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Life Cycle Assessment of a Sewage Sludge and Woody Biomass Co-gasification System

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Key words: *Waste-to-energy, Gasification of sewage sludge, Decentralised waste disposal, Biochar, Life cycle assessment.*

Abstract

Replacing a part of energy derived from fossil fuels with bioenergy derived from solid waste streams may be a promising method to tackle the dual crisis of increasing waste pile-up and global climate change. In this study we propose a decentralised sewage sludge and woody biomass co-gasification system for Singapore. We evaluate the greenhouse gas emission of the proposed system and compare it to the existing system through life cycle assessment. The proposed system is expected to provide a net annual emission reduction of 137.0 to 164.1 kilotonnes of CO₂eq. Increase in electricity recovery, carbon sequestration in the biochar produced and the avoidance of the use of supplementary fuel for sewage sludge incineration are the major contributors for the emission reduction. The proposed system is able to increase the net electricity production from sewage sludge and woody biomass by 3 to 24 %. This could lead to an annual increase in electricity recovery of 12.1 to 74.8 GWh. It is estimated that the proposed system can produce 34 kilotonnes of biochar annually. It is found that decentralisation helps to reduce the annual tonne-km driven by 4.23 million tonne-km which could decrease the number of on-road vehicles required for waste handling.

1. Introduction

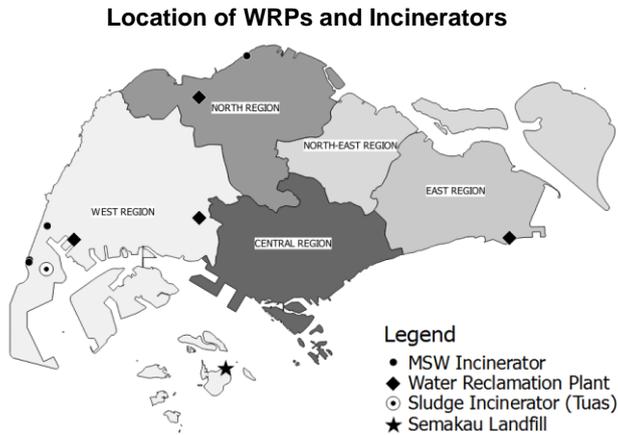
The diminution and supply uncertainty of fossil fuels together with an increasing energy demand and the climate change issue have urged a worldwide exploration of alternative energy sources. On the other hand, the annual urban municipal solid waste (MSW) production has been increasing consistently in the past decades. The global urban MSW production was estimated to be 1.3 billion tonnes in 2012 and is predicted to increase to 2.2 billion tonnes by 2025 [1]. Most of the MSW produced is presently being landfilled. Substituting fossil fuels with bioenergy from solid waste may be a promising method to tackle the dual crisis of increasing waste pile-up and global climate change. MSW disposal methods such as incineration and gasification are receiving increasing attention due to their potential to reduce waste volume and harvest energy [2]. For the place of our study, we selected Singapore as it is a densely populated city state with very limited space for landfilling. MSW constitutes for various waste streams. This study focusses on sewage sludge and woody biomass.

Water reclamation plants (WRPs) treat used water by effectively removing the solids and nutrients contained in it. Sewage sludge is an unavoidable solid waste generated at WRPs. Large quantities of sewage sludge are generated globally. USA generated 6.5 million tonnes of dry sewage sludge in 2004 [3]. China had produced close to 6.25 million tonnes of dry sewage sludge in 2013 [4]. The dry sewage sludge production in the European Union is expected to reach 13 million tonnes by 2020 [5]. Singapore does not have any natural aquifers. Reclaimed water currently supplies 40 % of Singapore's water needs [6]. Singapore generated approximately 64,372 tonnes of sewage sludge in

46 2013 [7,8]. The disposal of sewage sludge poses a severe problem as it contains a variety of toxic
47 and harmful substances [9].

48 In Singapore, solid waste is incinerated. Singapore has four WRPs. The sewage sludge from these
49 WRPs is transported to a sewage sludge incinerator in the west for incineration. Singapore produced
50 370.6 and 362.2 kilotonnes (kt) of wood and horticultural waste respectively in the year 2015 [10].
51 The non-recycled portion of this waste is incinerated at the four MSW incinerators. The bottom ash of
52 incineration (of both sewage sludge and MSW) is landfilled at the offshore Semakau landfill. The
53 location of Singapore's WRPs, incinerators and the landfill are shown in Fig 1.

54



55

56

Fig. 1: Location of WRP, sludge incinerator and MSW incinerator in Singapore

57 Incineration of sewage sludge requires supplementary fuel making the process less energy efficient.
58 Sewage sludge incineration causes the formation of pollutants such as dioxins and furans [11,12]
59 which needs to be removed from the exhaust gases before they are released into the atmosphere.
60 Since the woody biomass gets mixed with moisture laden food waste in the incinerator, the energy
61 recovery efficiency is reduced. A study of Fytili et al. concluded that gasification may be a better
62 technology compared to incineration in view of the treatment of incineration ash and pollutant
63 emission [2].

64 Gasification converts waste into syngas, biochar and ash, which could be turned into commercial
65 products such as electricity, soil conditioner, fuels and valuable chemicals. The electrical efficiency of
66 incineration is usually rather low at around 15 to 20 % [13–15]. The net electrical efficiency of
67 gasification (27% [16] or even larger [17]) is generally higher than the electrical efficiency of
68 incineration, and hence it leads to increased energy recovery. The aforementioned environmental
69 pollutants are not produced in the gasification process due to the oxygen-deficient atmosphere in the
70 gasifier. Biochar production followed by its storage in soils has been identified as a possible way to
71 reduce atmospheric CO₂ levels [18]. The carbon in biomass is fixed by plants through absorption of
72 CO₂ from the atmosphere during photosynthesis. Instead of being released back into the atmosphere
73 by combustion, if the carbon in biomass is fixed into a stabilised form such as charcoal or biochar, it
74 would lead to the sequestration of CO₂ from the atmosphere.

75 Studies have shown that incinerators are generally deployed as large-scale centralised systems
76 because of energy efficiency and economical requirements [19,20]. On the other hand, gasification is
77 well suited for a decentralised system [21,22] as well, which can further mitigate the greenhouse gas
78 (GHG) emissions caused by transportation of waste. At the Paris Summit 2015, Singapore
79 communicated that it aimed to reduce GHG its emission intensity by 36 % from 2005 levels by 2030,
80 with emissions peaking around 2030. Improvement in waste handling and energy recovery from
81 waste streams can help Singapore achieve its goals. Nevertheless, incinerators have the advantage
82 that can accept a heterogeneous feedstock such as MSW and hence are presently commonly used.
83 On the other hand gasification systems (in their present form) are very sensitive to the feedstock [22].
84 However, in this study, we focus on sewage sludge and woody biomass which has been proven as a
85 suitable feedstock for gasification [23].

86 In order to quantify the advantages of a decentralised gasification based sewage sludge and woody
87 biomass disposal system for Singapore over the existing system, we use life cycle assessment (LCA).
88 LCA addresses the environmental aspects and potential environmental impacts of a product/system
89 throughout its life cycle from raw material acquisition, through production, use, to end-of-life treatment
90 and final disposal [24]. It is a globally accepted technique for assessing the environmental impacts of
91 a product/system and is standardised by the International Organization for Standardization (ISO).
92 LCA is generally conducted through four phases: goal and scope definition, inventory analysis, impact
93 assessment and interpretation [25]. LCA is a powerful method and has varied applications. For
94 example, Ramachandran and Stimming conducted an LCA to assess the GHG emissions of the low
95 carbon alternatives for road traffic [24].

96 LCA has been used in evaluation of different waste management techniques. Numerous studies on
97 LCA of sewage sludge disposal methods exist in the literature [26–29]. Most studies on sewage
98 sludge disposal deal with sewage sludge as a separate waste stream. On the other hand co-
99 gasification of sewage sludge with other waste streams such as food waste and biomass waste has
100 gained attention recently [23]. High moisture and ash contents of the sewage sludge combined with
101 its low energy content leads to low energy generation efficiency of gasification. Ong et al. studied the
102 co-gasification of woody biomass and sewage sludge in a fixed-bed downdraft gasifier [23], validating
103 it as feedstock suitable for gasification. They found that a mixture of sewage sludge and wood chips
104 (20 wt% to 80 wt%) was ideal in terms of syngas productivity and continuous operation. However, this
105 study was limited to the experimental and numerical study of the co-gasification process. It did not
106 look at the process from a system perspective.

107 In this paper, we propose a decentralised sewage sludge and woody biomass co-gasification system
108 for Singapore. The GHG emissions of the existing sewage sludge and woody biomass waste disposal
109 system of Singapore are estimated. Then we compare it to GHG emissions of the proposed
110 decentralised sewage sludge-woody biomass co-gasification system through LCA. Since the final
111 products of the existing system (electricity and ash) and the proposed system (syngas, ash and char)
112 are different, transportation distances are altered and the energy conversion processes are different,
113 LCA becomes mandatory to make a meaningful comparison. LCA of such a system has not been
114 dealt with previously in literature. The impact decentralisation has on overall mileage (kg-km) and
115 emissions will be quantified and discussed which adds to the novelty of this work.

116

117 **2. Methodology**

118 **2.1 Description of the existing and the proposed systems**

119 The dried sewage sludge production process at each of the four WRPs in Singapore is explained
120 briefly in Fig. 2 [8]. Raw sewage sludge is produced from the incoming waste water through
121 processes such as filtration, sedimentation and biological treatment which are broadly classified into
122 preliminary treatment, primary treatment and secondary treatment processes. The sludge is thickened
123 in a centrifuge. The thickened sludge undergoes anaerobic digestion. The biogas produced during
124 anaerobic digestion is burnt and the thermal energy produced is entirely used to dry the dewatered
125 digestate. The moisture content (MC) of the dried sludge is approximately 10 % [8]. The sewage
126 sludge from the WRPs is transported to a sewage sludge incinerator where it is incinerated centrally.
127 Supplementary fuel is used for incineration of sewage sludge. The non-recycled portion of wood and
128 horticultural waste is incinerated in the MSW incinerator. The heat of incineration is used to generate
129 electricity through a steam turbine. The bottom ash of incineration (of both sewage sludge and MSW)
130 is landfilled at the offshore Semakau landfill. The existing sewage sludge and woody biomass
131 disposal system is explained in Fig.3 (a). The proposed decentralised sewage sludge and woody
132 biomass disposal system is explained in Fig. 3 (b). In the proposed system, each of the WRPs is
133 assumed to have a gasification unit in which the sewage sludge and woody biomass are co-gasified.

134 The decentralisation will help avoid the transportation of sewage sludge and reduce the transportation
 135 distance for woody biomass. Gasification produces syngas which is assumed to be converted to
 136 electricity through a gas engine. The biochar produced in the gasification process will be used as a
 137 soil conditioner. The ash generated is assumed to be landfilled in the offshore landfills of Singapore.
 138 The GHG emissions of the existing system and the proposed system will be evaluated and compared
 139 through LCA.

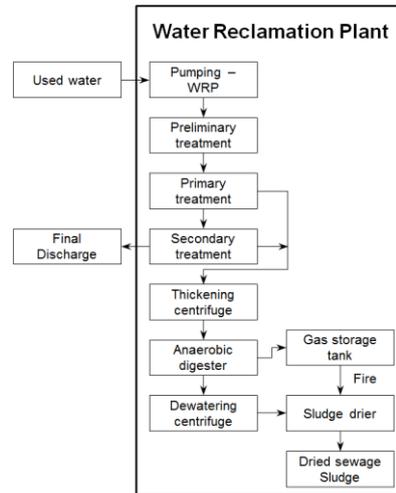


Fig. 2: Schematic representation of water treatment and sewage sludge generation at WRP [8]

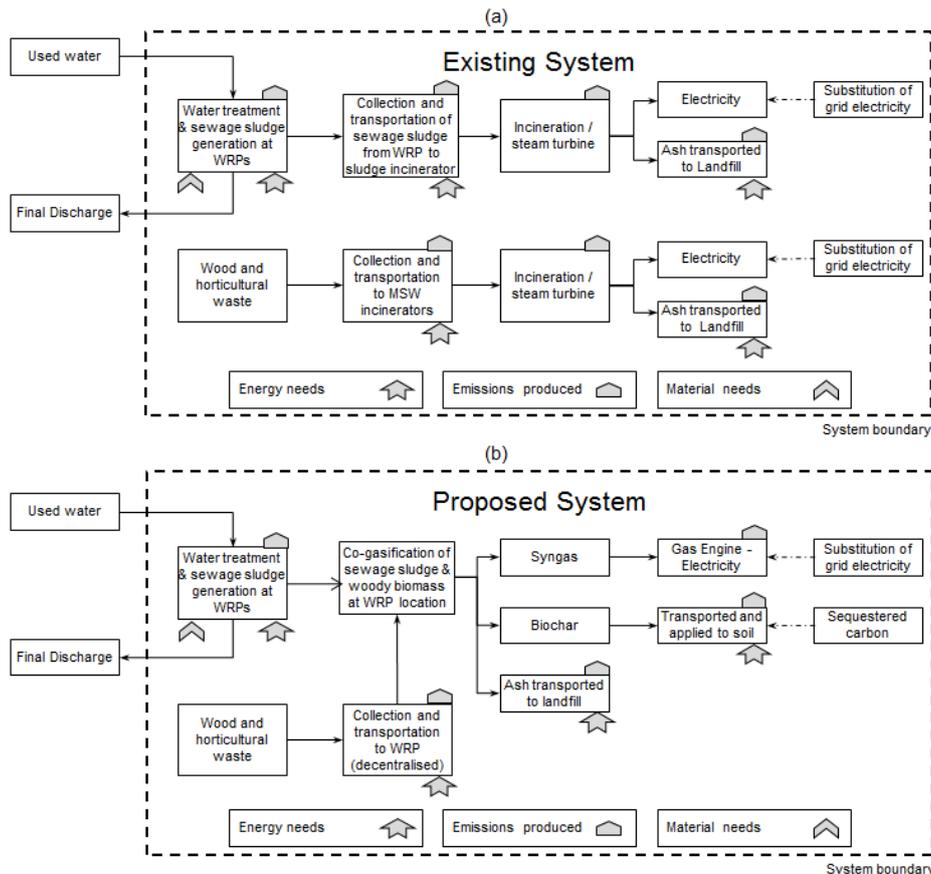


Fig. 3: Schematic representation of (a) The existing system and (b) The proposed system for the disposal of sewage sludge and woody biomass in Singapore

142 Choice of the gasification technology: To convert MSWs such as sewage sludge and woody biomass
 143 to usable energy, four main techniques can be used in current energy market: (i) direct combustion
 144

147 processes, (ii) thermochemical conversion processes, (iii) biochemical conversion processes and (iv)
148 agro-chemical conversion processes [30]. Thermochemical conversion is the most promising among
149 these. Amongst the different thermochemical conversion processes, downdraft gasification proves to
150 be a standout choice for small to medium size throughputs due to its higher efficiency as compared to
151 the other processes such as pyrolysis and liquefaction [31–34]. In a downdraft fixed bed gasifier, both
152 the feedstock and the feed gas move in a similar downward direction, with the syngas emerging from
153 the bottom at relatively high temperatures. These high temperatures aid in the consumption of tar,
154 which makes it the preferred type of gasifier for small scale power generation purposes. Hence we
155 chose the downdraft gasifier as the subject of study in the co-gasification of woody biomass and
156 sewage sludge. The results of the experimental studies done by Ong et al. on co-gasification of
157 sewage sludge and woody biomass are the basis for this study.

158 **2.2 Life cycle assessment**

159 **2.2.1 Goal:** The major goal of this LCA is to quantify the GHG emissions, energy production and
160 transportation distances of the existing sewage sludge and woody biomass disposal system in
161 Singapore (Fig. 3 (a)) and compare it to the proposed decentralised sewage sludge and woody
162 biomass co-gasification system (Fig. 3 (b)). The emissions and energy consumption associated with
163 construction and demolition of the system are not included in this work, as studies have shown that
164 their contribution towards emission and energy are negligible when compared to operation [29,35].

165 **2.2.2 Scope definition**

166 *2.2.2.1 Functional unit:* In the study of Ong et al. [23], a mixture of sewage sludge and wood chips
167 (20 wt% – 80 wt%) is shown to be ideal for syngas productivity and continuous operation. Hence the
168 functional unit (FU) is chosen to be 0.2 kg sewage sludge and 0.8 kg of woody biomass, i.e. 1 kg of
169 sewage sludge and woody biomass mixture. The MC of the sewage sludge produced at WRPs is 10
170 %. However, gasification requires a MC of 7.6 % in sewage sludge which is achieved through open
171 air solar drying which doesn't involve any dry matter loss and doesn't require any additional energy
172 input. The strong solar radiation in Singapore favours solar drying.

173 *2.2.2.2 System boundary:* The system boundaries for the LCA of the existing system and the
174 proposed system are shown in Fig. 3. The GHG emissions involved in sewage sludge generation,
175 biomass acquisition, transportation, incineration, gasification, carbon sequestration in char, syngas
176 utilisation and ash disposal are included in this study. The sewage sludge production process is
177 shown in Fig 2. The 'Water treatment and sludge generation' block in Fig. 3 represents the entire set
178 of processes described in Fig 2. Transport of used water to WRP and the pumping out final discharge
179 are outside the system boundary and are not considered. All the electricity required is assumed to
180 come from the grid. The carbon in woody biomass and sewage sludge is taken to be 100 % biogenic
181 based on Intergovernmental Panel on Climate Change (IPCC) guidelines [36]. Thus, the CO₂
182 emissions associated with direct combustion of biogenic carbon and derived syngas combustion are
183 assumed to have zero global warming potential (GWP).

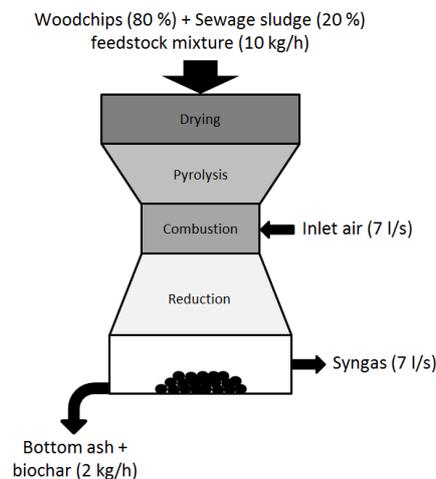
184 *2.2.2.3 System expansion:* When a system/process has more than one output, the LCA study has to
185 define the method through which the environmental impacts of these products are included. The two
186 major methodologies available for this purpose are substitution and allocation. Of the two, the
187 substitution method, also known as 'extension of system boundary', is chosen for this study as it
188 yields more reliable and realistic results [37]. The electricity produced is assumed to replace the grid
189 electricity and is credited by the emission equivalent calculated based on the grid emission factor of
190 Singapore. Each kWh of electricity produced in Singapore by its existing energy generation mix
191 produces 432.2 g CO₂eq [38]. In the existing system, heat of incineration is used to produce steam to
192 run a steam turbine to generate electricity. The syngas produced by gasification is assumed to be
193 converted to electricity by a gas engine. Gas engines are chosen as they are the most suitable option
194 for decentralised small scale operation. Biochar is accounted for by the amount of carbon it
195 sequesters which is explained in section 2.2.3.3. Heat produced is not considered as Singapore is a

196 tropical country with no domestic or district heating demand and hence the waste heat produced not
 197 of relevance.

198 **2.2.3 Life cycle inventory**

199 Life cycle inventory (LCI) is the collection of all the data and calculation procedures needed to perform
 200 an LCA. We acquire the data associated with the gasification process from experimental results
 201 published by Ong et al. [23]. Transportation distances are calculated using the method described in
 202 section 2.2.3.2. All the other relevant data are acquired from literature and tabulated in Table 4. It
 203 needs to be noted that since most of the data is acquired from literature, it may not represent the
 204 waste disposal scenario of Singapore exactly.

205 *2.2.3.1 Gasification technology:* The experimental data for sewage sludge and woody biomass co-
 206 gasification used in this paper was obtained from published work [23]. A schematic representation of
 207 the gasification process is illustrated in Fig. 4. The sewage sludge and wood chips are mixed at (20
 208 wt% to 80 wt%) and fed into the gasifier at the top of the reactor. The proximate and ultimate analysis
 209 of woodchips and sewage sludge is shown in Table 1. During the gasification process, the feedstock
 210 undergoes drying, pyrolysis, combustion, and reduction sequentially from top to bottom of the reactor
 211 and at the end biochar and bottom ash are produced. Air enters the reactor from the air inlet and
 212 flows towards the bottom of the reactor, which is in the same direction as the biomass feedstock. Both
 213 biochar and syngas are produced from the gasification process. The operating parameters and the
 214 experimental results of the gasification process are given in Table 2. In the work of Ong, et. al. [23],
 215 woodchips were used as a woody biomass sample to represent the gasification behaviour of woody
 216 biomass and sewage sludge. We made the same assumption in this work. It is also found from other
 217 literature sources that wood chips are commonly used to represent woody biomass in the gasification
 218 experiments [23,39–43].



219

220

Fig. 4: Schematic representation for biomass gasification [23]

	Wood Chips	Sewage Sludge
Proximate analysis (dry basis, wt%)		
Moisture	8.35	7.6
Volatile	68.5	50.8
Fixed Carbon	16.9	15.1
Ash	6.2	26.3
Ultimate analysis (wt%)		
C	43.8	35
H	5.8	4.8
O	42	27.8
N	1.5	5.2
S	0.75	1.7

221

Table 1: Proximate and ultimate analysis, feedstock materials [23]

Feed stock ratio	20 wt% to 80 wt% sludge to wood chips	
Total feedstock input (kg/h)	10	
Air inlet flowrate (l/s)	7	
Syngas composition (%)	O₂	1
	CO₂	12.7
	CO	15.6
	CH₄	2.1
	H₂	16.8
Syngas LHV (MJ/m³)	4.5	
Char + bottom ash production rate (kg/h)	2	

Table 2: Operating parameters and experiment results of the gasification process [23]

222

223 *2.2.3.2 Evaluation of transportation distances:* In this section, we calculate the transport distances
 224 necessary for evaluation of transport emissions. Fig.1 shows the location of WRPs, MSW incinerator
 225 and sludge incinerator in Singapore. The sludge from WRPs (at 10 % MC) is transported to the
 226 sludge incinerator. The treatment capacity of each WRP is given in Table 3 [44]. The amount of
 227 sewage sludge produced at each WRP is directly proportional to its treatment capacity. The road
 228 distance of these WRPs to the incinerators is evaluated using their location data and Singapore road
 229 network with the help of Quantum Geographic Information System (QGIS) software and tabulated in
 230 Table 3. The average transport distance per kg of sewage sludge is evaluated to be 34.7 km.

WRP location	Treatment capacity (1000 m³/day)	Transportation distance (km)
Kranji	155	25.4
Jurong	205	6.8
Ulu Pandan	360	20.0
Changi	800	50.2
Total	1520	

Table 3: Treatment capacity of WRP and their transport distance to sludge incinerators[44]

231

232 The non-recycled woody biomass is disposed of in the MSW incinerators. Singapore has four MSW
 233 incinerators localised to two regions as seen from Fig.1. A map-based approach is adopted for
 234 evaluating the average transport distance of woody biomass to the incinerators (in the existing
 235 system) and WRPs (for the proposed system). It is assumed that the woody biomass is equally
 236 distributed throughout Singapore. Singapore is divided into 323 smaller subzones. Each smaller
 237 region is assumed to possess woody biomass proportional to its area. The road transport distance
 238 from centroid of each region to the closest MSW incinerator (closest WRP in case of the proposed
 239 system) is evaluated using Singapore road map data in QGIS. The average transport distance to the
 240 MSW incinerators and WRPs is found using the following formula,

$$Average\ transport\ distance = \sum_{i=1}^{323} \frac{a_i}{A} \cdot \min(x_{i(a)}, x_{i(b)}, x_{i(c)}, x_{i(d)}),$$

241 where a_i is the land area of each of the subzones, A is the total land area of Singapore and
 242 $x_{i(a)}, x_{i(b)}, x_{i(c)}$ and $x_{i(d)}$ are the road distances of the centroid of each subzone to the MSW
 243 incinerators (or WRPs in case of the proposed system). The average transport distance to the MSW
 244 incinerator was evaluated to be 16.6 km and the average transport distance to WRPs was found to be
 245 10.1 km. The average transportation distance is reduced by 39 % because WRPs are better
 246 distributed across Singapore. The ash from the MSW incinerators and gasification units are
 247 transported to the Tuas Marine Transfer Station (TMTS) by road. From there, the ashes are
 248 transported to Semakau islands by sea through tugboats, where it is landfilled. The average
 249 transportation distances required and the emissions of the refuse collection truck, long haul transport
 250 truck and tugboats, required for the calculation of transportation emissions are tabulated in Table 4.

251 *2.2.3.3 Climate change mitigation potential of biochar:* Biochar is a by-product of the gasification
252 process. One of its various applications is its use as a soil conditioner. In this study, the biochar
253 produced by the gasification process is assumed to be distributed across Singapore and used as a
254 soil conditioner. Production of biochar followed by its use as a soil conditioner helps mitigate climate
255 change primarily because of the stable carbon content of biochar. The carbon in biochar is classified
256 into recalcitrant (stable – over a long period) and labile (unstable – decomposes and mineralises
257 quickly when applied to soil). The carbon stability factor (CSF) defines the amount of recalcitrant
258 carbon in biochar. Studies have shown that close to 80 % of the carbon in biochar remains stable for
259 over 30 years [45,46]. Hence we adopted a CSF of 0.8 for this study. The amount of carbon in the
260 biochar is taken to be 80 % [45]. The biochar production rate is evaluated by subtracting the ash flow
261 rate in the feedstock from the residue flow rate (bottom ash + biochar) and tabulated in Table 4. Each
262 kg of char is estimated to have 0.64 kg of stable carbon in it and hence would sequester 2.345 kg of
263 CO₂eq (calculated based on stoichiometry) which is credited to the proposed system based on the
264 amount of biochar produced. The transportation is done by collection trucks (the same ones used for
265 wood collection) and the distances are assumed to be the same as that of wood collection. The
266 corresponding emissions are calculated and included in the LCA.

267 Biochar's application to soil also helps in climate change mitigation by suppressing the emission of
268 N₂O and CH₄ from the soil, improving the fertiliser efficiency, increasing the crop yield and enhancing
269 the soil's water retention capacity. However, these are not considered in this study due to the
270 uncertainties associated with them. Moreover, studies show that the major contribution comes from
271 the recalcitrant nature of biochar [18,45].

272 The primary objective of this study is to evaluate the GHG emissions of the proposed system and
273 compare it to the GHG emissions of the existing system. Since we are focussing only on GHG
274 emissions, we do not require a separate life cycle impact assessment method. The entire GHG
275 emissions associated with the energy conversion process and transportation and distribution of
276 waste, ashes and char are calculated and added up. The electricity produced is credited for by
277 replacement of grid electricity. The char produced is accounted for by the amount of carbon it
278 sequesters. The credits are subtracted from the summation of emissions which gives us the overall
279 emissions. The emissions of other environmental pollutants are not included in the present study as at
280 the moment, we do not have the necessary data from gasification experiments to carry out the
281 pollutants emissions study very accurately.

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Name	Value	Unit	Source
Sewage sludge production at WRP			
Sludge production rate	0.11	kg dry sludge/m ³ treated water	[8]
Energy requirement for pumping	0.1600	kWh/m ³ treated water	
Energy requirement for preliminary treatment	0.0020	kWh/m ³ treated water	
Energy requirement for primary treatment	0.0156	kWh/m ³ treated water	
Energy requirement for secondary treatment	0.1590	kWh/m ³ treated water	
Sludge thickening	0.1330	kWh/kg dry sludge	
Sludge digestion	0.0440	kWh/kg dry sludge	
Sludge dewatering	0.0730	kWh/kg dry sludge	
Material needs (polymer)	20	kg polymer/tonne dry sludge	
GHG of polymer	0.0020	kg CO ₂ /kg polymer	[29]
Gasification			
Electrical efficiency of IC engine	35	%	[17]
Electricity need per feed for operation	0.6667	kWh/tonne feedstock	Calculated
Ash production rate	0.1022	kg/kg feedstock	Calculated
Biochar production rate	0.0978	kg/kg feedstock	Calculated
Electricity needs for gas cleaning	0.65	Wh/Nm ³ syngas	[17]
Incineration – sewage sludge			
Electricity production rate	3.476	MJe/kg dry sludge	[47]
Electricity need per feed for operation	0.25	MJe/kg dry sludge	
Emission in exhaust production rate (non-biogenic)	800	CO ₂ eq/kg dry sludge	
Ash production rate	0.2	kg/kg dry sludge	
Incineration – woody biomass			
Net el efficiency of wood incineration in MSW incinerator	20 – 25 ^a	%	Assumed
Ash production rate	0.2 ^b	kg/kg woody biomass	Assumed
^a The normal ash production rate is around 0.3 kg ash/kg MSW [48,49]. However a conservative value of 0.2 was chosen since we consider only woody biomass fraction of the MSW. ^b The efficiency of incineration woody biomass portion of MSW in a MSW incinerator is not directly available from literature. The electrical efficiency of an MSW incinerator generally lies in the range of 15 % to 20 % [13–15]. However, since we are considering only the woody biomass portion, we consider a slightly higher range of 20 % to 25 % which bodes well with biomass incineration plant efficiencies [50–52]. A range instead of specific value is assumed to counter the uncertainty in the numbers from the literature.			
Transport distances			
Average road transport distance from WRP to sludge incinerator	34.7	km	Calculated
Average road transport distance of wood waste to MSW incinerator	16.6	km	
Average road transport distance of wood waste to WRP	10.1	km	
Average transport distance from MSW incinerator to TMTS	10.8	km	
Sea transport distance from TMTS to Semakau	30	km	[53]
Transportation emissions			
Emissions of collection trucks	180	g CO ₂ eq/tonne km	[54]
Emissions of long haul trucks	74.7	g CO ₂ eq/tonne km	[55]
Emissions of tug boats	28	g CO ₂ eq/tonne km	[56]
Biochar			
CSF	0.8	–	[45]
Carbon content	80	%	
Other variables			
LHV of sewage sludge (at 7.6 % MC)	13.3	MJ/kg	Calculated
LHV of woody biomass	16.2	MJ/kg	Calculated
Grid emission factor	432.2	g CO ₂ eq/kWh	[38]

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Table 4: Life cycle inventory

297

298 3. Results, Discussion and Conclusion

299 The efficiency of woody biomass incineration is taken to be in a range of 20 % to 25 % as mentioned
300 in Table 4. Hence the results of the existing system are presented as a range with lower and upper
301 bound (which corresponds to 25 and 20 % efficiency of woody biomass incineration efficiency).

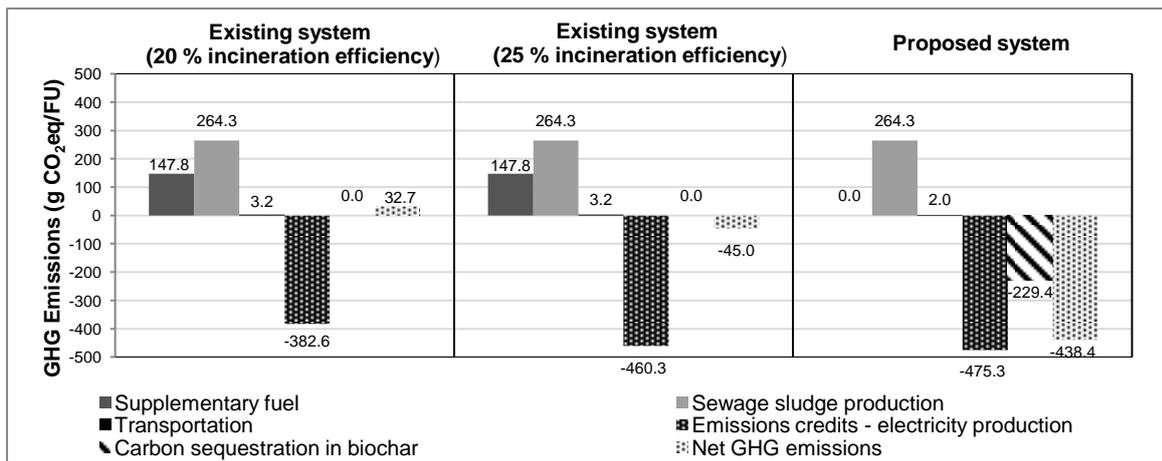
302 **3.1 Overall emissions**

303 The net emissions of the existing and proposed sewage sludge disposal system along with the
 304 contribution from the individual factors are shown in Fig. 5. The net GHG emissions of the existing
 305 system lie in the range of -45.0 to 32.7 g CO₂eq/FU. The major reasons for the net negative GHG
 306 emissions are (1) CO₂ emission from biogenic carbon sources has no GWP and (2) the CO₂ for
 307 replacement of grid electricity. The shift from negative to positive net emissions when the efficiency of
 308 woody biomass incineration is decreased from 25 % to 20 % shows that the overall emissions are
 309 very sensitive to the woody biomass incineration efficiency. Incineration of sewage sludge uses
 310 supplementary fuel which causes direct fossil emissions of 147.8 g CO₂eq/FU.

311 On the other hand, the net GHG emissions of the proposed system are -438.4 g CO₂eq/FU. Apart
 312 from the biogenic nature of emissions and carbon credits for grid electricity replacement, the biggest
 313 contribution to net negative emission in the proposed system comes from the CO₂ sequestered in
 314 biochar. Each FU produces close to 97.8 g of biochar which sequesters 229.4 g CO₂eq. This scheme
 315 does not use any supplementary fuel for sewage sludge incineration and therefore avoids that portion
 316 of direct fossil emissions which are present in the existing system.

317 The proposed system offers emission savings in the range of 373.3 to 471.1 g CO₂eq/FU in
 318 comparison to the existing system. The net annual savings are in the range of 137.0 to 164.1.0 to kt
 319 of CO₂eq. These emission savings are approximately equivalent to the annual emission savings
 320 provided by the replacement of approximately 71,000 to 85,000 petrol passenger cars (12 % to 14 %
 321 of the entire fleet), by battery electric cars in Singapore (Evaluated based on the fact that there are
 322 approximately 600,000 [57] passenger cars in Singapore, and the GHG emissions of an average
 323 petrol car and battery electric vehicle in Singapore are 209 g CO₂eq/km and 106 g CO₂eq/km [58]
 324 respectively).

325 The emissions from biomass are considered to have no GWP as per IPCC norms. However, if we
 326 consider the CO₂ emissions from biomass to have GWP, then the carbon sequestered in biochar
 327 would not get any sequestration credits. In such a case, the net emissions of the existing system
 328 would be in the range of 1573.3 to 1496.5 g CO₂ eq/FU (calculated based on the assumption that the
 329 entire carbon in waste is converted to CO₂ at stoichiometric ratio). The emissions of the proposed
 330 system would be 1249.9 g CO₂ eq/FU thus offering a savings potential of 245.5 to 323.3 g CO₂eq/FU.



331

332

Fig. 5: GHG emissions of existing and proposed system per FU and their contributing factors.

333 **3.2 Energy recovery**

334 The energy recovered in the existing system lies in the range of 0.89 to 1.07 kWh/FU. The electricity
 335 requirement for sewage sludge production process is 0.61 kWh/FU. Thus the net electricity production
 336 lies in the range of 0.27 to 0.45 kWh/FU. In the proposed system the gross and net electricity
 337 production are 1.10 kWh/FU and 0.49 kWh/FU respectively. The increase in net electricity production

338 in the existing system is 0.034 to 0.214 kWh/FU. The proposed system could yield a net annual
339 increase in electricity generation of 12.1 GWh to 74.8 GWh. The reason for the increase in electricity
340 generation is the higher electrical efficiency of gasification.

341 **3.3 Transportation distances and emissions**

342 As seen from Fig. 5, the contribution of reduction in transportation emissions in overall emission
343 reduction is negligible compared to the contributions of emission savings from carbon sequestration in
344 biochar and carbon credits of increased electricity production. However, decentralisation leads to a
345 reduction of direct transport emissions by 38 %. The total transportation kg-km driven reduces by 43
346 % and the road kg-km driven reduces by 42 %. This calls for a reduction of the number of trucks on
347 the road which contributes to reducing road traffic. Decentralisation indirectly benefits through lower
348 operation and maintenance cost. The annual reduction in kg-km driven of the proposed system is
349 implemented is 4.23 million tonne-km. The reduction in kg-km driven is caused by the reduction of
350 both transportation distances and the amount of material (sewage sludge and ash) transported.
351 However, a cost benefit analysis needs to be done to analyse the actual economic benefits that the
352 decentralisation of sewage sludge and woody biomass disposal could offer.

353 **3.4 Conclusion**

354 Compared to the existing system, decentralised co-gasification of sewage sludge and woody biomass
355 increases the net annual emission savings by 138.9 to 165.9 million kg CO₂eq. The major
356 contributions for the emission saving potential come from, (1) increased efficiency, (2) no requirement
357 of supplementary fuel for sludge disposal and (3) CO₂ sequestration in biochar. The decentralised
358 system reduces the kg-km driven by 42 %. Production of biochar from organic sources contributes
359 greatly to emission abatement through biogenic carbon sequestration.
360

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365

366 **Glossary**

367 **Abbreviations**

CSF	Carbon stability factor
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
MC	Moisture content
MSW	Municipal solid waste
QGIS	Quantum Geographic Information System
TMTS	Tuas Marine Transfer Station
WRP	Water reclamation plant

368

369 **Nomenclature of symbols used**

a	Area of smaller region
A	Area of Singapore
x	distance from centroid of each region to incinerator/WRP

370

371 **Nomenclature of subscripts used**

i	Area of smaller region
a, b, c, d	Individual incinerator/WRP

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