a significant difference in the environmental impacts of groundwater recharge (1.2 E-04 personal equivalent/m^3) and Reverse Osmosis (2.15 E-04 personal equivalent/m^3), when wind turbines and solar cells have been considered to provide energy for treatment and pumping (Godskeseen et al. 2011). The research found that for two comparable systems that reverse osmosis has the strongest environmental impact. This is a similar result to the one that has been found by this research.

5.5 Effect of V-Sep on the emissions from the groundwater scheme

V-Sep is a technology that is being used to reduce waste from the MIEX® cycle. This is done by using a vibrating membrane to separate the MIEX® waste into a concentrated waste stream and a product stream which can be reused in the process. Figure 6 gives a visual depiction of the plant. Despite currently being in a testing and research phase, the project is showing very promising results. [Hamilton S, Water Corporation, Perth, personal communication, March 31, 2016]

V-Sep presents an opportunity to reduce the GHG emissions as it allows for a reduction in the amount of salt, waste, and waste transport from the MIEX® system. Table 5 shows how V-Sep compares to the standard method in terms of CO_2 Equivalent generation. The data was provided by a V-Sep weekly report. [Hamilton S, Water Corporation, personal communication, May 10, 2016]. From Table 5 we can see a reduction of 4.03 tonne of CO_2 equivalent per GL from the process overall. This is a significant loss of CO_2 saved by the V-Sep process and represents a very good investment for the Water Corporation.

Vibrational separation (V-Sep) was also studied in relation to reducing the CO_2 equ of the plant. V-Sep is the process of concentrating waste from the MIEX® process by removing some of the regeneration chemicals that would otherwise be sent to waste. It is completed by using a vibrating membrane. Using V-Sep allows for the amount of CO_2 eq to be lowered via two methods; lowering transport emissions due to less waste being trucked for ocean disposal and lowering the requirement of chemicals. It was found that the trial V-Sep plant at Wanneroo, results in a 4.03 tonne of CO_2 eq saving per GL of water produced by the plant.

6 Conclusion

This analysis found that 1,300 tonne of CO_2 equivalent would be produced from the groundwater recycling trial scheme as it has been proposed for a volume of 1 GL of water. It was found that the majority (83.1%) of the greenhouse gases were emitted from the generation of the electrical power being used within the plants. From this, it can be seen that the amount of greenhouse gases that are emitted could be easily changed through the use of renewable energy instead of the current Western Australia power mixture. Western Australia has adequate renewable energy resource potential and government level institutional supports to promote renewable energy to address its energy water nexus in an environmentally friendly manner to ensure long term guaranteed water supply.

The groundwater recycling trial scheme produced 72% more GHG emissions than the existing seawater desalination plant due to fact that the former used 100% grid electricity and latter is powered by 100% renewable energy. The groundwater recycling trial scheme can only be environmentally competitive with the desalination power supply option if 100% of the electricity used is generated from renewable energy with mixes between 50% wind and 50% solar and 75% wind and 25% solar. The similar ground water recycling scenario can be considered in other states of Australia such as Tasmania and South Australia where there exists water scarcity but major portion of electricity is generated from renewable energy sources (i.e. 93% RE in Tasmania and 36% RE in South Australia) (Climate Council of Australia Ltd 2014).

Apart from renewable energy, continued use of the V-Sep system or similar waste treatment systems could lower the amount of chemicals required and waste removed from the plant.

This current research concludes that the water scarce region around the globe with high renewable energy potential can operate energy intensive groundwater recycling scheme using renewable energy technologies to deliver long term water supply with a minimum level of global warming impacts.

Acknowledgements

Many thanks are given to Eduardo Cosa and Chris Meyers of Water Corporation Perth for the assistance in data collection and Kate Tonta of Water Corporation Perth for her support throughout the project

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Table 1 Life cycle inventory of 1GL of water production.

Input / Output	Data Source from Water Corporation, Perth documents	Value/unit
WWTP		
Power	Plant Performance Spreadsheet	2189 kilowatt hour (kWh)/GL produced water
Chlorine	Plant Performance Spreadsheet	1250 kg/GL produced water
Sodium hypochlorite (NaClO)	Plant Performance Spreadsheet	3640 L/GL produced water (4040 kg/GL produced water)
Sodium Hydroxide (NaOH)	Plant Performance Spreadsheet	634.9 L/GL produced water (50%)(965 kg/GL produced water)
Dissolved Air Flotation Thickener (DAFT)	Plant Performance Spreadsheet	674.2 kg/GL produced water
Centrifuge Polyelectrolyte (STF)	Plant Performance Spreadsheet	10555 L/GL produced water (7916.25 kg/GL produced water)
GWRT		
Power	GWRT Power Total	1019669 kWh/GL produced water
Sulfuric acid (H_2SO_4)	Process Control Table	50640 L/GL produced water (91152 kg/GL produced water)
NaClO	Process Control Table	65832 L/GL produced water (78998 kg/GL produced water)
Ammonium (NH_4)	Process Control Table	10159 L/GL produced water (7416 kg/GL produced water)
GWTP		
Power	Monthly Operating Spreadsheet	219205 kWh/GL produced water
MIEX® Resin	Monthly Operating Spreadsheet	1481 L/GL produced water
Alum	Monthly Operating Spreadsheet	77438 L/GL produced water (87890 kg/GL produced water)
Polyelectrolyte (LT-25)	Polyflow Spreadsheet	171371 L/GL produced water
HCl	Monthly Operating Spreadsheet	1563 L/GL produced water (1814 kg/GL produced water)
NaOH	Monthly Operating Spreadsheet	785 L/GL produced water (50%)(1193kg/GL produced water)
Chlorine	Chlorine Spreadsheets	5020 kg/GL produced water
FSA (Flourosilicic Acid)	SCADA Screenshot	3649 kg/GL produced water
Salt	Salt Usage Spreadsheet	23708 kg/GL produced water

Note: Beenyup Wastewater Treatment Plant (WWTP) would need to operate for 13.19 days, the groundwater replenishment trial plant (GWRT) for 211days and the Wanneroo groundwater treatment plant (GWTP) for 9.24 days to produce 1GL (Giga Litres) of water at the outlet pipe into the Wanneroo reservoir. Data for most of the plant was sourced from the Water Corporation. [Hamilton S, Water Corporation, Perth, personal communication , April 29, 2016]

Table 2 Transportation information of inputs.

Chemical	Amount (tonne)	Km Travelled (Source)	CO_2 equivalent
WWTP			
Chlorine	1.25	3944 (IXOM (Botany))	0.5 tonne CO_2 eq
Sodium hypochlorite (NaClO)	4.04	63 (Coogee Chemicals)	0.027 tonne CO_2 eq
Sodium hydroxide (NaOH)	0.965	63 (Coogee Chemicals)	0.0065 tonne CO_2 eq
DAFT	0.674	37 (BASF)	0.0027 tonne CO_2 eq
Cent Poly	7.92	37 (BASF)	0.03 tonne CO_2 eq
GWRP			
Sulfuric acid (H_2SO_4)	91.15	63 (Coogee Chemicals)	0.61 tonne CO_2 eq
NaClO	78.99	63 (Coogee Chemicals)	0.53 tonne CO_2 eq
Ammonium (NH_4)	7.42	10 (Environex)	0.0079 tonne CO_2 eq
GWTP			
MIEX® Resin	1.78	3944 (IXOM (Botany))	0.75 tonne CO_2 eq
Alum	87.89	76 (Coogee Chemicals)	0.71 tonne CO_2 eq
Polyelectrolyte (LT-25)	128.53	36 (BASF)	0.50 tonne CO_2 eq
Hydrochloric acid (HCl)	1.81	76 (Coogee Chemicals)	0.02 tonne CO_2 eq
NaOH	1.19	76 (Coogee Chemicals)	0.01 tonne CO_2 eq
Chlorine	2.17	3944 (IXOM (Botany))	0.92 tonne CO_2 eq
FSA (Flourosilicic Acid)	3.65	77 (CSBP Kwinana)	0.03 tonne CO_2 eq
Salt	23.71	50 (WA Salt Supply)	0.13 tonne CO_2 eq

Note: It was assumed that all transport takes place by 28t fleet average truck. This truck has an emission of 0.107 kg CO_2 equivalent (eq) per tkm (or tonne*km travelled) found using the AusLCI database on SimaPro.

Table 3 Emission factors.

Input / Output	Value	CO_2 Equivalent	Library Used
WWTP			
Power	2189 kWh	1.9 tonne	AusLCI
Chlorine	1250 kg	2.42 tonne	AusLCI
NaClO	3640 L (4040 kg)	5.83 tonne	AusLCI
NaOH	634.9 L (50%)(965 kg)	1.77 tonne	AusLCI
GWRP			
Power	1019669 kWh	887 tonne	AusLCI
H_2SO_4	50640 L (91152 kg)	94.5 tonne	AusLCI
NaClO	65832 L (78998 kg)	114 tonne	AusLCI
NH_4	10159 L (7416 kg)	15.4 tonne	AusLCI
GWTP			
Power	219205 kWh	191 tonne	AusLCI
Alum	77438 L (87890 kg)	52.3 tonne	AusLCI
HCl	1563 L (1814 kg)	2.62 tonne	AusLCI
NaOH	785 L (50%)(1193kg)	2.18 tonne	AusLCI
Chlorine	5020 kg	9.73 tonne	AusLCI
FSA (Flourosilicic Acid)	3649 kg	0.32 tonne	AusLCI
Salt	23708 kg	2.09 tonne	(Lake Deborah 2016)

Table 4 Comparison of Emissions Distribution (tonnes CO_2 eq/GL)

	Groundwater Scheme			Desalination	
	GE	100% RE(50%S+50% W)	100% RE (25%S +75%W)	GE	SSDP's current mix 100% RE
Power	1080 (83.0%)	133 (79%)	73 (25%)	3,583(92.1%)	59 (16%)
Transport	7 (0.5%)	7(1%)	7 (3%)	16 (0.4%)	16 (4%)
Chemicals and Waste	213 (16.5%)	213 (20%)	213 (72%)	292 (7.5%)	292 (80%)
Total	1,300	353	293	3.891	367

GE= Grid Electricity; RE = Renewable Energy; S= Solar; W= Wind

Table 5 Effect of V-Sep (per week)

Input / Output	CO_2 equivalent Effect
Salt (20.12 tonne produced)	- 1.77 tonne
Waste Trucked (5 less)	- 1.3 tonne
Chemicals	Cannot be determined due to proprietary nature
Power Usage (15.4 kWh)	+ 0.0134 tonne
Total saving	-3.06 tonne per week - 4.03 tonne per GL

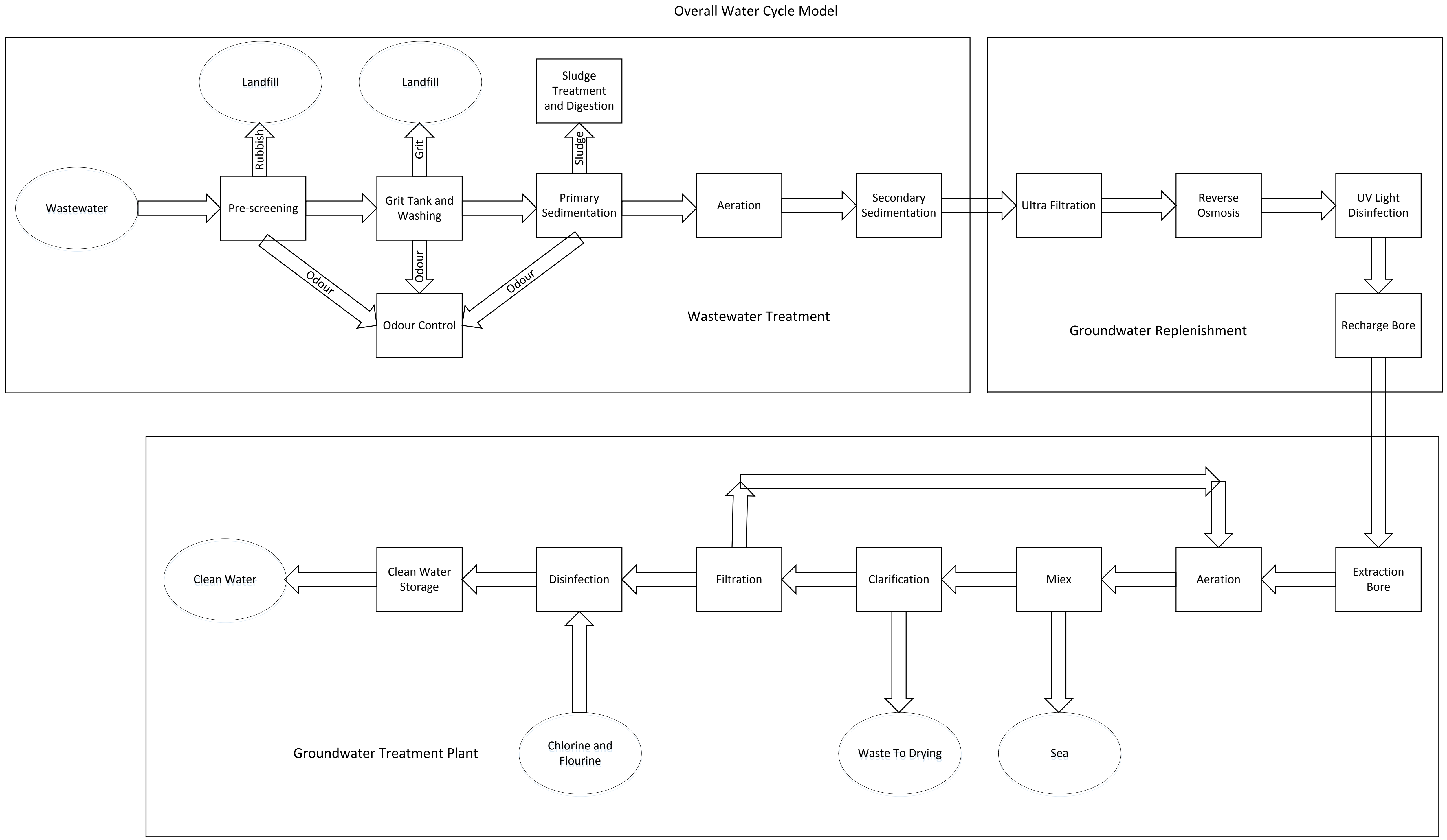
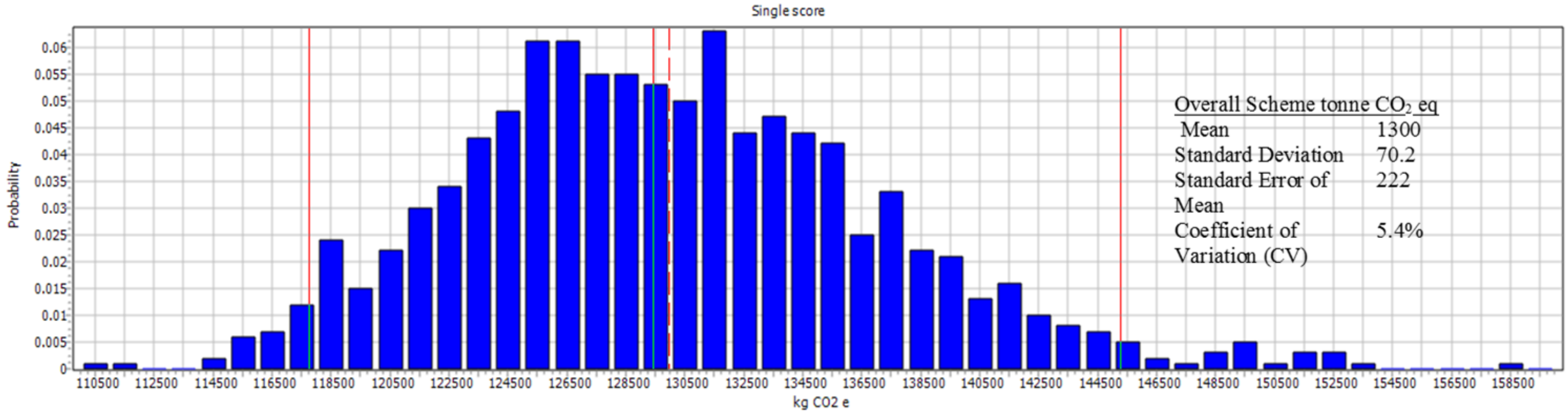


Fig. 1 Overall Water Model (developed from tour and Water Corporation videos (Water Corporation 2016b and 2016c; Godskeseen et al. 2011).



Method: Australian indicator set V2.01 / Australian per capita, confidence interval: 95 %

Uncertainty analysis of 0.55 p 'Overall Better',

Fig. 2 Monte Carlo Simulation results.

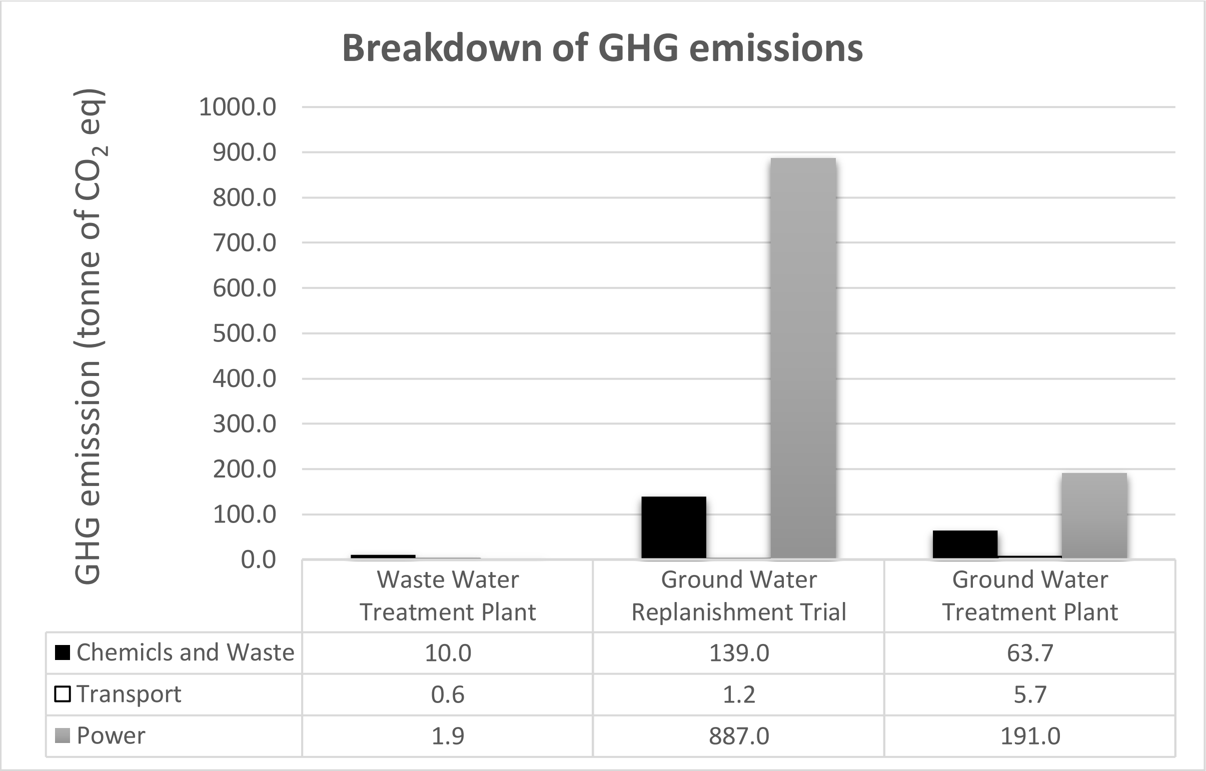


Fig. 3 Carbon footprint breakdown in terms of inputs for three systems.

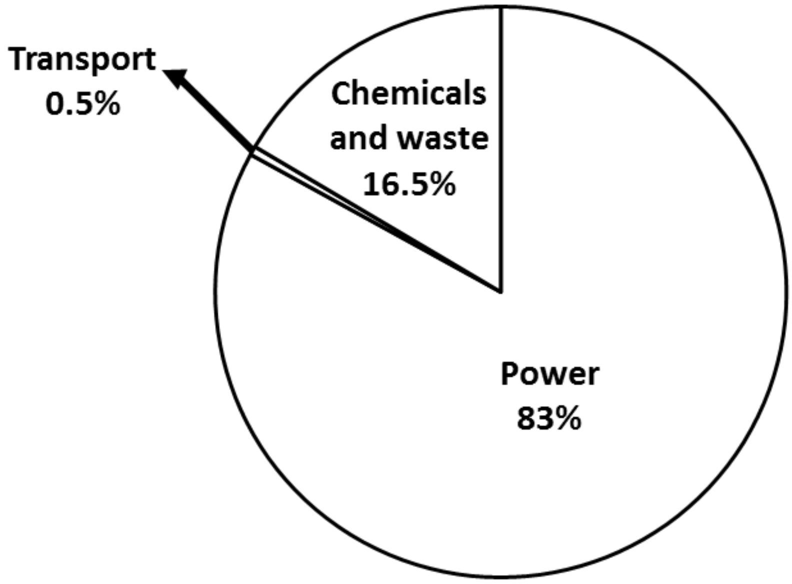


Fig. 4 Share of CO_2 eq inputs of the whole system.

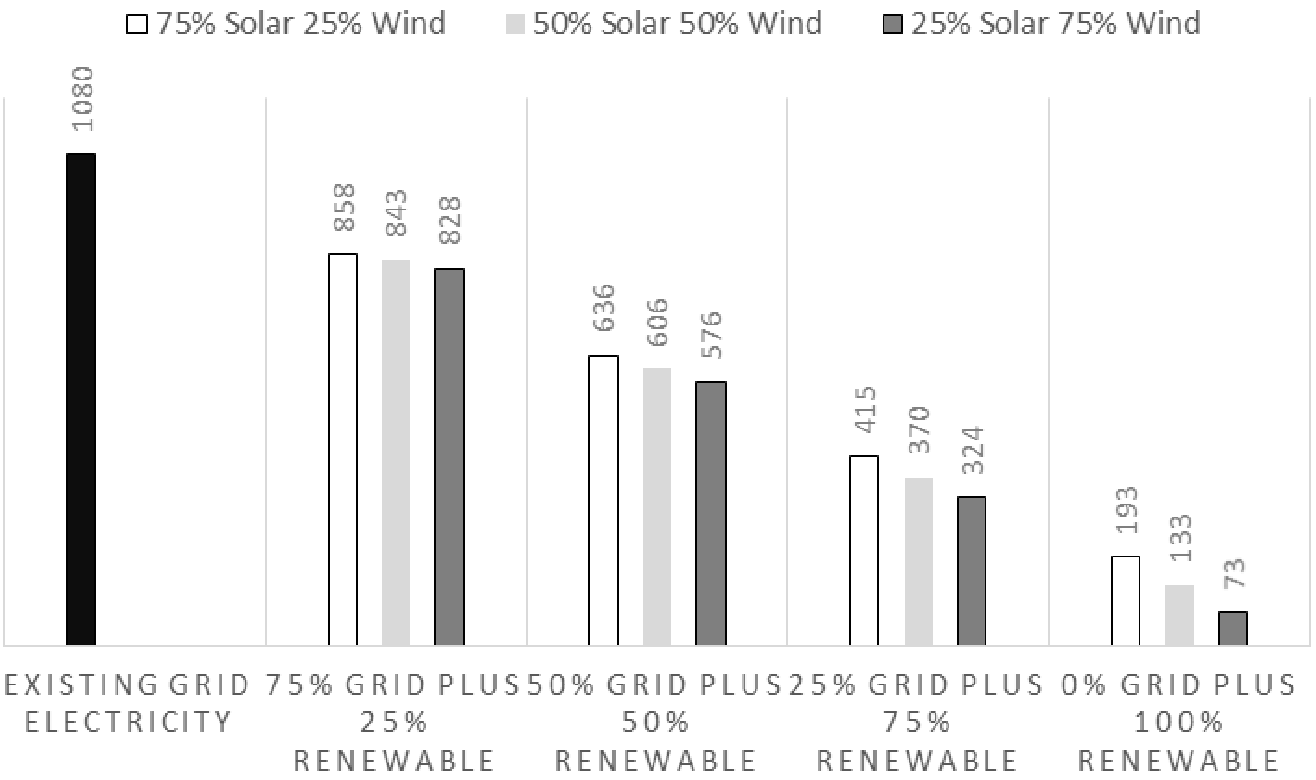


Fig. 5 Carbon footprint implications of the use of solar and wind powered electricity

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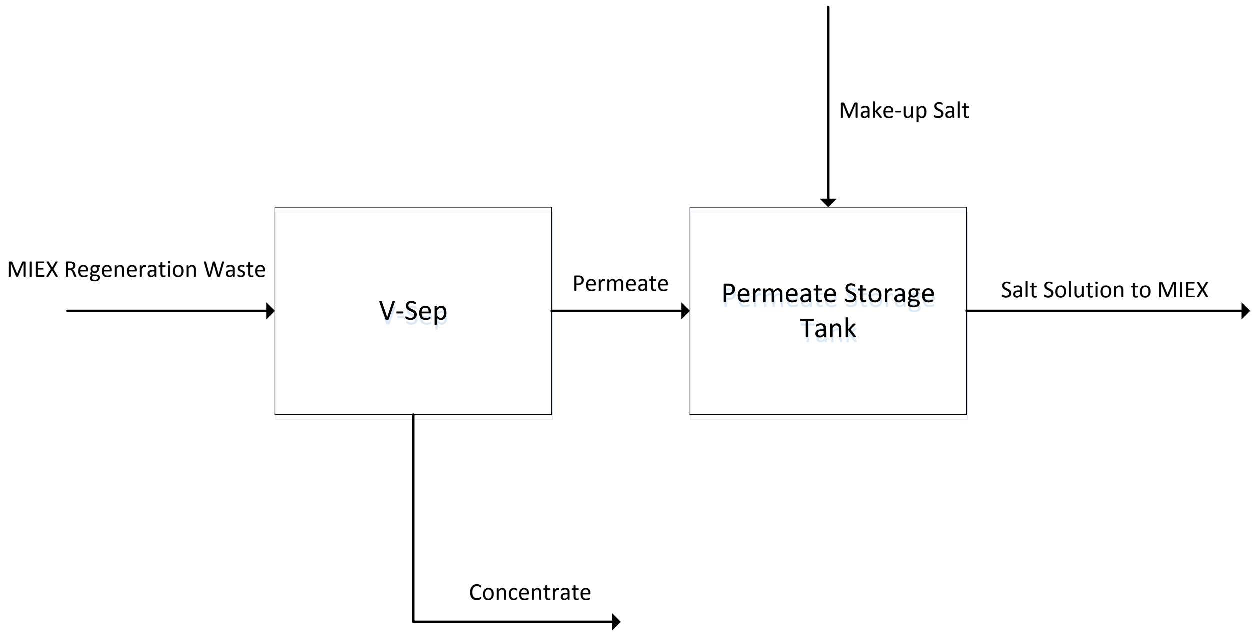

Fig. 6 V-Sep flow diagram (Leong et al. 2016)