

# 1 **Carbon footprint assessment of Western Australian Groundwater**

## 2 **Recycling Scheme**

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6

7 **Abstract** This research has determined the carbon footprint or the carbon dioxide equivalent  
8 (CO<sub>2</sub>eq) of potable water production from a groundwater recycling scheme, consisting of the  
9 Beenyup wastewater treatment plant (WWTP), the Beenyup groundwater replenishment trial  
10 plant (GWRT) and the Wanneroo groundwater treatment plant (GWTP) in Western Australia  
11 (WA), using a life cycle assessment (LCA) approach. It was found that the scheme produces  
12 1,300 tonnes of CO<sub>2</sub>eq per gigalitre (GL) of water produced, which is 933 tonnes of CO<sub>2</sub>eq  
13 higher than the desalination plant at Binningup in WA powered by 100% renewable energy  
14 generated electricity. A Monte Carlo Simulation uncertainty analysis calculated a Coefficient  
15 of Variation value of 5.4%, thus confirming the accuracy of the simulation. Electricity input  
16 accounts for 83% of the carbon dioxide equivalent produced during the production of potable  
17 water. The chosen mitigation strategy was to consider the use of renewable energy to generate  
18 electricity for carbon intensive GWRT. Depending on the local situation, a maximum of 93%  
19 and a minimum of 21% GHG saving from electricity use can be attained at GWRT by replacing  
20 grid electricity with renewable electricity. In addition, the consideration of vibrational

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21 separation (V-Sep) that helps reduce wastes generation and chemical use resulted in a 4.03  
22 tonne of CO<sub>2</sub> eq saving per GL of water produced by the plant.

23

24 **Keywords** Groundwater recycling, carbon footprint, Western Australia

25

26

27 **1 Introduction**

28

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

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

46 In 2014–15, 17% of water supplied into the Integrated Water Supply Scheme (IWSS) came  
47 from surface water (dams), 42% from groundwater and 41% from desalinated seawater (Water  
48 Corporation 2015; Shahabi et al. 2014). The use of groundwater replenishment within Western  
49 Australia, could help Water Corporation to supply water with a lower impact on the

50 environment in comparison with desalination (DoE 2016). It will also allow for the greater  
51 extraction of water in the future as the aquifers may not become depleted in the near future  
52 (Department of Water 2011). It was estimated that this water source could potentially provide  
53 up to 20% of Perth's drinking water supplies by 2060 (Water Corporation 2016). Groundwater  
54 replenishment has been successfully implemented in other parts of the world, including  
55 Singapore's Newater initiative and the Orange County Water District Groundwater  
56 Replenishment System (Newater 2015). All of these systems are based on similar technologies,  
57 including pre-purification (traditional wastewater management), microfiltration, and reverse  
58 osmosis (RO) and UV light treatment before water distribution (NeWater 2015; Orange County  
59 Water District, 2016). Orange County also treats the water with hydrogen peroxide (a  
60 disinfectant) to further purify the water (Newater 2015). The Newater plant in Singapore adds  
61 chemicals to the water to make it drinkable or usable to industry. It is then pumped either back  
62 into the Singapore water supply or to factories (majorly wafer fabrication plants due to their  
63 requirement for high quality water), where it is reused (NeWater 2015). Orange County uses  
64 the water it produces for two main things: one third of the water produced is pumped in the  
65 'seawater intrusion barrier', which is designed to stop seawater from entering the groundwater  
66 table due to its extremely low level in relation to the sea, whilst the other two thirds is pumped  
67 into recharge bores with the plan being that it can be removed many years later (Orange County  
68 Water District, 2016). The Perth groundwater replenishment trial acted on the same principle,  
69 however, all of the water from the Perth groundwater trial project was recharged into  
70 underground aquifers (Water Corporation 2011). The main reason for the water being  
71 recharged into aquifers instead of being used directly is to remove the societal stigma  
72 associated with drinking recycled water (Kemp et al. 2012).

73 In 2009 the Water Corporation began the construction of a trial groundwater  
74 replenishment plant next to the Beenyup wastewater treatment plant and this plant was

75 operational for 4 years before being decommissioned to construct a full scale plant, due to  
76 become operational in 2017 (Water Corporation 2016b and 2016c). The full-scale groundwater  
77 replenishment scheme cannot only address WA's water scarcity issue, but there may be CO<sub>2</sub>  
78 emission saving opportunity associated with the production of recycled water.

79 Desalination plants accounting for Western Australia's largest water supply in the  
80 metropolitan area have been found to be a more carbon intensive water supply option compared  
81 to other existing options. For example, a local WA study found that to produce 1 GL of  
82 desalinated water, 3,890 tonnes of CO<sub>2</sub> equivalent emissions would be evolved when grid  
83 electricity is the main source of energy, which is extremely high compared to other water  
84 supply options (Biswas and Yek 2016). This is also similar to a study in Denmark that found  
85 that groundwater was the least polluting in terms of greenhouse effect while desalination was  
86 the greatest polluting source (Godskesen et al. 2011). In another study, desalination  
87 technologies were compared with Memstill that involves the use of an external thermal energy  
88 resource to reduce chemical requirements. It was identified that due to the lower energy  
89 requirement of the Memstill unit it had a lower environmental impact than a similar sized  
90 reverse osmosis unit (Tarnacki et al. 2011).

91 The extraction, treatment and distribution of water has a significant energy footprint. The  
92 severe water scarcity that has been experienced in Australia over the last few decades have  
93 driven water utilities to consider and implement a range of energy intensive sources of water  
94 such as desalination and advanced water treatment. The energy intensity for water production  
95 is the highest for desalination through reverse osmosis (i.e. 3.64 – 5 MWh/ML), followed by  
96 groundwater extraction (0.13 – 0.6 MWh/ML), recycled water through advanced treatment (i.e.  
97 0.08 – 0.32 MWh/ML), and surface water pumping (i.e. 0.04 – 0.30 MWh/ML) (Stanford  
98 University 2013; ISF 2013). If energy is generated predominantly from fossil fuels, then the  
99 increase in energy intensity of water production will increase the intensity of GHG emissions.

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

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

107 A life cycle assessment (LCA) that followed the ISO 14040-44 guideline has been used to  
108 estimate the carbon footprints of water supply and wastewater treatment options. The use of  
109 LCAs within the wastewater treatment industry is relatively common and was first seen in the  
110 1990s (Newater 2015).

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

121 LCA has been used to determine that chemical treatment processes that would deliver  
122 required water quality with reduced level of GHG emissions (Foley et al. 2010). The changing  
123 of the conventional electrical energy source (coal to wind power) could significantly reduce

124 the environmental impacts (Li et al. 2013). The comparative LCA also found that the enhanced  
125 conventional plant causes far greater amounts of environmental damage than the nanofiltration  
126 plant when both plants are powered via hydroelectricity (Bonton et al. 2012).

127 There is however one comparative LCA which compares three pathways for water supply  
128 for Scottsdale, USA: importation, advanced water recycling and desalination (Lyons et al.  
129 2009). The report found that desalination was the largest emitter of greenhouse gas emissions,  
130 with water transportation the second and water recycling the lowest emitter. Also, it was found  
131 that when comparing desalination to advanced water recycling, the environmental impacts  
132 associated with the use of chemicals in advanced water recycling was higher than that of the  
133 desalination.

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

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

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

147

148 **2 Groundwater cycle scheme components**

149

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

154 The overview of the stages of these three plants has been completed via the information  
155 given during a tour of the Water Corporation’s facilities, as well as the virtual tours which the  
156 Water Corporation has created to show the public where water comes from in Western  
157 Australia. [Hamilton S, Water Corporation, Perth, personal communication, March 31,  
158 2016](Water Corporation 2016b, 2016c and 2016d).

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

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

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



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

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

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

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

193 Secondary Sedimentation: Secondary sedimentation tanks are not covered as the water is  
194 already quite clean and odourless. This is used as a polishing step to remove any particles which

195 may have been carried over by the process before it is either sent back to the ocean or pumped  
196 to the groundwater replenishment circuit.

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

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

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

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

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

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

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

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

235 Aeration: Water which has come from the ground is often high in H<sub>2</sub>S and iron, and as  
236 such must be treated to remove them. Aeration involves spraying the water into the air which  
237 oxidises contaminants such as hydrogen sulfide and iron sulfide. This is the cheapest and most  
238 effective way of removing these particles.

239 MIEX<sup>®</sup> (Magnetic Ion Exchange): MIEX<sup>®</sup> resin is used to remove the organic matter from  
240 the water. The MIEX<sup>®</sup> resin particles bind to the organic matter and due to its magnetic  
241 properties, make it heavier so it sinks to the bottom faster than conventional resin. This bottom

242 stream is then taken away for regeneration, whilst the top stream is the relatively clean water  
243 which then goes to clarification.

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

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

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

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

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

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

268

### 269 **3 Methodology**

270

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

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

280 The carbon footprint (CO<sub>2</sub> equivalent or CO<sub>2</sub> eq) of the scheme was chosen not only because  
281 Australia had committed to reduce GHG emissions but also this indicator is the most commonly  
282 recognised and referenced GHG emissions (Worldwatch Institute 2011). This means that the  
283 scheme can be easily compared and contrasted to other schemes and processes (Worldwatch  
284 Institute 2011). From data generated on the carbon footprint both a hotspot analysis, as well as  
285 a comparison to other 'climate independent' water sources can be completed.

286 The LCA of the groundwater recycling scheme consists of three main plants, wastewater  
287 treatment, groundwater pre-injection treatment and groundwater treatment. Each of these  
288 plants are then broken into stages as shown in Figure 1. Emissions from equipment and capital

289 that has a long life span is not included in the system boundary (Sharrad 2008), however short  
290 lifespan items or operational items have been considered.

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

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

305 Impact Assessment: The values for the impact of global warming are expressed over time  
306 horizons of 20, 100 and 500 years respectively to allow relevant climate change decisions to  
307 be made. As such, GHG emissions from around the scheme must be converted to their CO<sub>2</sub>  
308 equivalent values using established conversion factors (IPCC 2007). In this research, the 100  
309 year horizon has been considered, as it is usually a reference point by policy makers. According  
310 to the IPCC data on global warming potential factors, at 100 years, CO<sub>2</sub> has a factor of one,  
311 CH<sub>4</sub> a factor of 25 and N<sub>2</sub>O a factor of 298 (IPCC 2007). These factors must be considered  
312 when working out the CO<sub>2</sub> equivalent calculations.

313 Once the inventory data was collected, they were entered into SimaPro program to calculate  
314 the GHG emissions for each LCI item. This LCA software program contains libraries (i.e.  
315 emission databases) for the GHG emissions for various chemical and energy inputs. A library  
316 in Simapro is an emission database of chemicals and processes which give GHG (CO<sub>2</sub>, N<sub>2</sub>O,  
317 CH<sub>4</sub>) values associated with their production. This value was then converted within SimaPro,  
318 using the global warming potential factors to the CO<sub>2</sub> equivalent value. These values were then  
319 totalled up to give the total CO<sub>2</sub> eq value.

320 Table 3 shows the different inputs and outputs, the libraries used and their associated CO<sub>2</sub>  
321 equivalent values as well as the totals for each stage of the overall scheme. The unit of the data  
322 required from the inventory is dependent on what value each database requires. Where possible  
323 local databases i.e. AusLCI (Australian Life Cycle Inventory) has been used, however in the  
324 event where a local value has not been available (Life Cycle Strategy Pty Ltd. 2015), a new  
325 database has been created representing the local situation (Table 3). The value for the CO<sub>2</sub> of  
326 the salt used at the GWTP was found from the WA Salt Group which produces it (Lake  
327 Deborah 2016). Where chemicals were required to be transported by truck, it was assumed that  
328 a 28 tonne articulated truck was used.

329

#### 330 **4 Limitations of the Study**

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

333 BASF ZETag 8165 ( 11082.75 kg per GL used)

334 BASF ZETag 7563 ( 674.2 kg per GL used)

335 IXOM MIEX® Resin ( 1481.48 L per GL used)

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

337 Hydrex 4703 ( 38 L used per week)

338 Hydrex 4705 ( 38 L used per week)

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

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

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

353

354

## 355 **5 Results and Discussion**

356

### 357 **5.1 Monte Carlo Simulation (Uncertainty Analysis)**



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

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

373

## 374 **5.2 Breakdown of Western Australia's groundwater recycling scheme's GHG emissions**

375 Figure 3 shows the distribution of GHGs over the overall groundwater recycling scheme in  
376 terms of 1 GL of water produced. The groundwater replenishment section produces the greatest  
377 amount of greenhouse gases (i.e. 1,027 tonnes CO<sub>2</sub> eq/GL, 79%). This is mainly due to the  
378 large amount of energy which is required for the RO pumps in order to get the water pressure  
379 up high enough for the RO membranes to operate as required.

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

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

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

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

397 Figure 4 shows the breakdown of these emissions in terms of key inputs. Electricity  
398 accounts for the majority (83%) of the greenhouse gas emissions from the parts of the scheme.  
399 As can be demonstrated in Figure 4, the emissions associated with transport account for only  
400 0.5% of the total greenhouse gas emissions. This is because the majority of the transport occurs  
401 on a local basis. The final section being chemicals and waste accounts for 16.5 % of the overall  
402 emissions. This can also be regarded as a significant source of emissions for the project.

403

### 404 **5.3 GHG Mitigation potential**

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

417 Renewable energy was chosen as power generation was identified as a hotspot, and  
418 because renewable energy has currently being considered for use within the Water Corporation  
419 at their Southern Seawater Desalination Plant (SSDP) as all of its energy needs are met by the  
420 10 Megawatt Greenough River solar farm and 55 Megawatt Mumbida wind farm (Water  
421 Corporation 2016e). It was found that there is a reasonably direct relationship between the  
422 amount of renewable energy used and the reduction in carbon dioxide equivalent emissions.  
423 Should a similar initiative be introduced to the groundwater recycling scheme, there would be  
424 a significant reduction in emissions.

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

429 2030 (Clean Energy Council 2011). About 43% and 39% of this projected renewable energy  
430 supply will come from wind and solar respectively.

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

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

444 The maximum GHG emissions from the generation of electricity from wind turbines and  
445 PV are 9.7 and 217 tons CO<sub>2</sub> -eq per GWh energy generated, respectively (Lund and Biswas  
446 2008). These emission factors have been considered when estimating GHG emissions from  
447 GWRT using renewable energy as a partial replacement of grid electricity. Figure 5 shows that  
448 GHG mitigation from electricity use at GWRT can be ranged from 21% (i.e.  $1,080 - 858 = 222$   
449 tonne CO<sub>2</sub> eq) for replacing 25% grid electricity with renewable electricity (i.e. 75% solar and  
450 25% wind) to 93% (i.e.  $1,080 - 73 = 1007$  tonne of CO<sub>2</sub> eq.) for replacing 100% grid electricity  
451 with that produced from 25% solar and 75% wind.

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

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

470

471

#### 472 **5.4 Comparison of Groundwater recycling scheme with existing SSDP**

473 The groundwater recycling scheme compares favourably to desalination for several reasons.  
474 Whilst the main reason is because of reduced cost, there are also several major environmental  
475 considerations that need to be considered. Using a similar plant as described in LCA of SSDP

476 in WA, a desalination plant would produce 3,890 tonnes CO<sub>2</sub> equivalent per GL with no  
477 renewable energy considered and 367 tonnes CO<sub>2</sub> when renewable energy is considered  
478 (Biswas 2009). Interestingly, this desalination plant is now using all of its energy from  
479 renewable sources. In comparison the groundwater recycle plant produces 1,300 tonnes CO<sub>2</sub>  
480 equ as grid electricity is the main source of power. However, this water supply option can only  
481 be environmentally competitive with SSDP if 100% of the electricity used is generated from  
482 renewable energy for energy mixes of wind and solar between (50%W+50%S) and  
483 (75%W+25%S) (Table 4). The GHG emissions can be reduced to 353 tonnes of CO<sub>2</sub> and 293  
484 tonnes of CO<sub>2</sub> per GL of water produced for energy mixes of 50%W+50%S and 75%W+25%S,  
485 respectively. Also Figure 5 shows the level of GHG emissions that can be mitigated due to  
486 other energy mixes. These results would help Perth's full scale groundwater replenishment  
487 plant which is due to operational in 2017 to consider the optimum energy mix for delivering  
488 water with the lowest possible amount of GHG emissions.

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

496

## 497 **5.5 Effect of V-Sep on the emissions from the groundwater scheme**

498 V-Sep is a technology that is being used to reduce waste from the MIEX<sup>®</sup> cycle. This is done  
499 by using a vibrating membrane to separate the MIEX<sup>®</sup> waste into a concentrated waste stream

500 and a product stream which can be reused in the process. Figure 6 gives a visual depiction of  
501 the plant. Despite currently being in a testing and research phase, the project is showing very  
502 promising results. [Hamilton S, Water Corporation, Perth, personal communication, March 31,  
503 2016]

504 V-Sep presents an opportunity to reduce the GHG emissions as it allows for a reduction in  
505 the amount of salt, waste, and waste transport from the MIEX<sup>®</sup> system. Table 5 shows how V-  
506 Sep compares to the standard method in terms of CO<sub>2</sub> Equivalent generation. The data was  
507 provided by a V-Sep weekly report. [Hamilton S, Water Corporation, personal communication,  
508 May 10, 2016]. From Table 5 we can see a reduction of 4.03 tonne of CO<sub>2</sub> equivalent per GL  
509 from the process overall. This is a significant loss of CO<sub>2</sub> saved by the V-Sep process and  
510 represents a very good investment for the Water Corporation.

511 Vibrational separation (V-Sep) was also studied in relation to reducing the CO<sub>2</sub> equ of the  
512 plant. V-Sep is the process of concentrating waste from the MIEX<sup>®</sup> process by removing some  
513 of the regeneration chemicals that would otherwise be sent to waste. It is completed by using a  
514 vibrating membrane. Using V-Sep allows for the amount of CO<sub>2</sub> eq to be lowered via two  
515 methods; lowering transport emissions due to less waste being trucked for ocean disposal and  
516 lowering the requirement of chemicals. It was found that the trial V-Sep plant at Wanneroo,  
517 results in a 4.03 tonne of CO<sub>2</sub> eq saving per GL of water produced by the plant.

518

## 519 **6 Conclusion**

520

521 This analysis found that 1,300 tonne of CO<sub>2</sub> equivalent would be produced from the  
522 groundwater recycling trial scheme as it has been proposed for a volume of 1 GL of water. It  
523 was found that the majority (83.1%) of the greenhouse gases were emitted from the generation

524 of the electrical power being used within the plants. From this, it can be seen that the amount  
525 of greenhouse gases that are emitted could be easily changed through the use of renewable  
526 energy instead of the current Western Australia power mixture. Western Australia has adequate  
527 renewable energy resource potential and government level institutional supports to promote  
528 renewable energy to address its energy water nexus in an environmentally friendly manner to  
529 ensure long term guaranteed water supply.

530 The groundwater recycling trial scheme produced 72% more GHG emissions than the  
531 existing seawater desalination plant due to fact that the former used 100% grid electricity and  
532 latter is powered by 100% renewable energy. The groundwater recycling trial scheme can only  
533 be environmentally competitive with the desalination power supply option if 100% of the  
534 electricity used is generated from renewable energy with mixes between 50% wind and 50%  
535 solar and 75% wind and 25% solar. The similar ground water recycling scenario can be  
536 considered in other states of Australia such as Tasmania and South Australia where there exists  
537 water scarcity but major portion of electricity is generated from renewable energy sources (i.e.  
538 93% RE in Tasmania and 36% RE in South Australia) (Climate Council of Australia Ltd 2014).

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

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

546

547



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549

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553

554

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676

677

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

Input / Output	Data Source from Water Corporation, Perth documents	Value/unit
<i>WWTP</i>		
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)
<i>GWRT</i>		
Power	GWRT Power Total	1019669 kWh/GL produced water
Sulfuric acid (H <sub>2</sub> SO <sub>4</sub> )	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 <sub>4</sub> )	Process Control Table	10159 L/GL produced water (7416 kg/GL produced water)
<i>GWTP</i>		
Power	Monthly Operating Spreadsheet	219205 kWh/GL produced water
MIEX <sup>®</sup> 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 211 days 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 <sub>2</sub> equivalent
<i>WWTP</i>			
Chlorine	1.25	3944 (IXOM (Botany))	0.5 tonne CO <sub>2</sub> eq
Sodium hypochlorite (NaClO)	4.04	63 (Coogee Chemicals)	0.027 tonne CO <sub>2</sub> eq
Sodium hydroxide (NaOH)	0.965	63 (Coogee Chemicals)	0.0065 tonne CO <sub>2</sub> eq
DAFT	0.674	37 (BASF)	0.0027 tonne CO <sub>2</sub> eq
Cent Poly	7.92	37 (BASF)	0.03 tonne CO <sub>2</sub> eq
<i>GWRP</i>			
Sulfuric acid (H <sub>2</sub> SO <sub>4</sub> )	91.15	63 (Coogee Chemicals)	0.61 tonne CO <sub>2</sub> eq
NaClO	78.99	63 (Coogee Chemicals)	0.53 tonne CO <sub>2</sub> eq
Ammonium (NH <sub>4</sub> )	7.42	10 (Environex)	0.0079 tonne CO <sub>2</sub> eq
<i>GWTP</i>			
MIEX <sup>®</sup> Resin	1.78	3944 (IXOM (Botany))	0.75 tonne CO <sub>2</sub> eq
Alum	87.89	76 (Coogee Chemicals)	0.71 tonne CO <sub>2</sub> eq
Polyelectrolyte (LT-25)	128.53	36 (BASF)	0.50 tonne CO <sub>2</sub> eq
Hydrochloric acid (HCl)	1.81	76 (Coogee Chemicals)	0.02 tonne CO <sub>2</sub> eq
NaOH	1.19	76 (Coogee Chemicals)	0.01 tonne CO <sub>2</sub> eq
Chlorine	2.17	3944 (IXOM (Botany))	0.92 tonne CO <sub>2</sub> eq
FSA (Flourosilicic Acid)	3.65	77 (CSBP Kwinana)	0.03 tonne CO <sub>2</sub> eq
Salt	23.71	50 (WA Salt Supply)	0.13 tonne CO <sub>2</sub> 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<sub>2</sub> equivalent (eq) per tkm (or tonne\*km travelled) found using the AusLCI database on SimaPro.



**Table 3** Emission factors.

Input / Output	Value	CO <sub>2</sub> Equivalent	Library Used
<i>WWTP</i>			
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
<i>GWRP</i>			
Power	1019669 kWh	887 tonne	AusLCI
H <sub>2</sub> SO <sub>4</sub>	50640 L (91152 kg)	94.5 tonne	AusLCI
NaClO	65832 L (78998 kg)	114 tonne	AusLCI
NH <sub>4</sub>	10159 L (7416 kg)	15.4 tonne	AusLCI
<i>GWTP</i>			
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)

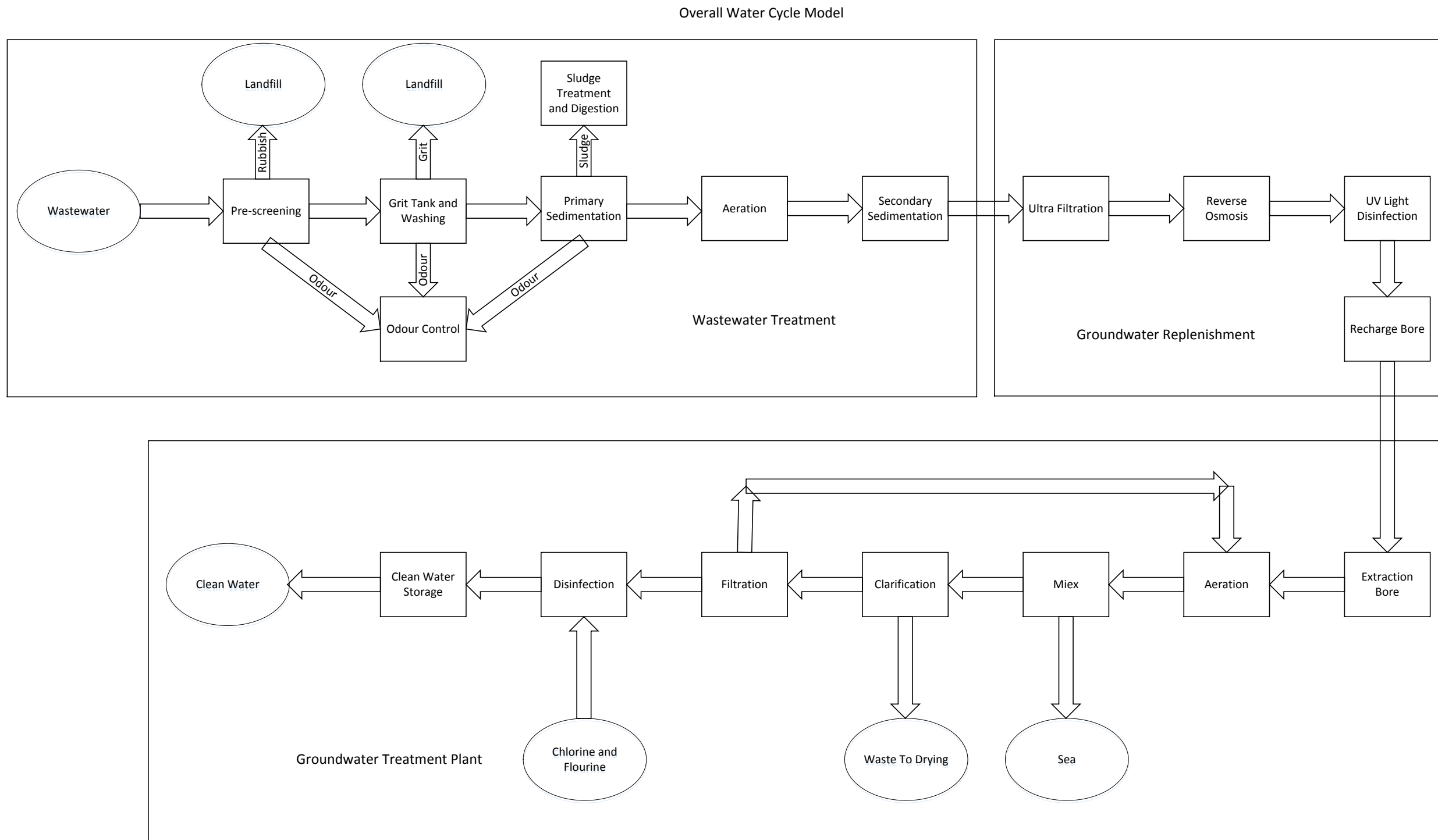
**Table 4** Comparison of Emissions Distribution (tonnes CO<sub>2</sub> eq/GL)

	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

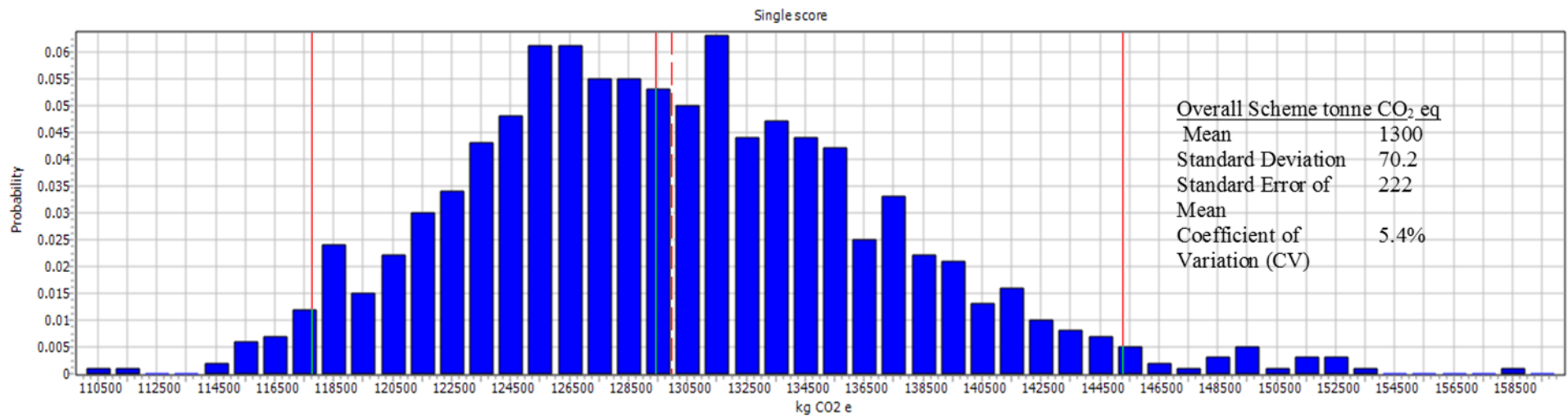
GE= Grid Electricity; RE = Renewable Energy; S= Solar; W= Wind

**Table 5** Effect of V-Sep (per week)

Input / Output	CO <sub>2</sub> 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



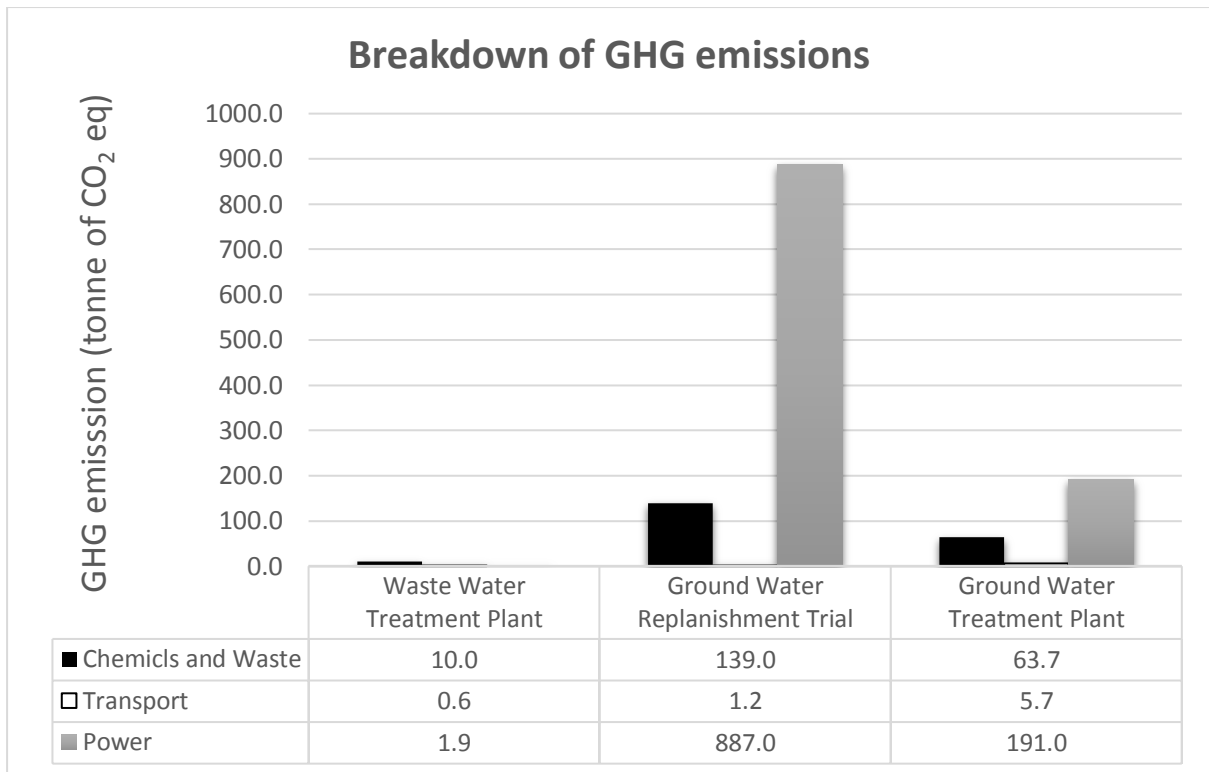
**Fig. 1** Overall Water Model (developed from tour and Water Corporation videos (Water Corporation 2016b and 2016c; Godskeseen et al. 2011 ).



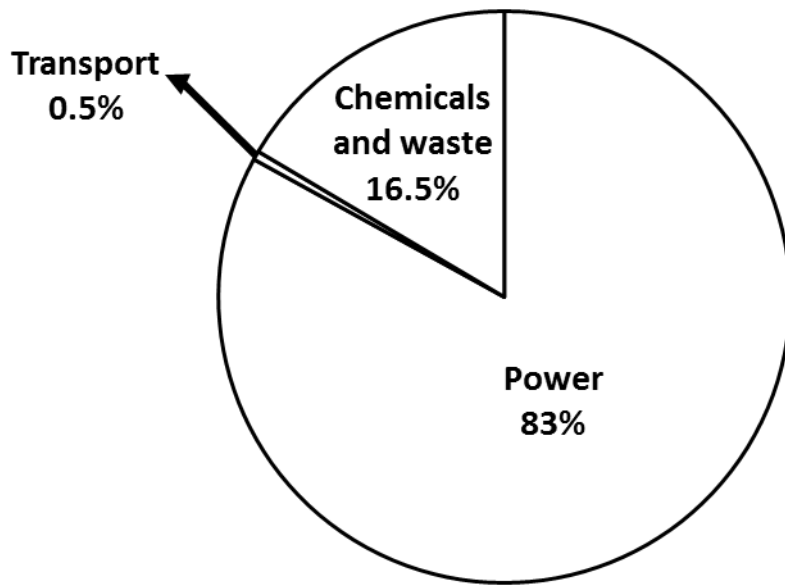
Method: Australianindicator set V2.01/ Australian percapita, confidence interval: 95 %

Uncertainty analysis of 0.55 p 'Overall Better',

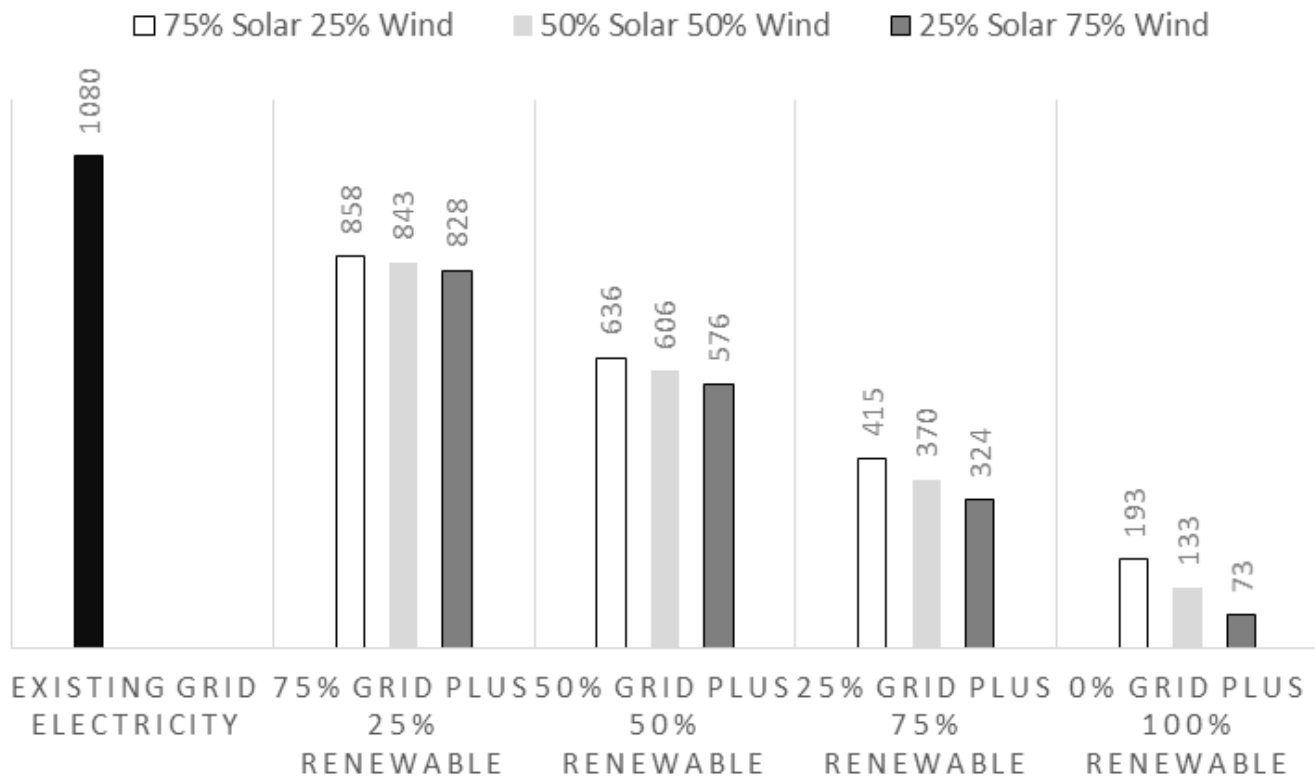
**Fig. 2** Monte Carlo Simulation results.



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

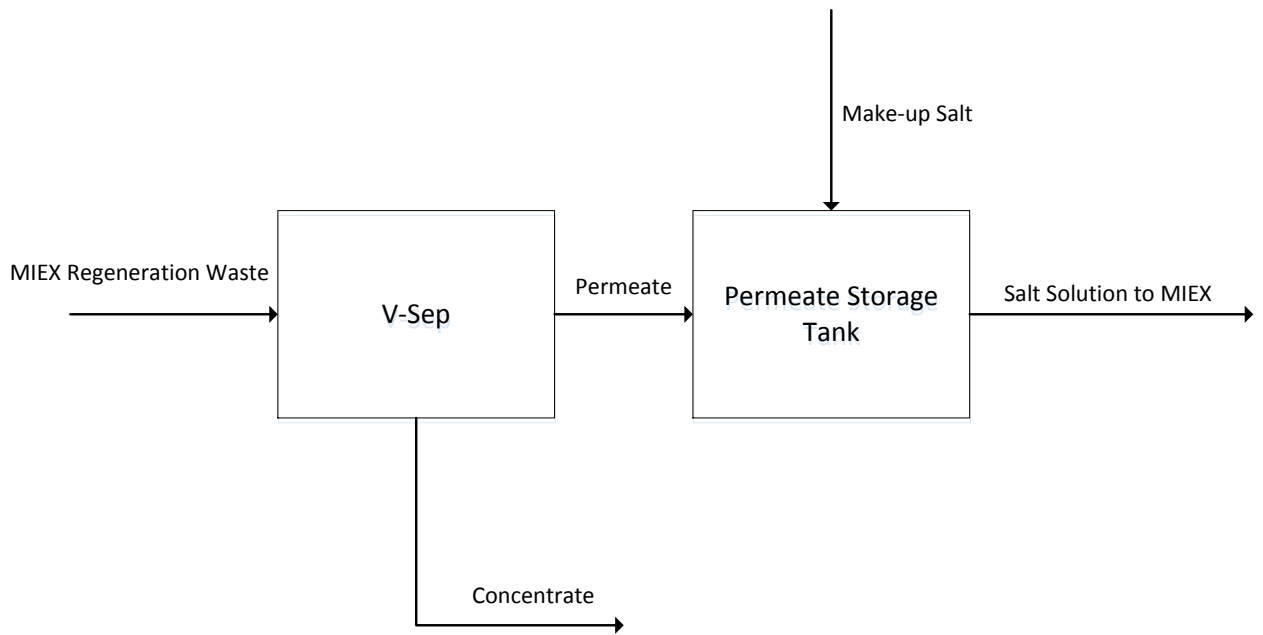


**Fig. 4** Share of CO<sub>2</sub> eq inputs of the whole system.



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





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