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

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The final published version of this article is available at https://doi.org/10.1016/j.energy.2017.04.139.

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 CO_2eq. 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.

Keywords (5):
Waste-to-energy, Gasification of sewage sludge, Decentralised waste disposal, Biochar, Life cycle assessment.

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

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

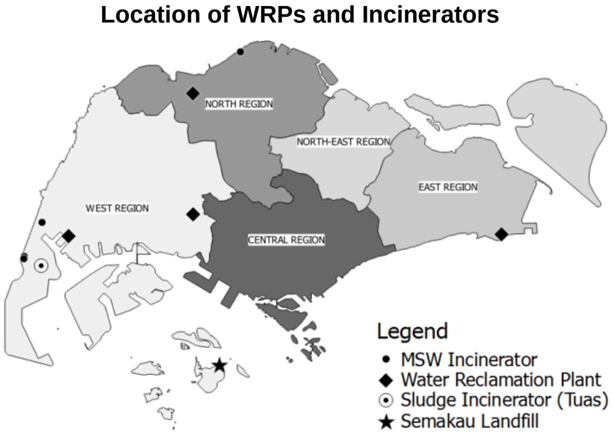

Fig. 1: Location of WRP, sludge incinerator and MSW incinerator in Singapore

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

Gasification converts waste into syngas, biochar and ash, which could be turned into commercial products such as electricity, soil conditioner, fuels and valuable chemicals. The electrical efficiency of incineration is usually rather low at around 15 to 20 % [13–15]. The net electrical efficiency of gasification (27% [16] or even larger [17]) is generally higher than the electrical efficiency of incineration, and hence it leads to increased energy recovery. The aforementioned environmental pollutants are not produced in the gasification process due to the oxygen-deficient atmosphere in the gasifier. Biochar production followed by its storage in soils has been identified as a possible way to reduce atmospheric CO_2 levels [18]. The carbon in biomass is fixed by plants through absorption of CO_2 from the atmosphere during photosynthesis. Instead of being released back into the atmosphere by combustion, if the carbon in biomass is fixed into a stabilised form such as charcoal or biochar, it would lead to the sequestration of CO_2 from the atmosphere.

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

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

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

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

2. Methodology

2.1 Description of the existing and the proposed systems

The dried sewage sludge production process at each of the four WRPs in Singapore is explained briefly in Fig. 2 [8]. Raw sewage sludge is produced from the incoming waste water through processes such as filtration, sedimentation and biological treatment which are broadly classified into preliminary treatment, primary treatment and secondary treatment processes. The sludge is thickened in a centrifuge. The thickened sludge undergoes anaerobic digestion. The biogas produced during anaerobic digestion is burnt and the thermal energy produced is entirely used to dry the dewatered digestate. The moisture content (MC) of the dried sludge is approximately 10 % [8]. The sewage sludge from the WRPs is transported to a sewage sludge incinerator where it is incinerated centrally. Supplementary fuel is used for incineration of sewage sludge. The non-recycled portion of wood and horticultural waste is incinerated in the MSW incinerator. The heat of incineration is used to generate electricity through a steam turbine. The bottom ash of incineration (of both sewage sludge and MSW) is landfilled at the offshore Semakau landfill. The existing sewage sludge and woody biomass disposal system is explained in Fig.3 (a). The proposed decentralised sewage sludge and woody biomass disposal system is explained in Fig. 3 (b). In the proposed system, each of the WRPs is assumed to have a gasification unit in which the sewage sludge and woody biomass are co-gasified. The decentralisation will help avoid the transportation of sewage sludge and reduce the transportation distance for woody biomass. Gasification produces syngas which is assumed to be converted to electricity through a gas engine. The biochar produced in the gasification process will be used as a soil conditioner. The ash generated is assumed to be landfilled in the offshore landfills of Singapore. The GHG emissions of the existing system and the proposed system will be evaluated and compared through LCA.

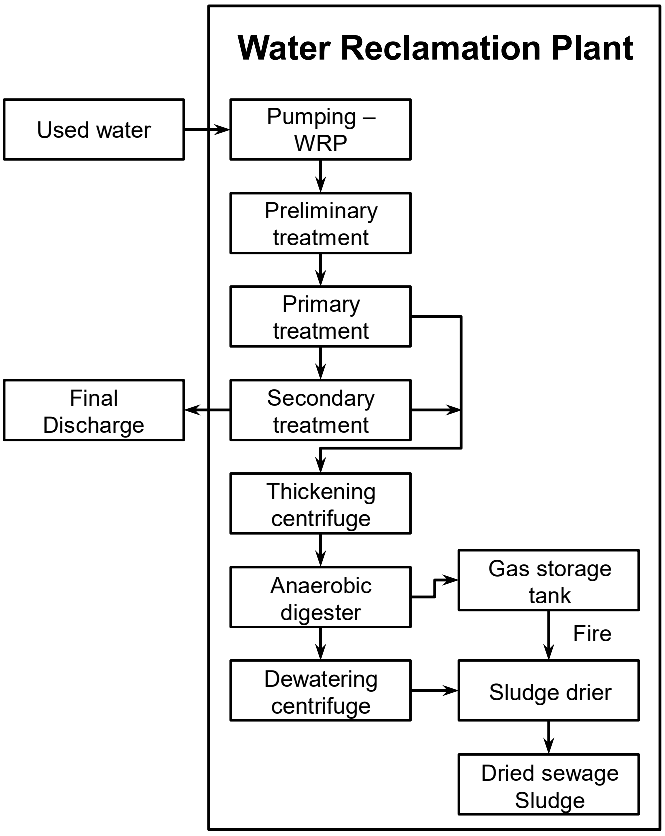

Fig. 2: Schematic representation of water treatment and sewage sludge generation at WRP [8]

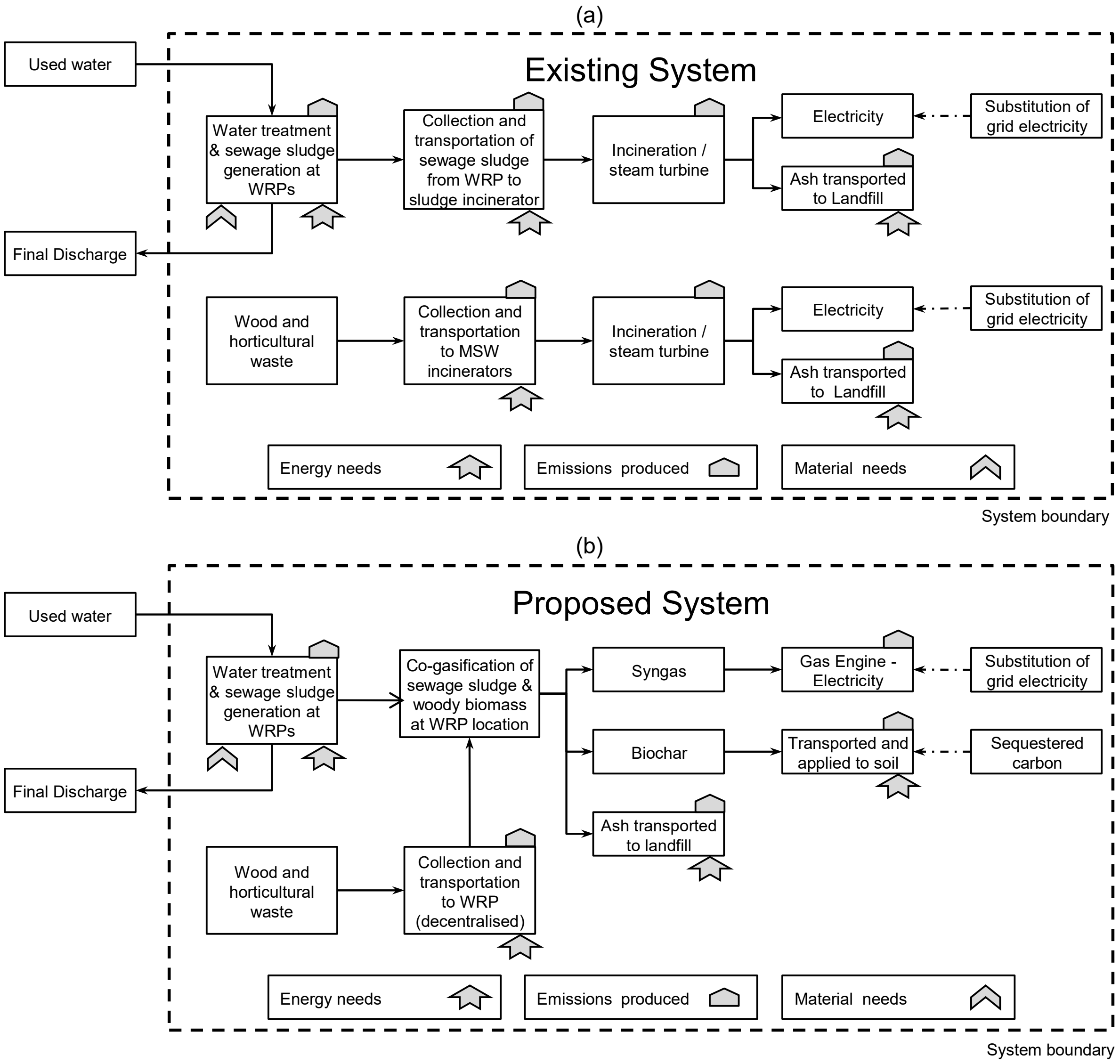

Fig. 3: Schematic representation of (a) The existing system and (b) The proposed system for the disposal of sewage sludge and woody biomass in Singapore

Choice of the gasification technology: To convert MSWs such as sewage sludge and woody biomass to usable energy, four main techniques can be used in current energy market: (i) direct combustion processes, (ii) thermochemical conversion processes, (iii) biochemical conversion processes and (iv) agro-chemical conversion processes [30]. Thermochemical conversion is the most promising among these. Amongst the different thermochemical conversion processes, downdraft gasification proves to be a standout choice for small to medium size throughputs due to its higher efficiency as compared to the other processes such as pyrolysis and liquefaction [31–34]. In a downdraft fixed bed gasifier, both the feedstock and the feed gas move in a similar downward direction, with the syngas emerging from the bottom at relatively high temperatures. These high temperatures aid in the consumption of tar, which makes it the preferred type of gasifier for small scale power generation purposes. Hence we chose the downdraft gasifier as the subject of study in the co-gasification of woody biomass and sewage sludge. The results of the experimental studies done by Ong et al. on co-gasification of sewage sludge and woody biomass are the basis for this study.

2.2 Life cycle assessment

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

2.2.2 Scope definition

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

2.2.2.2 System boundary: The system boundaries for the LCA of the existing system and the proposed system are shown in Fig. 3. The GHG emissions involved in sewage sludge generation, biomass acquisition, transportation, incineration, gasification, carbon sequestration in char, syngas utilisation and ash disposal are included in this study. The sewage sludge production process is shown in Fig 2. The 'Water treatment and sludge generation' block in Fig. 3 represents the entire set of processes described in Fig 2. Transport of used water to WRP and the pumping out final discharge are outside the system boundary and are not considered. All the electricity required is assumed to come from the grid. The carbon in woody biomass and sewage sludge is taken to be 100 % biogenic based on Intergovernmental Panel on Climate Change (IPCC) guidelines [36]. Thus, the CO_2 emissions associated with direct combustion of biogenic carbon and derived syngas combustion are assumed to have zero global warming potential (GWP).

2.2.2.3 System expansion: When a system/process has more than one output, the LCA study has to define the method through which the environmental impacts of these products are included. The two major methodologies available for this purpose are substitution and allocation. Of the two, the substitution method, also known as 'extension of system boundary', is chosen for this study as it yields more reliable and realistic results [37]. The electricity produced is assumed to replace the grid electricity and is credited by the emission equivalent calculated based on the grid emission factor of Singapore. Each kWh of electricity produced in Singapore by its existing energy generation mix produces 432.2 g CO_2eq [38]. In the existing system, heat of incineration is used to produce steam to run a steam turbine to generate electricity. The syngas produced by gasification is assumed to be converted to electricity by a gas engine. Gas engines are chosen as they are the most suitable option for decentralised small scale operation. Biochar is accounted for by the amount of carbon it sequesters which is explained in section 2.2.3.3. Heat produced is not considered as Singapore is a tropical country with no domestic or district heating demand and hence the waste heat produced not of relevance.

2.2.3 Life cycle inventory

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

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

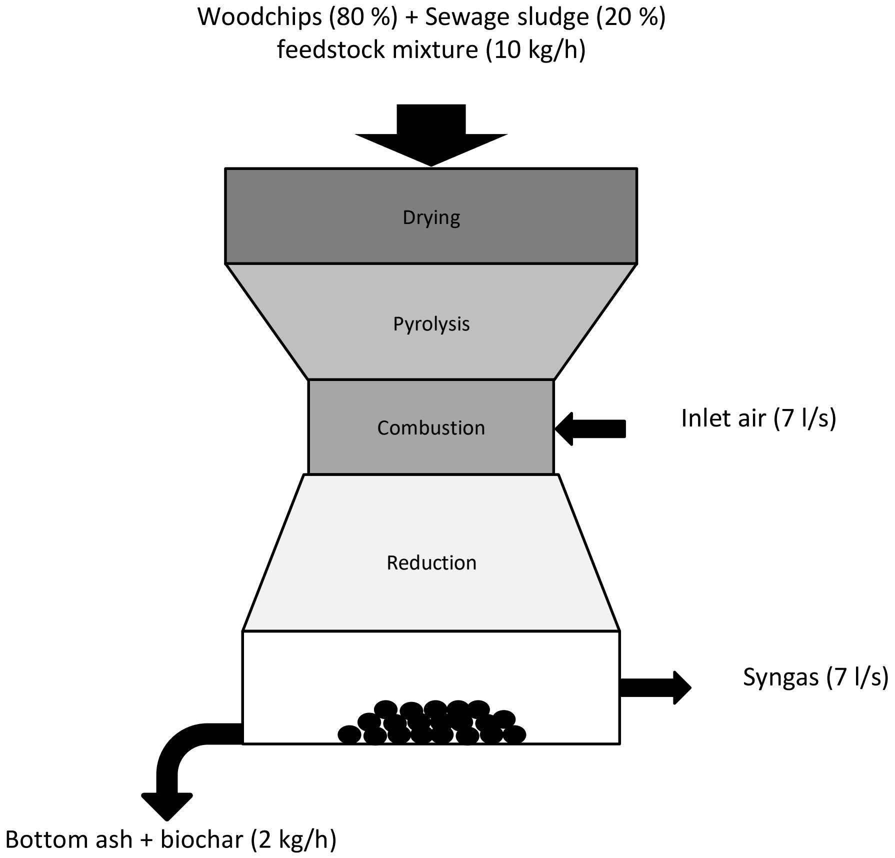

Fig. 4: Schematic representation for biomass gasification [23]

	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

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 (%)	**O_2**	1
	CO_2	12.7
	CO	15.6
	CH_4	2.1
	H_2	16.8
Syngas LHV (MJ/m^3)		4.5
Char + bottom ash production rate (kg/h)		2

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

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

WRP location	**Treatment capacity** (1000 m^3/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]

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

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

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

2.2.3.3 Climate change mitigation potential of biochar: Biochar is a by-product of the gasification process. One of its various applications is its use as a soil conditioner. In this study, the biochar produced by the gasification process is assumed to be distributed across Singapore and used as a soil conditioner. Production of biochar followed by its use as a soil conditioner helps mitigate climate change primarily because of the stable carbon content of biochar. The carbon in biochar is classified into recalcitrant (stable – over a long period) and labile (unstable – decomposes and mineralises quickly when applied to soil). The carbon stability factor (CSF) defines the amount of recalcitrant carbon in biochar. Studies have shown that close to 80 % of the carbon in biochar remains stable for over 30 years [45,46]. Hence we adopted a CSF of 0.8 for this study. The amount of carbon in the biochar is taken to be 80 % [45]. The biochar production rate is evaluated by subtracting the ash flow rate in the feedstock from the residue flow rate (bottom ash + biochar) and tabulated in Table 4. Each kg of char is estimated to have 0.64 kg of stable carbon in it and hence would sequester 2.345 kg of CO_2eq (calculated based on stoichiometry) which is credited to the proposed system based on the amount of biochar produced. The transportation is done by collection trucks (the same ones used for wood collection) and the distances are assumed to be the same as that of wood collection. The corresponding emissions are calculated and included in the LCA.

Biochar's application to soil also helps in climate change mitigation by suppressing the emission of N_2O and CH_4 from the soil, improving the fertiliser efficiency, increasing the crop yield and enhancing the soil's water retention capacity. However, these are not considered in this study due to the uncertainties associated with them. Moreover, studies show that the major contribution comes from the recalcitrant nature of biochar [18,45].

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

3. Results, Discussion and Conclusion

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

3.1 Overall emissions

The net emissions of the existing and proposed sewage sludge disposal system along with the contribution from the individual factors are shown in Fig. 5. The net GHG emissions of the existing system lie in the range of −45.0 to 32.7 g CO_2eq/FU. The major reasons for the net negative GHG emissions are (1) CO_2 emission from biogenic carbon sources has no GWP and (2) the CO_2 for replacement of grid electricity. The shift from negative to positive net emissions when the efficiency of woody biomass incineration is decreased from 25 % to 20 % shows that the overall emissions are very sensitive to the woody biomass incineration efficiency. Incineration of sewage sludge uses supplementary fuel which causes direct fossil emissions of 147.8 g CO_2eq/FU.

On the other hand, the net GHG emissions of the proposed system are −438.4 g CO_2eq/FU. Apart from the biogenic nature of emissions and carbon credits for grid electricity replacement, the biggest contribution to net negative emission in the proposed system comes from the CO_2 sequestered in biochar. Each FU produces close to 97.8 g of biochar which sequesters 229.4 g CO_2eq. This scheme does not use any supplementary fuel for sewage sludge incineration and therefore avoids that portion of direct fossil emissions which are present in the existing system.

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_2eq/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 $^{\alpha}$	%	Assumed
Ash production rate	0.2 $^{\beta}$	kg/kg woody biomass	Assumed
$^{\alpha}$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. $^{\beta}$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 ranger 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_2eq/tonne km	[54]
Emissions of long haul trucks	74.7	g CO_2eq/tonne km	[55]
Emissions of tug boats	28	g CO_2eq/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_2eq/kWh	[38]

Table 4: Life cycle inventory

The proposed system offers emission savings in the range of 373.3 to 471.1 g CO_2eq/FU in comparison to the existing system. The net annual savings are in the range of 137.0 to 164.1.0 to kt of CO_2eq. These emission savings are approximately equivalent to the annual emission savings provided by the replacement of approximately 71,000 to 85,000 petrol passenger cars (12 % to 14 % of the entire fleet), by battery electric cars in Singapore (Evaluated based on the fact that there are approximately 600,000 [57] passenger cars in Singapore, and the GHG emissions of an average petrol car and battery electric vehicle in Singapore are 209 g CO_2eq/km and 106 g CO_2eq/km [58] respectively).

The emissions from biomass are considered to have no GWP as per IPCC norms. However, if we consider the CO_2 emissions from biomass to have GWP, then the carbon sequestered in biochar would not get any sequestration credits. In such a case, the net emissions of the existing system would be in the range of 1573.3 to 1496.5 g CO_2 eq/FU (calculated based on the assumption that the entire carbon in waste is converted to CO_2 at stoichiometric ratio). The emissions of the proposed system would be 1249.9 g CO_2 eq/FU thus offering a savings potential of 245.5 to 323.3 g CO_2eq/FU.

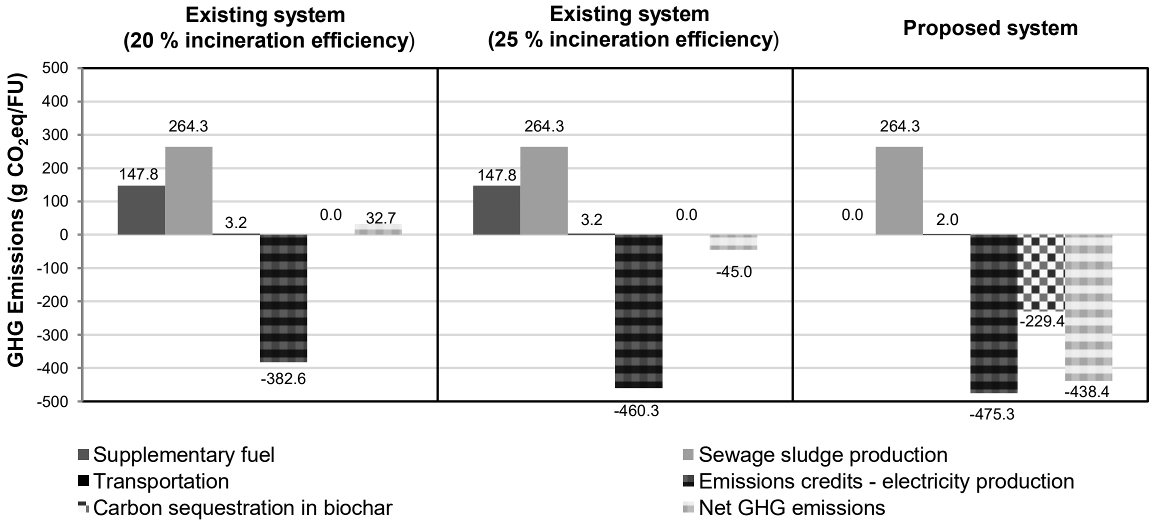

Fig. 5: GHG emissions of existing and proposed system per FU and their contributing factors.

3.2 Energy recovery

The energy recovered in the existing system lies in the range of 0.89 to 1.07 kWh/FU. The electricity requirement for sewage sludge production process is 0.61 kWh/FU. Thus the net electricity production lies in the range of 0.27 to 0.45 kWh/FU. In the proposed system the gross and net electricity production are 1.10 kWh/FU and 0.49 kWh/FU respectively. The increase in net electricity production in the existing system is 0.034 to 0.214 kWh/FU. The proposed system could yield a net annual increase in electricity generation of 12.1 GWh to 74.8 GWh. The reason for the increase in electricity generation is the higher electrical efficiency of gasification.

3.3 Transportation distances and emissions

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

3.4 Conclusion

Compared to the existing system, decentralised co-gasification of sewage sludge and woody biomass increases the net annual emission savings by 138.9 to 165.9 million kg CO_2eq. The major contributions for the emission saving potential come from, (1) increased efficiency, (2) no requirement of supplementary fuel for sludge disposal and (3) CO_2 sequestration in biochar. The decentralised system reduces the kg-km driven by 42 %. Production of biochar from organic sources contributes greatly to emission abatement through biogenic carbon sequestration.

Acknowledgement

This work was financially supported by the Singapore National Research Foundation under its Campus for Research Excellence and Technological Enterprise (CREATE) programme. The support by Newcastle University is gratefully acknowledged.

Glossary

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

Nomenclature of symbols used

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

Nomenclature of subscripts used

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

References

[1] Hoornweg D, Bhada-Tata P. What A Waste - A Global Review of Solid Waste Management. The World Bank, http://siteresources.worldbank.org/INTURBANDEVELOPMENT/Resources/336387-1334852610766/What_a_Waste2012_Final.pdf (accessed February 25, 2017).

[2] Fytili D, Zabaniotou A. Utilization of sewage sludge in EU application of old and new methods-A review. Renew Sustain Energy Rev 2008;12:116–40. doi:10.1016/j.rser.2006.05.014.

[3] Yu X, Xue J, Yao H, Wu Q, Venkatesan AK, Halden RU, et al. Occurrence and estrogenic potency of eight bisphenol analogs in sewage sludge from the U.S. EPA targeted national sewage sludge survey. J Hazard Mater 2015;299:733–9. doi:10.1016/j.jhazmat.2015.07.012.

[4] Yang G, Zhang G, Wang H. Current state of sludge production, management, treatment and disposal in China. Water Res 2015;78:60–73. doi:10.1016/j.watres.2015.04.002.

[5] Kelessidis A, Stasinakis AS. Comparative study of the methods used for treatment and final disposal of sewage sludge in European countries. Waste Manag 2012;32:1186–95. doi:10.1016/j.wasman.2012.01.012.

[6] Public Utilities Board. NEWater, https://www.pub.gov.sg/watersupply/fournationaltaps/newater (accessed February 25, 2017).

[7] Singapore Government. Water supply - used water treated, https://data.gov.sg/dataset/water-supply-used-water-treated (accessed February 25, 2016).

[8] Ng BJH, Zhou J, Giannis A, Chang VWC, Wang JY. Environmental life cycle assessment of different domestic wastewater streams: Policy effectiveness in a tropical urban environment. J Environ Manage 2014;140:60–8. doi:10.1016/j.jenvman.2014.01.052.

[9] Sommers LE. Chemical Composition of Sewage Sludges and Analysis of Their Potential Use as Fertilizers. J Environ Qual 1977;6:225. doi:10.2134/jeq1977.00472425000600020026x.

[10] National Environment Agency. NEA - Waste Statistics and Overall Recycling 2016. http://www.nea.gov.sg/energy-waste/waste-management/waste-statistics-and-overall-recycling (accessed February 25, 2017).

[11] Fullana A, Conesa JA, Font R, Sidhu S. Formation and destruction of chlorinated pollutants during sewage sludge incineration. Environ Sci Technol 2004;38:2953–8. doi:10.1021/es034896u.

[12] McKay G. Dioxin characterisation, formation and minimisation during municipal solid waste (MSW) incineration: Review. Chem Eng J 2002;86:343–68. doi:10.1016/S1385-8947(01)00228-5.

[13] Cheng H, Hu Y. Municipal solid waste (MSW) as a renewable source of energy: current and future practices in China. Bioresour Technol 2010;101:3816–24. doi:10.1016/j.biortech.2010.01.040.

[14] Tsai W-T. Analysis of municipal solid waste incineration plants for promoting power generation efficiency in Taiwan. J Mater Cycles Waste Manag 2016;18:393–8. doi:10.1007/s10163-014-0345-8.

[15] Malkow T. Novel and innovative pyrolysis and gasification technologies for energy efficient and environmentally sound MSW disposal. Waste Manag 2004;24:53–79. doi:10.1016/S0956-053X(03)00038-2.

[16] Murphy JD, McKeogh E. Technical, economic and environmental analysis of energy production from municipal solid waste. Renew Energy 2004;29:1043–57. doi:10.1016/j.renene.2003.12.002.

[17] Baratieri M, Baggio P, Bosio B, Grigiante M, Longo GA. The use of biomass syngas in IC engines and CCGT plants: A comparative analysis. Appl Therm Eng 2009;29:3309–18. doi:10.1016/j.applthermaleng.2009.05.003.

[18] Woolf D, Amonette JE, Street-Perrott FA, Lehmann J, Joseph S. Sustainable biochar to mitigate global climate change. Nat Commun 2010;1:56. doi:10.1038/ncomms1053.

[19] Longden D, Brammer J, Bastin L, Cooper N. Distributed or centralised energy-from-waste policy? Implications of technology and scale at municipal level. Energy Policy 2007;35:2622–34. doi:10.1016/j.enpol.2006.09.013.

[20] Azapagic A. Energy from municipal solid waste: Large-scale incineration or small-scale pyrolysis?. Environ Eng Manag J 2007;6:337–46.

[21] Zabaniotou AA, Skoulou VK, Mertzis DP, Koufodimos GS, Samaras ZC. Mobile gasification units for sustainable electricity production in rural areas: The SMARt-CHP project. Ind Eng Chem Res 2011;50:602–8. doi:10.1021/ie100202p.

[22] Arena U. Process and technological aspects of municipal solid waste gasification. A review. Waste Manag 2012;32:625–39. doi:10.1016/j.wasman.2011.09.025.

[23] Ong Z, Cheng Y, Maneerung T, Yao Z, Tong YW, Wang CH, et al. Co-gasification of woody biomass and sewage sludge in a fixed-bed downdraft gasifier. AIChE J 2015;61:2508–21. doi:10.1002/aic.14836.

[24] Ramachandran S, Stimming U. Well to wheel analysis of low carbon alternatives for road traffic. Energy Environ Sci 2015;8:3313–24. doi:10.1039/C5EE01512J.

[25] The International Standards Organisation. Environmental management — Life cycle assessment — Principles and framework. ISO 14040, vol. 2006, 2006, p. 1–28. doi:10.1136/bmj.332.7550.1107.

[26] Hospido A, Moreira T, Martín M, Rigola M, Feijoo G. Environmental evaluation of different treatment processes for sludge from urban wastewater treatments: anaerobic digestion versus

thermal processes. Int J Life Cycle Assess 2005;10:336–45. doi:10.1065/lca2005.05.210.

[27] Xu C, Chen W, Hong J. Life-cycle environmental and economic assessment of sewage sludge treatment in China. J Clean Prod 2014;67:79–87. doi:10.1016/j.jclepro.2013.12.002.

[28] Cao Y, Pawłowski A. Life cycle assessment of two emerging sewage sludge-to-energy systems: Evaluating energy and greenhouse gas emissions implications. Bioresour Technol 2013;127:81–91. doi:10.1016/j.biortech.2012.09.135.

[29] Mills N, Pearce P, Farrow J, Thorpe RB, Kirkby NF. Environmental & economic life cycle assessment of current & future sewage sludge to energy technologies. Waste Manag 2014;34:185–95. doi:10.1016/j.wasman.2013.08.024.

[30] Babu B V. Biomass pyrolysis: a state-of-the-art review. Biofuels, Bioprod Biorefin 2008;2:393–414. doi:10.1002/bbb.92.

[31] Janajreh I, Al Shrah M. Numerical and experimental investigation of downdraft gasification of wood chips. Energy Convers Manag 2013;65:783–92. doi:10.1016/j.enconman.2012.03.009.

[32] Bridgwater A V. Renewable fuels and chemicals by thermal processing of biomass. Chem Eng J 2003;91:87–102. doi:10.1016/S1385-8947(02)00142-0.

[33] Demirbas A. Combustion characteristics of different biomass fuels. Process Energy Combust Sci 2004;30:219–30. doi:10.1016/j.pecs.2003.10.004.

[34] Stiegel GJ, Maxwell RC. Gasification technologies: The path to clean, affordable energy in the 21st century. Fuel Process Technol 2001;71:79–97. doi:10.1016/S0378-3820(01)00138-2.

[35] Righi S, Oliviero L, Pedrini M, Buscaroli A, Della Casa C. Life cycle assessment of management systems for sewage sludge and food waste: centralized and decentralized approaches. J Clean Prod 2013;44:8–17. doi:10.1016/j.jclepro.2012.12.004.

[36] IPCC. Waste - IPCC good practice guidance and uncertainty management in national greenhouse gas inventories, http://www.ipcc-nggip.iges.or.jp/public/gp/english/5_Waste.pdf (accessed February 25, 2017).

[37] Edwards R, Larivé J-F, Rickeard D, Weindorf W. WELL-TO-TANK Report Version 4.a - now. JRC Technical Reports, https://iet.jrc.ec.europa.eu/about-jec/sites/iet.jrc.ec.europa.eu.about-jec/files/documents/report_2014/wtt_report_v4a.pdf (accessed February 25, 2017).

[38] Energy Market Authority. Other energy-related statistics 2016. https://www.ema.gov.sg/cmsmedia/Publications_and_Statistics/Publications/ses/2015/other-energy-related-statistics/index.html (accessed February 25, 2017).

[39] Umeki K, Yamamoto K, Namioka T, Yoshikawa K. High temperature steam-only gasification of woody biomass. Appl Energy 2010;87:791–8. doi:10.1016/j.apenergy.2009.09.035.

[40] Kim YD, Yang CW, Kim BJ, Kim KS, Lee JW, Moon JH, et al. Air-blown gasification of woody biomass in a bubbling fluidized bed gasifier. Appl Energy 2013;112:414–20. doi:10.1016/j.apenergy.2013.03.072.

[41] Pohořelý M, Jeremiáš M, Skoblia S, Beňo Z, Šyc M, Svoboda K. Transient Catalytic Activity of Calcined Dolomitic Limestone in a Fluidized Bed during Gasification of Woody Biomass. Energy and Fuels 2016;30:4065–71. doi:10.1021/acs.energyfuels.6b00169.

[42] Elango B, Uisung L, Chung JN. High Temperature steam gasification of woody biomass-a combined experimental and mathematical modeling approach. Eff Br Mindfulness Interv Acute Pain Exp An Exam Individ Differ 2015;1:1689–99. doi:10.1017/CBO9781107415324.004.

[43] Oike T, Kudo S, Yang H, Tahara J, Kim H, Koto R, et al. Sequential Pyrolysis and Potassium-Catalyzed Steam − Oxygen Gasi fi cation of Woody Biomass in a Continuous Two-Stage Reactor. Energy & Fuels 2014;28:6407–18. doi:10.1021/ef5015296.

[44] Hin YW. Overview of Singapore's deep tunnel sewerage system, http://www.pub.gov.sg/dtss/Documents/SWA_30Apr2015.pdf (accessed February 25, 2017).

[45] Wang Z, Dunn JB, Han J, Wang MQ. Effects of co-produced biochar on life cycle greenhouse gas emissions of pyrolysis-derived renewable fuels. Biofuels, Bioprod Biorefining 2014;8:189–204. doi:10.1002/bbb.1447.

[46] Lehmann J, Gaunt J, Rondon M. Bio-char sequestration in terrestrial ecosystems - A review. Mitig Adapt Strateg Glob Chang 2006;11:403–27. doi:10.1007/s11027-005-9006-5.

[47] Akwo NS. A Life Cycle Assessment of Sewage Sludge Treatment Options. Master Thesis in Environmental Management, Department of Devolpment and Planning, Alaborg University, http://projekter.aau.dk/projekter/files/14465524/final_thesis.pdf (accessed February 25, 2017).

[48] Morselli L, Bartoli M, Bertacchini M, Brighetti A, Luzi J, Passarini F, et al. Tools for evaluation of impact associated with MSW incineration: LCA and integrated environmental monitoring system. Waste Manag 2005;25:191–6. doi:10.1016/j.wasman.2004.12.008.

[49] Lam CHK, Ip AWM, Barford JP, McKay G. Use of incineration MSW ash: A review. Sustainability 2010;2:1943–68. doi:10.3390/su2071943.

[50] Shafie SM, Mahlia TMI, Masjuki HH, Ahmad-Yazid a. A review on electricity generation based on biomass residue in Malaysia. Renew Sustain Energy Rev 2012;16:5879–89. doi:10.1016/j.rser.2012.06.031.

[51] International Renewable Energy Agency (IRENA). Biomass for Power Generation - Renewable energy technologies: Cost analysis series, https://www.irena.org/DocumentDownloads/Publications/RE_Technologies_Cost_Analysis-BIOMASS.pdf (accessed February 25, 2017).

[52] Biomass Energy Resource Center. BIOMASS ENERGY: Efficiency, Scale, and Sustainability, http://www.biomasscenter.org/policy-statements/FSE-Policy.pdf (accessed February 25, 2017).

[53] National Environment Agency. Tuas marine transfer station (TMTS) 2016. http://www.nea.gov.sg/energy-waste/waste-management/tuas-marine-transfer-station-(tmts) (accessed February 25, 2017).

[54] Argonne National Laboratory. GREET - Greenhouse Gases, Regulated Emissions, and Energy use in Transportation Model 2016 - Retreived from the GREET Computer Programme.

[55] Poulsen TG, Hansen J a. Strategic environmental assessment of alternative sewage sludge management scenarios. Waste Manag Res 2003;21:19–28.

[56] Walker H, Conolly C, Norris J, Murrells T. Greenhouse gas emissions from inland waterways and recreational craft in the UK. AEA Technol Plc, https://uk-air.defra.gov.uk/assets/documents/reports/cat07/1106231031_IP_Task_25_Inland_Waterways_Issue_1.pdf (accessed February 25, 2017).

[57] Land Transport Authority. Annual vehicle statistics 2015. htt5s://www.lta.gov.sg/content/dam/ltaweb/corp/PublicationsResearch/files/FactsandFigures/MVP01-1_MVP_by_type.pdf (accessed February 26, 2017).

[58] Reuter B, Schönsteiner K, Wagner M, Gleyzes D, Massier T, Hamacher T, Lienkamp M. Life cycle greenhouse gas analysis for automotive applications – A case study for taxis in Singapore. Int J Smart Grid Clean Energy 2014. doi: 10.12720/sgce.3.2.127-134.