Environmental Impact Assessment of Municipal Solid Waste Management Incorporating Mechanical Treatment of Waste and Incineration in Hangzhou, China

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Abstract

Municipal solid waste (MSW) management is becoming increasingly popular around the world as a means of accommodating the increasing amounts of waste that the growing global population generates. China currently produces more MSW than any other country. As such, this area of the world is facing challenges on an unprecedented scale. MSW management in China is highly dependent on landfilling, and the development of sanitary landfills is currently a top priority for the Chinese government. Hangzhou is one of the most developed cities in China. In fact, in 2013, the amount of incinerated MSW in Hangzhou represented 56% of total MSW. MSW incineration is primarily performed via a process of co-incineration with coal because MSW has a low heating value.

This paper employs a environmental impact assessment by LCA program to determine whether refuse-derived fuel (RDF) production and incineration can have a more positive impact on the environment than the co-incineration of MSW with coal in Hangzhou, China. According to the results, RDF production and incineration could improve Hangzhou’s MSW management global warming potential from -33% to 0%, the acidification potential from -90% to 34%, and the eutrophication potential from -1 200% to 350% in comparison to the co-incineration of MSW with coal. The treatment of organic reject material from RDF production has a significant effect on the results; as such, it should be utilized in energy production rather than landfilled.

Keywords: Life cycle assessment, Municipal solid waste, RDF, Organic reject

1. Introduction

Municipal solid waste (MSW) management is an important issue for the urbanizing world, especially in developing countries, where economic development and expansion have significantly increased the generation of MSW. The vast amount of MSW generated in growing cities around the world requires sustainable management. The majority of waste is currently disposed of in landfills from where it emits landfill gas (LFG) that contains methane, a substance that makes a significant contribution to global warming. Waste and waste water together account for 3% of the global greenhouse gas (GHG) emissions, with landfill gas methane being the largest source (IPCC, 2014).

The amount of MSW in China has increased rapidly in recent years, and China is now the world’s largest producer of MSW. In 2004, China generated 155 million tons (120 kg per capita) of MSW (National Bureau of Statistic of China, 2005) and by 2013 this figure had reached 172 million tons (126 kg per capita) (National Bureau of Statistic of China, 2014). These statistics do not include the waste collected by pickers, which is estimated to represent 8-10% of the total MSW generated (Chen et al., 2010).

The MSW that is generated in China is predominantly treated via landfilling and incineration. For example, in 2010, 79% of MSW was landfilled, 19% was incinerated, and 2% was composted (Dong et al., 2014a). Between 2002 and 2010, the proportion of incineration steadily increased from 3.7% to 19%. Modern landfill sites in China employ LFG collection equipment and modern leachate treatment systems to satisfy national pollution standard requirements. To be considered environmentally sound, cities in China should have safe disposal rates, which include landfilling, incineration, and composting, of between 85% to 90% (Chen et al., 2010).

In 2010, the share of mixed MSW disposed of in landfills in Hangzhou, which is one of the most developed areas in China, was 51%, while the rest was sent to incineration (Chi et al., 2014). The first MSW landfill (Tianziling Solid Waste Landfill) was constructed in Hangzhou in 1991, and it utilizes cement curtain technology to prevent leachate from polluting groundwater (Zhang et al., 2010).

Life cycle assessment (LCA) is used to deduce the impacts that different activities, including waste management systems, have on the environment with the intention of comparing how different configurations of the given systems vary (Cleary, 2009; Coventry et al., 2016; Ekvall et al., 2007; Fernández-Nava et al., 2014; Finnveden, 1999; Laurent et al., 2014; Turner et al., 2016; W. Zhao et al., 2009a).

Many researchers have conducted LCAs of waste management systems. Dong et al. (2013) examined the effect that source separation had on MSW management in Hangzhou and found that 23% of GHG emissions could be reduced in comparison to the base scenario. Chi et al. (2014) calculated that it was possible to achieve a 30% reduction in GHG in Hangzhou through improving source separation. More recently, Dong et al. (2014b) compared the disposal of MSW into landfills with and without LFG recovery and incineration and concluded that incineration is the most viable option for waste management in Hangzhou. Zhao et al. (2009b) used a LCA approach to estimate emissions from Hangzhou’s MSW management system and found that landfills made the biggest contribution to the emissions that cause global warming, while incineration contributed the most to acidification. Zhao et al. (2011) examined MSW management in Tianjin using LCA and life cycle costing (LCC) and concluded that the operation of current and new landfills in combination with LFG recovery would represent a promising approach to waste management in Tianjin.

To date, the LCA studies that have assessed Chinese MSW management systems have focused on the incineration of mixed MSW with coal and improving source separation or improving landfill disposal practices. These studies have ignored the potential of refuse-derived fuel (RDF) production through the mechanical treatment and utilization of RDF in waste incineration. The production of RDF from mixed MSW could potentially be used to improve the fuel qualities of mixed MSW, thus removing the need to use coal as an auxiliary fuel in waste incineration plants in China. This mechanical treatment could also enable the recovery of recyclable waste from the MSW. In addition to RDF, there is also a significant organic reject fraction coming from mechanical treatment that requires treatment. To that end, the current study had two main objectives. The first of these objectives was to assess the change in the environmental impacts that transitioning from mixed MSW co-combustion with coal to the mechanical treatment of mixed MSW in combination with the incineration of RDF would have. The second objective was to determine the most environmentally sound method by which the organic reject from the mechanical treatment of mixed MSW could be processed.

2. Materials and Methods

A environmental impact assessment was conducted in accordance with ISO standards 14040 and 14044 using life cycle assessment (LCA) tool GaBi 6 (ISO 14040, 2006; ISO 14044, 2006). The four major phases in the environmental impact assessment include goal and scope definition, inventory analysis, impact assessment, and the interpretation of results. Environmental impact assessment is a relative approach that requires a functional unit that defines what is being studied. All subsequent analyses are related to the selected functional unit. In the current study, the functional unit was the mass of MSW produced in the case study region in 2013. The waste management system includes processes that have multiple purposes; for example, the incineration plant produces energy, utilizes waste, and recovers materials. To avoid allocation between outputs, as is advised in Standard 14044, a system expansion was used to account for the substitution of energy and virgin material productions. An assumption of zero burden condition was used in the study, meaning that the waste enters the system boundary without any burden related to the production and use of materials. This facilitates a comparison of the treatment options that are available for a given amount of waste but is not suitable for an analysis in situations in which the quantity of waste changes; for example, as a result of waste minimization efforts (Finnveden, 1999; Hagberg et al., 2009; Laurent et al., 2014).

2.1. Goal and Scope Definition

The objective of the study is to investigate the change in environmental impacts that transitioning from MSW co-combustion with goal to mechanical treatment of MSW and RDF incineration would have in a Chinese city and to identify the most environmentally sound method of treating the organic rejects of RDF production. Hangzhou was selected as the case city for this research because the amount of MSW produced in Hangzhou has increased rapidly over the course of the last decade at an average annual growth rate of 10%, as presented in Figure 1. The MSW management system in Hangzhou is based on landfilling and incineration. The share of waste incinerated has rapidly increased in the past ten years, reaching 44% in 2013. At the same time, the share of waste landfilled decreased to 58% in 2013. The MSW management system includes two landfills, four incineration plants, and a biogas plant for food waste treatment. The first phase of the MSW landfill at the Hangzhou Tianziling Solid Waste Landfill site was built in 1991 and closed in 2006. The second phase of the Tianziling landfill is expected to reach its full capacity in 5-6 years due to the significant increase in the amount of MSW generated and an insufficient growth in the city's incineration capacity (Hangzhou Municipal Solid Waste Disposal Center, 2014).

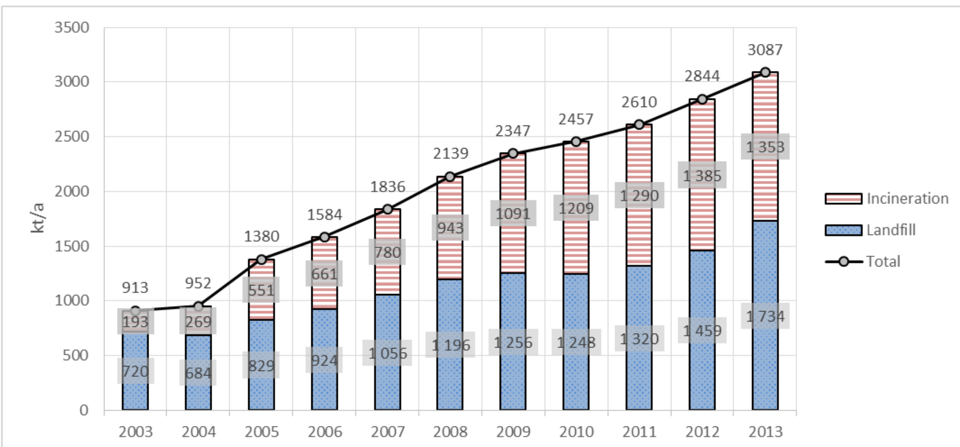

Figure 1. The MSW mass generated and treated in Hangzhou between 2003 and 2013 (Dong et al., 2013; Hangzhou Municipal Solid Waste Disposal Center, 2014)

Hangzhou MSW management includes a four-bin collection system for waste, which was established in Hangzhou in 2010 (Dong et al., 2013). Once collected, the waste is transported directly to the treatment site without the use of transfer stations. The four-bin source separation system enables hazardous waste, food waste, recyclables, and other waste to be collected separately. In addition, unofficial agents collect waste from households and bins before selling this waste to recyclers.

As is the case with the majority of MSW in China in general, Hangzhou's MSW contains a large percentage of food waste, and this varied from 47% to 64% between 2005 and 2011. The second largest waste fraction was plastic waste (14% to 27%). Together with paper, the third largest component of waste, these three waste types represent between 70% and 90% of the total MSW mass. The composition of waste documented in the study is presented in Figure 2.

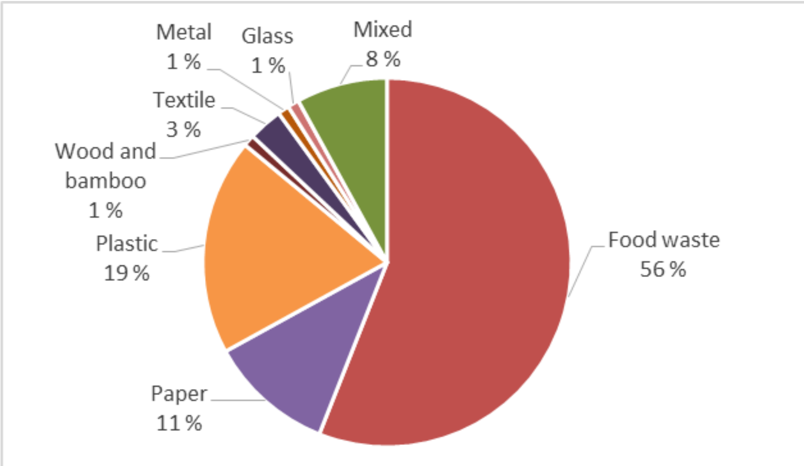

Figure 2. Average mixed MSW composition in Hangzhou (Chi et al., 2014; Hangzhou Municipal Solid Waste Disposal Center, 2014; Zhang et al., 2010).

A environmental impact assessment of the MSW management system in Hangzhou was conducted using three scenarios: a present conditions case scenario and two scenarios involving RDF production from MSW. The present condition scenario (Scenario 0) represented the state of the MSW management system in 2013. Scenario 1 represented RDF production and incineration at three waste incineration plants (Qiaosi, Yuhang, and Xiaoshan) replacing MSW and coal co-incineration, while the Lvneng incineration plant, where no coal is used, would continue MSW co-incineration. The fuel energy of RDF in Scenarios 1 and 2 was assumed to be the same as the total fuel energy of coal and MSW in Scenario 0. In Scenario 2, the same RDF mass (same fuel energy) as that applied in Scenario 1 was assumed to be directed to several new waste incineration plants (hypothetically replacing the old plants in Qiaosi, Yuhang, and Xiaoshan) with higher electric efficiency plants. Table 1 summarizes the MSW mass directed to incineration, RDF production, or landfilling in the scenarios studied.

Four treatment possibilities for the organic reject from RDF production were considered in Scenarios 1 and 2: disposal to landfill (1), biodrying (2), anaerobic digestion (3), or ethanol production (4). It was assumed that the organic fraction of waste was disposed of to the Tianziling landfill site. It was also assumed that the biodried organic reject was incinerated in the same plant as that in which the RDF was produced. The incineration of the organic reject after biodrying reduced the mass of the RDF compared to the scenarios without the incineration of the organic reject because the total fuel energy that went to incineration was assumed to remain the same in all Scenarios 0, 1 and 2. It was assumed that the digestate from anaerobic digestion of the organic fraction was directed to pile composting and then used as landfill cover material.

Table 1. The MSW mass directed to incineration, RDF production, and landfill disposal in the scenarios studied, including method for organic reject treatment (Landfill = LF, anaerobic digestion = AD, ethanol production = EtOH and biodrying).

Scenario		0	1.1 & 1.3 & 1.4	1.2	2.1 & 2.3 & 2.4	2.2
Org. reject treatment		-	LF, AD or EtOH	Biodrying	LF, AD or EtOH	Biodrying
Lvneng	kt/a	204	204	204	204	204
Qiaosi	kt/a	411	490	394	0	0
Yuhang	kt/a	256	343	276	0	0
Xiaoshan	kt/a	416	604	487	0	0
New plants	kt/a	0	0	0	1494	1201
Landfill Liugongduan	kt/a	366	13	293	0	248
Landfill Tianziling	kt/a	1432	1432	1432	1388	1432
Total	kt/a	3086	3086	3086	3086	3086

The system boundary of the study (Figure 3) included the transport of MSW to the incineration plants and landfills, the unit operations at the treatment sites, and the unit operations required to produce the energy need for transportation and unit operations. The direct emissions from the operations and the indirect emissions produced during the process of procuring fuels and electricity were both accounted for. The present anaerobic digestion of source-separated food waste at the Tianziling landfill site was excluded from the environmental impact assessment because the only data obtained from this plant were the mass flow of food waste to the plant (200 t/d) and the share of reject from that food waste stream (one-third is rejected). The emissions that were avoided by displacing the average electricity production in China with the electricity produced from the MSW incineration and as a result of the gas turbine utilizing LFG from the Tianziling landfill were also accounted for. There is no district heat demand in Hangzhou; therefore, only electricity was recovered.

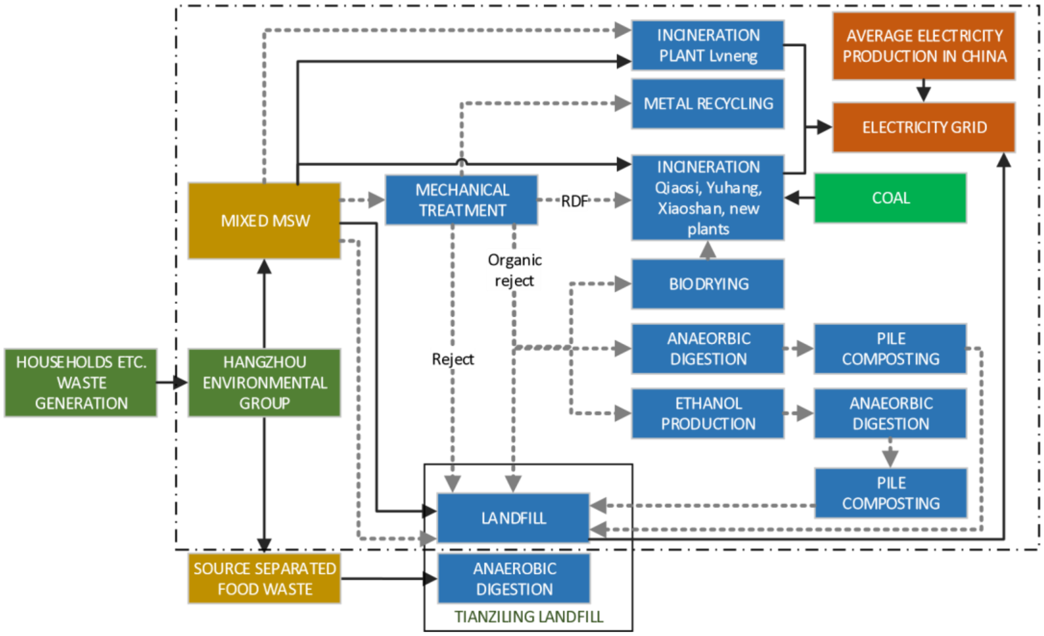

Figure 3. Hangzhou MSW management Scenario 0 (solid line) and Scenarios 1 and 2 (dotted line).

2.2. Inventory Analysis

Inventory analysis is one of the most resource-intensive processes involved in an environmental impact assessment. In the current study, the inventory data were collected using a process-LCA technique that included collecting data from the inputs and outputs of the unit processes.

2.2.1. Landfilling

In 2013, 56% of the mixed MSW in Hangzhou was disposed of in the Liugongduan and Tianziling landfills. The landfill disposal was calculated according to the information gathered during previous studies (Chi et al., 2014; Dong et al., 2014a, 2014b; Nielsen et al., 2008) and the information received during site visits to the Tianziling landfills, as summarized in Table 2. LFG was only collected at the Tianziling landfill site, and the gas collected was directed to a gas engine. Diesel was consumed by the bulldozer used at the landfill, and the emissions of this bulldozer are summarized in supplementary material SI2.

Table 2. Parameters for calculating MSW disposal into landfill.

Parameter	Value	Unit
Diesel use	0.00014	kg diesel/kg MSW
LFG	0.120	m^3/kg MSW
LFG CH4 content	50	%
LFG CH4 oxidation	10	%
LFG collection		
Liugongduan	0	%
Tianziling	25	%
LFG combustion in gas engine		
Electric efficiency	39	%
CH_4 emission	0.000323	kg CH_4/MJ
N_2O emission	0.0000005	kg N_2O/MJ
Leachate treatment		
Leachate	0.2	kg/kg MSW
Electricity use	0.0015	MJ/kg MSW
CH_4 emission	0.00006	kg/kg MSW
Leachate pollutants after treatment		
NH_3	0.00081	kg/kg leachate
P tot	0.000012	kg/kg leachate

2.2.2. The incineration of MSW

MSW incineration in Hangzhou is primarily based on fluidized bed technology because three of the four incineration plants utilize fluidized bed technology (Qiaosi, Yuhang, and Xiaoshan), with only Lvneng using grate technology. Data on the incineration plants were collected by visiting the incineration plants and through surveys with the plant operators. The three fluidized bed boiler incineration plants utilized coal as an auxiliary fuel. It was assumed that the coal was transported from a coal mine that was located 600 km away from Hangzhou. The operations data of the four plants are summarized in Table 3, and these data were used to calculate Scenario 0. More information about the waste incineration plants is presented in supplementary material SI3. The lower heating value of MSW as received (LHV_{ar}) in Hangzhou was low, varying between 4 and 5 MJ/kg. In all of the incineration plants, a small share of metal (0.07 % of the utilized MSW mass) was recovered in a pretreatment phase and then recycled. It was assumed that the composition of this metal was 50% steel and 50% aluminum (Dong et al., 2014a). The metal recycling emission credits are presented in supplementary material SI3. It was assumed that the coal came from the Huaibei coal mine, which is approximately 600 km from Hangzhou.

Table 3. Operations data for the four existing incineration plant in Hangzhou.

Operation Data			**Lvneng**	**Qiaosi**	**Yuhang**	**Xiaoshan**
MSW	Mass	kt/a	204	411	256	416
	LHV_{ar}	MJ/kg	3.9	4.2	4.2	4.6
Coal	Mass	kt/a	0	2	8	23
	Share	% of MSW	0	0.57	3.2	5.5
	LHV_{ar}	MJ/kg	0	21	21	21
Fuel energy	MSW	GWh/a	220	480	299	531
	Coal	GWh/a	0	14	46	134
	Share	% of total	0	3	13	20
	Total	GWh/a	220	494	345	666
Electricity efficiency		%	24	20	16	19
Own use		% of produced	19	29	25	21
Ash		of MWS	20	16	18	22
Bottom ash		of ash	85	63	55	55
Fly ash		of ash	15	38	45	45

The calculation accounted for the flue gas emissions and the treatment of solid residues. The average fossil carbon content of MSW was calculated to be 12.5 % of the mixed MSW mass. This calculation is presented in supplementary material SI3. The other emissions were obtained from the plant operators and are summarized in Table 4. The bottom ash was assumed to be made into bricks by adding cement to 30% of the bottom ash mass and sold directly from the plant. The transportation of any sold bricks was not included in the calculations. The fly ash was solidified by adding water 5% and cement 3% to the fly ash mass. The solidified fly ash was then transported to the landfill. It was assumed that the cement was transported from a nearby cement mill in Hangzhou. The distances the mixed MSW, fly ash, and cement were transported are summarized in supplementary information SI1.

Table 4. Flue gas emissions of existing incineration plants in Hangzhou.

	Lvneng	**Qiaosi**	**Yuhang**	**Xiaoshan**
Dust (kg/a)	7 000	27 000	18 000	39 000
SO_2 (kg/a)	26 000	27 000	17 000	38 000
HCl (kg/a)		6 800	4 400	9 600
NO_2 (kg/a)	110 000	150 000	94 000	200 000
CO (kg/a)		62 000	40 000	85 000
Hg (kg/a)		7	4	9
Cd (kg/a)		3	2	4
Pb (kg/a)		3	2	4
Dioxin (mg/a)		740	480	1 000

2.2.3. Refuse derived fuel production and incineration

In Scenarios 1 and 2, the MSW was assumed to be directed to a mechanical treatment center located near the incineration plants for the production of RDF. The modeled mechanical treatment line included shredding, screening for organic fraction separation, magnetic separation of ferrous metals, eddy current separation of non-ferrous metals, and air separation for heavy fraction separation. The recovery rates (shares removed from the material stream going to RDF) of the machinery used were calculated according to the approach employed by Nasrullah et al., (2015), who previously studied the production of RDF from MSW. The process is summarized in supplementary material SI4. The energy consumption of the RDF production line was assumed to be 70 kWh/t MSW (Nasrullah et al., 2015). According to the calculation, 68% of the MSW ended up as RDF, and approximately 30% was removed as organic reject. The LHV_{ar} of the RDF was calculated by assuming that the RDF contained 86% of the energy content of the MSW (Nasrullah et al., 2015). The outputs of the mechanical treatment line for the scenarios in which the organic reject was not incinerated (i.e., Scenarios 1.1, 1.3, 1.4, 2.1, 2.3, and 2.4) are summarized in Table 5.

Table 5. Mechanical treatment outputs in Scenarios 1.1, 1.3, 1.4, 2.1, 2.3, and 2.4.

	Unit	**Qiaosi**	**Yuhang**	**Xiaoshan**	**New plants**
RDF	kt/a	335	235	413	1 022
RDF LHV_{ar}	MJ/kg	5.3	5.3	5.8	5.3
Fuel energy	GWh/a	494	345	666	1 505
Organic reject	kt/a	149	105	184	456
Metal	kt/a	3	2	4	10
Non-magnetic metal	kt/a	1	0	1	2
Heavy reject	kt/a	1	1	2	5

2.2.4. Organic reject treatment

Four methods of treating the organic reject that was generated during the RDF production were considered: landfilling, biodrying, anaerobic digestion, and ethanol production. The first method involved directing the organic reject to Tianziling landfill, where the LFG generation was estimated to be 0.12 m^3/kg (Dong et al., 2014a).

The second treatment method involved biodrying, which was assumed to occur close to the incineration and RDF plants. The biodrying process was assumed to be an aerobic process through which the moisture content was reduced, thereby improving the combusting properties of wet organic reject (Zhang et al., 2009) and making it suitable for co-incineration with the produced RDF. The life cycle inventory (LCI) data for the biodrying process and its associated inputs and outputs are summarized in supplementary material SI5.1.

Because the fuel energy directed to incineration was assumed to be same in the plants and the incineration of the dried organic reject reduces the need for RDF, the mass of RDF and organic reject was calculated so that the fuel energy of a given plant remained the same in all scenarios. The outputs of the mechanical treatment and subsequent biodrying of organic reject are summarized in Table 6. The LHV_{ar} of the RDF that was produced were the same in Scenarios 1 and 2.

Table 6. Mechanical treatment outputs in Scenarios 1.2 and 2.2.

	Unit	**Qiaosi**	**Yuhang**	**Xiaoshan**	**New plants**
RDF	kt/a	270	189	333	822
RDF LHV_{ar}	MJ/kg	5.3	5.3	5.8	5.3
Dried org. reject	kt/a	58	41	72	177
Dried org. reject LHV_{ar}	MJ/kg	6.0	6.0	6.5	6.0
Fuel energy	GWh/a	494	345	666	1 505
Metal	kt/a	3	2	3	8
Non-magnetic metal	kt/a	0	0	1	1
Heavy reject	kt/a	1	1	1	4

The third method was wet mesophilic anaerobic digestion. The biogas was directed to a gas turbine for the purposes of generating electricity and heat. The electricity that was produced was directed to the electricity grid, and part of the produced heat was directed for heating the reactor. It was assumed that any residual heat that was generated was wasted because there is no district heat grid in Hangzhou. The generated digestate was assumed to be dewatered by a centrifuge and treated by pile composting. It was also assumed that the rejected water was directed to dilute the incoming feedstock in order to reduce the need for fresh water. The LCI data of the anaerobic digestion and pile composting processes are summarized in supplementary material SI5.2. It was assumed that the compost was used as a landfill cover at the Tianziling landfill site.

The fourth method was ethanol production. This method was considered because the biowaste contains sugars that can be fermented into ethanol. The ethanol production was assumed to occur close to the RDF plant. The LCI data of the ethanol production process are summarized in supplementary material SI5.3. The production of ethanol requires alpha-amylase enzymes and glucoamylase enzymes, and the emissions from the enzyme production were calculated according to approach recommended by Nielsen et al. (2007). The stillage was assumed to be directed to dry anaerobic digestion, and the digestate was further directed to dewatering and pile composting, similar to the digestate from the anaerobic digestion of organic reject. The LCI data related to the dry anaerobic digestion are summarized in supplementary material SI5.3. It was assumed that the compost was used as a landfill cover at the Tianziling landfill site.

2.2.5. Uncertainty analysis

The parameters of the mixed MSW management system studied were expected to vary. Therefore, an uncertainty analysis was performed to assess how different parameters affected the results of the present environmental impact assessment study. The range of values for the parameters used in the analysis was selected from the references used to obtain the default values for these parameters. These default values were then used to calculate the minimum and maximum values of the net impact assessment results for all scenarios. The highest uncertainty in the data was related to the LHV of waste. In the uncertainty analysis, the LHV of MSW was changed within a reasonable range of values appropriate for MSW in China, which, in turn, changed the LHV of RDF and the dried organic reject. Another significant factor was the electric efficiency, which also varied. Landfilling mixed MSW was anticipated to have a significant impact on the results; as such, the LFG yield in the Tianziling and Liugongduan landfills were changed, as was the rate at which LFG was collected in the Tianziling landfill. The parameters used in the analysis are summarized in Table 7.

Table 7. The parameters applied in the sensitivity analysis.

Parameter	**Scenario**	**Values Applied**			
		Low	High	Default	
LFG collection rate	All scenarios	15	35	25	%
LFG yield	All scenarios	0.1	0.14	0.12	m^3/kg MSW
Electric efficiency	Scenario 0, 1	15	24	19	%
Electric efficiency	Scenario 2	26	32	29	%
LHV MSW	Scenario 0	3.5	5.0	4.3	MJ/kg
LHV RDF	Scenario 1.1-.4	4.6	6.4	5.5	MJ/kg
LHV RDF	Scenario 2.1-2.4	4.4	6.2	5.3	MJ/kg
LHV dried org. reject	Scenario 1.2	5.4	7.0	6.2	MJ/kg
LHV dried org. reject	Scenario 2.2	5.2	6.8	6.0	MJ/kg

2.3. Impact Assessment

In the impact assessment phase, the potential environmental impacts were evaluated using the inventory analysis data. In this phase, the inventory data is associated with impact categories and indicators (ISO 14040, 2006; ISO 14044, 2006). In the current study, the environmental impact categories included global warming potential (GWP), acidification potential (AP), and eutrophication potential (EP). The impact assessment was conducted until the characterization phase, and there was no normalization or weighting of the results. The impact assessment was performed using GaBi 6.0 software and the CML2010 April 2013 life cycle impact assessment methodology (Thinkstep, 2015).

3. Results and Discussion

The results of the life cycle assessment of the study scenarios are presented as total values of GWP (Figure 4), AP (Figure 5), and EP (Figure 6). The figures also include the results of the uncertainty calculation, which are represented by the error bars. The order of scenarios remained unchanged during the uncertainty analysis. According to the uncertainty calculation, the highest uncertainty was related to the EP values with the changes related to the default value being, on average, between -322% and 198%. The change in GWP results was between -31% and 29%, and the change with the AP results between -81% and 46%. The results highlighted that the annual GWP was lower in the alternative MSW management systems represented by Scenarios 1 and 2 than it was in the reference scenario. The GWP was reduced by between 0 and 33%, with the best scenarios being 2.3 and 2.4, where the MSW was directed to RDF production and the resulting RDF was incinerated in new plants that had a higher electric efficiency, with the resulting organic reject directed to energy recovery by anaerobic digestion (Scenario 2.3) or ethanol production (Scenario 2.4). In all of the scenarios, the net GWP was positive, which was mainly due to the high emissions from landfilling and the lack of emission reductions from displacing fossil heat production because there was no heat recovery from waste incineration.

In all scenarios, the landfill emissions caused the highest share of GWP, representing 48-67% of the total GWP. Incineration, the second most polluting activity, accounted for 29-37% of the total GWP. The organic treatment emissions in Scenarios 1.1 and 2.1 were 7 to 23 times higher than those in other scenarios due to the LFG emissions from directing organic reject into landfill, being 15% and 16% of the emissions in Scenarios 1.1 and 2.1 respectively. The emissions avoided from electricity displacement (el disp.) generated from waste incineration compared to the emissions from waste incineration were 36-41% in old plants and 62%-73% in new plants, where the electric efficiency was higher.

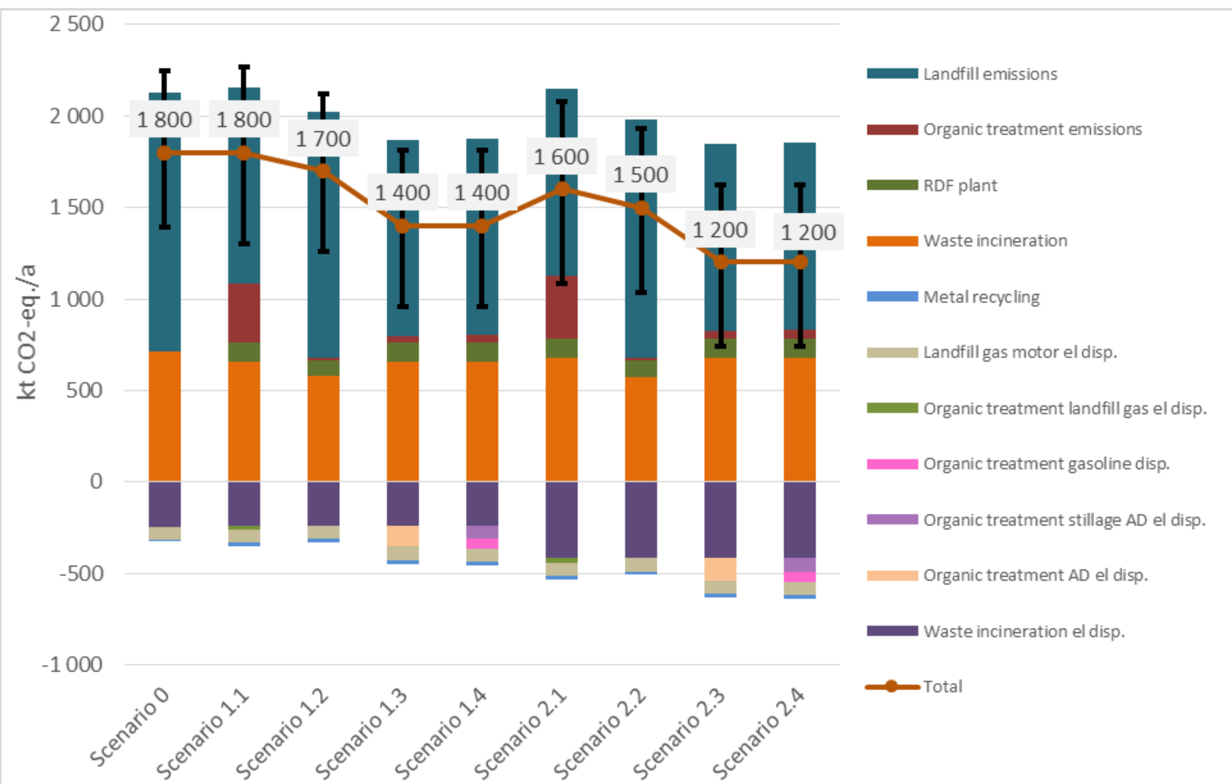

Figure 4. Annual global warming potential ($kt_{CO2,eq.}/a$) of Hangzhou MSW management.

Electricity use and avoided electricity production are playing a greater role in emissions that cause acidification than it does in emissions that cause GWP. In the current study, the net AP was negative in all scenarios due to the high emissions reductions caused by displacing the average electricity production with the electricity produced from waste. The emissions from the incineration caused the main emissions in Scenario 0 (86%); however, in the remaining scenarios, the electricity used to produce RDF caused the highest emissions (46%-57%), followed by incineration (34-39%). Scenarios 1.1 and 1.2 had a higher net AP than the reference scenario because of the emissions from electricity use for RDF production. In Scenarios 1.3 and 1.4, the organic reject treatment produced additional electricity, which resulted in a higher emission displacement than that observed in Scenarios 1.1 and 1.2. The scenario that involved a new incineration plant that combined RDF incineration and anaerobic digestion of organic reject proved to be the best option in terms of the net AP.

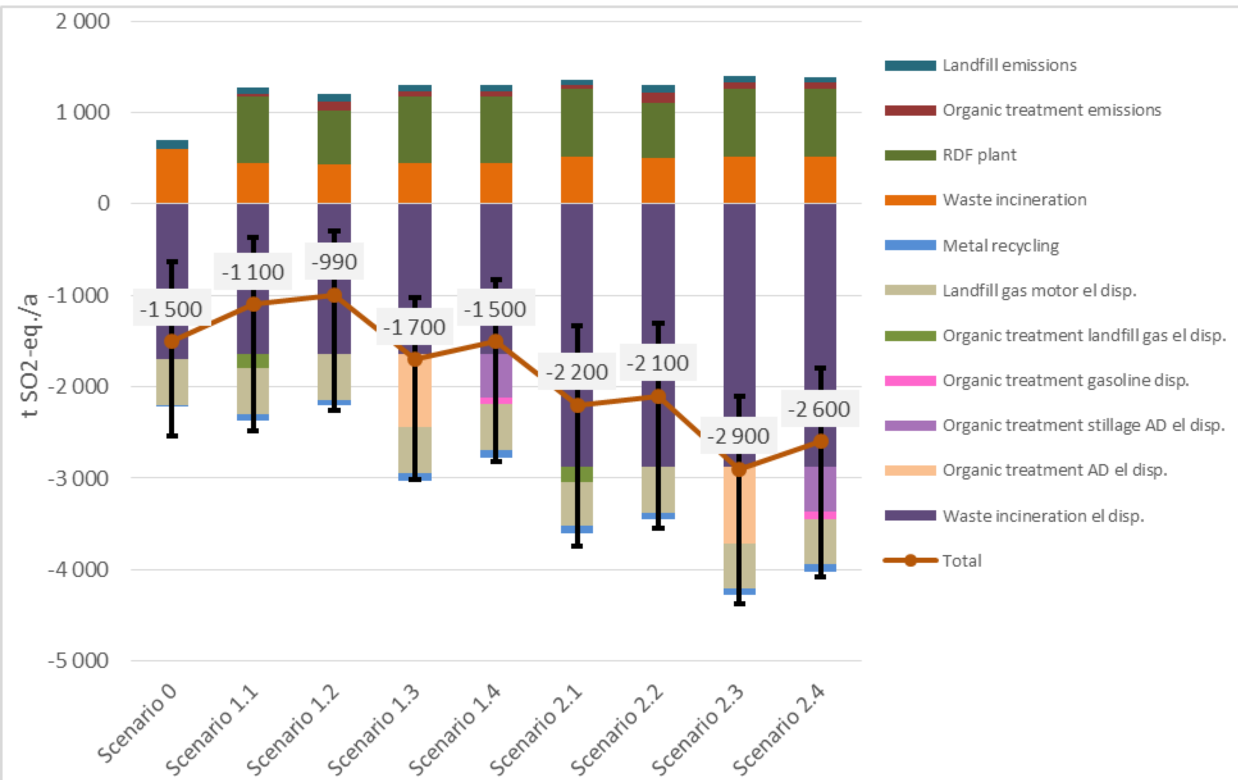

Figure 5. Annual acidification potential ($t_{SO2,eq.}$/a) of Hangzhou MSW management.

The emissions causing eutrophication are similar to the GWP caused primarily by the emissions that resulted from the disposal of MSW into landfills. In Scenario 0, they are more important and are responsible for 56% of all emissions, while in other scenarios, they are slightly less significant and cause 35% to 45% of all emissions. The use of electricity in RDF plants is also a significant source of emissions and is responsible for 25% to 35% of the total emissions. The net EP is negative in most of the scenarios due to the emissions that are avoided as a result of electricity displacement. Scenarios 1.1 and 1.2 have higher net emissions than the reference Scenario 0 because of the increased emissions caused by the RDF plant's electricity use, while the avoided emissions were not increased as much. The net emissions from Scenarios 1.3 and 1.4 were lower than those in Scenario 0 because of the increased emission reductions caused by electricity production from the organic reject.

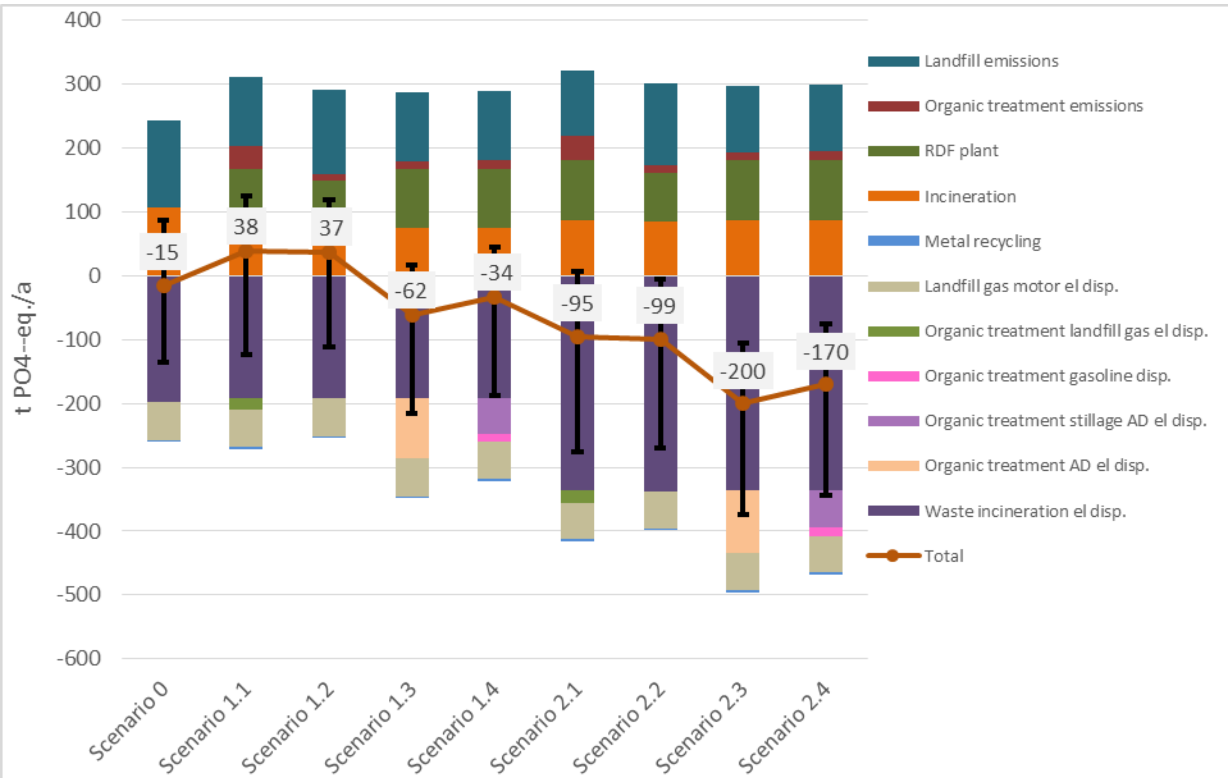

Figure 6. Annual eutrophication potential ($t_{PO4,eq.}$/a) of Hangzhou MSW management.

The calculated net emission factors of different treatment possibilities are summarized in Table 8. Landfilling waste results in higher net GWP potential than incineration due to the methane emissions contained in LFG and the emissions that are avoided from electricity produced by MSW or RDF incineration. The importance of utilizing organic reject from RDF production in energy recovery rather than landfilling is highlighted. As an example, the net GWP from landfilling organic reject can be as high as 690 $kg_{CO2,eq}$/t, whereas energy production from organic reject would result in negative net GWP.

Table 8. Calculated net emission factors of utilizing MSW, RDF, and organic reject in Hangzhou in relation to the processed waste mass.

	GWP $kg_{CO2,eq.}$/t	Acidification $g_{SO2,eq.}$/t	Eutrophication $g_{PO4,eq.}$/t
Landfill	710	-280	36
Incineration			
MSW	360	-860	-72
RDF (old plants)	400	-1 300	-120
RDF (new plants)	230	-2 400	-250
RDF + dried reject (old plants)	340	-1 300	-130
RDF + dried reject (new plants)	140	-2 400	-250
RDF plant	74	500	63
Org reject landfill	690	-280	40
Org reject AD	-190	-1 700	-190
Org reject EtOH	-180	-1 100	-120

The focus of previous LCA studies on MSW management in the literature has been primarily on GWP, and less attention has been given to AP and EP. A short review of the existing literature that describes incineration and landfilling, which are the two main treatment methods assessed in this study, is presented in Table 9. The net GWP of incineration of MSW and RDF from this study is at the higher end in comparison to that presented in the literature. This is most likely the result of the lack of heat recovery from incineration in Hangzhou. Similarly, the net GWP of landfilling waste is greater than the average in the literature, which can be primarily attributed to the relatively low LFG collection rate in the Tianziling landfill and the lack of LFG collection in the Liugongduan landfill.

Table 9. Net emission factors of MSW and RDF management LCA studies.

	GWP kgCO2,eq./t	Acidification gSO2,eq,/t	Eutrophication gPO4,eq./t	Reference
Landfill				
MSW	-69 - 162	-	-	(Manfredi et al., 2009)
MSW	490	-440	-	(Arena et al., 2003)
OFMSW	843	104	-	(Evangelisti et al., 2014)
MSW	234	-	-	(Hupponen et al., 2015)
MSW	595 - 1311	127-374	86	(Cherubini et al., 2009)
Incineration				
MSW	-844 - -126	-	-	(Astrup et al., 2009)
MSW	390	-	-	(Arena et al., 2015)
MSW	46	-4600	-	(Arena et al., 2003)
RDF	95	-3660	-	(Arena et al., 2003)
RDF co-combustion	-1 512 - 563	-	-	(Astrup et al., 2009)
MSW	-92 - 140	-	-	(Hupponen et al., 2015)
MSW	273	2370	354	(Chaya and Gheewala, 2007)

4. Conclusions

The life cycle assessment study presented in this paper demonstrated that the environmental situation in Hangzhou could be improved by changing the MSW management system that is currently employed in the area. The highest improvement potential arises from producing RDF that is of a higher quality than the original MSW for energy recovery. However, the benefits gained may be easily diminished if the organic reject from RDF production is landfilled. To prevent this, the organic reject from RDF production should, instead, be used in energy recovery; e.g., by anaerobic digestion. In addition, the environmental situation in Hangzhou could be improved even further if the waste incineration plants combined heat and power production to produce heat for industry. Still, the main problem in Hangzhou is linked to inefficient source separation, especially in relation to food waste, which deteriorates the quality of any MSW that is directed to incineration. Reducing the share of food waste would mean that the heating value of MSW would be higher, more electricity from the incineration could be produced, the auxiliary coal in waste incineration could be reduced, less reject from the RDF would be produced, and RDF production energy demand would be lower. In conclusion, technologically advanced systems could partly improve the environmental situation, while officials from Hangzhou’s

MSW management should treat educating the general public about the benefits of source separation as a top priority.

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References

Arena, U., Ardolino, F., Di Gregorio, F., 2015. A life cycle assessment of environmental performances of two combustion- and gasification-based waste-to-energy technologies. Waste Manag. 41, 60–74.

Arena, U., Mastellone, M.., Perugini, F., 2003. The environmental performance of alternative solid waste management options: a life cycle assessment study. Chem. Eng. J. 96, 207–222.

Astrup, T., Moller, J., Fruergaard, T., 2009. Incineration and co-combustion of waste: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 789–799.

Chaya, W., Gheewala, S.H., 2007. Life cycle assessment of MSW-to-energy schemes in Thailand. J. Clean. Prod. 15, 1463–1468.

Chen, X., Geng, Y., Fujita, T., 2010. An overview of municipal solid waste management in China. Waste Manag. 30, 716–724.

Cherubini, F., Bargigli, S., Ulgiati, S., 2009. Life cycle assessment (LCA) of waste management strategies: Landfilling, sorting plant and incineration. Energy 34, 2116–2123.

Chi, Y., Dong, J., Tang, Y., Huang, Q., Ni, M., 2014. Life cycle assessment of municipal solid waste source-separated collection and integrated waste management systems in Hangzhou, China. J. Mater. Cycles Waste Manag. 17, 695-706.

Cleary, J., 2009. Life cycle assessments of municipal solid waste management systems: A comparative analysis of selected peer-reviewed literature. Environ. Int. 35, 1256–1266.

Coventry, Z.A., Tize, R., Karunanithi, A.T., 2016. Comparative life cycle assessment of solid waste management strategies. Clean Technol. Environ. Policy 18, 1–10.

Dong, J., Chi, Y., Zou, D., Fu, C., Huang, Q., Ni, M., 2014a. Energy–environment–economy assessment of waste management systems from a life cycle perspective: Model development and case study. Appl. Energy 114, 400–408.

Dong, J., Chi, Y., Zou, D., Fu, C., Huang, Q., Ni, M., 2014b. Comparison of municipal solid waste treatment technologies from a life cycle perspective in China. Waste Manag. Res. 32, 13–23.

Dong, J., Ni, M., Chi, Y., Zou, D., Fu, C., 2013. Life cycle and economic assessment of source-separated MSW collection with regard to greenhouse gas emissions: a case study in China. Environ. Sci. Pollut. Res. Int. 20, 5512–24.

Ekvall, T., Assefa, G., Björklund, A., Eriksson, O., Finnveden, G., 2007. What life-cycle assessment does and does not do in assessments of waste management. Waste Manag. 27, 989–996.

Evangelisti, S., Lettieri, P., Borello, D., Clift, R., 2014. Life cycle assessment of energy from waste via anaerobic digestion: A UK case study. Waste Manag. 34, 226–237.

Fernández-Nava, Y., del Río, J., Rodríguez-Iglesias, J., Castrillón, L., Marañón, E., 2014. Life cycle assessment of different municipal solid waste management options: a case study of Asturias (Spain). J. Clean. Prod. 81, 178–189.

Finnveden, G., 1999. Methodological aspects of life cycle assessment of integrated solid waste management systems. Resour. Conserv. Recycl. 26, 173–187.

Hagberg, L., Särnholm, E., Gode, J., Ekvall, T., Rydberg, T., 2009. LCA calculations on Swedish wood pellet production chains. Stockholm.

Hangzhou Municipal Solid Waste Disposal center, 2014. Development report of the MSW treatment in Hangzhou (In Chinese).

Hupponen, M., Grönman, K., Horttanainen, M., 2015. How should greenhouse gas emissions be taken into account in the decision making of municipal solid waste management procurements? A case study of the South Karelia region, Finland. Waste Manag. 42, 196–207.

IPCC, 2014. Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Core Writing Team, R.K. Pachauri and L.A. Meyer (eds.)]. IPCC, Geneva, Switzerland, 151 pp.

ISO 14040, 2006. Environmental management. Life cycle assessment. Principles and framework.

ISO 14044, 2006. Environmental management — Life cycle assessment — Requirements and guidelines.

Laurent, A., Bakas, I., Clavreul, J., Bernstad, A., Niero, M., Gentil, E., Hauschild, M.Z., Christensen, T.H., 2014. Review of LCA studies of solid waste management systems - Part I: Lessons learned and perspectives. Waste Manag. 34, 573–588.

Manfredi, S., Tonini, D., Christensen, T.H., Scharff, H., 2009. Landfilling of waste: accounting of greenhouse gases and global warming contributions. Waste Manag. Res. 27, 825–836.

Nasrullah, M., Vainikka, P., Hannula, J., Hurme, M., Kärki, J., 2015. Mass, energy and material balances of SRF production process. Part 3: solid recovered fuel produced from municipal solid waste. Waste Manag. Res. 33, 146–56.

National Bureau of Statistic of China, 2014. China Statistical Yearbook 2013. 8-20 Collection, Transport and Disposal of Consumption Wastes in Cities by Region (2013) (in Chinese).

National Bureau of Statistic of China, 2005. China Statistical Yearbook. 2005. 12-12 Collection, Transport and Disposal of Consumption Wastes in Cities by Region (2004) (in Chinese).

Nielsen, O.-K., Lyck, E., Mikkelsen, M.H., Hoffman, L., Gyldenkærne, S., Winther, M., Nielsen, M., Fauser, P., Thomsen, M., Plejdrup, M.S., Illerup, J.B., Sørensen, P.B., Vesterdal, L., 2008. Denmark’s National Inventory Report 2008. Aarhus.

Nielsen, P.H., Oxenbøll, K.M., Wenzel, H., 2007. Cradle-to-gate environmental assessment of enzyme products produced industrially in denmark by novozymes A/S. Int. J. Life Cycle Assess. 12, 432–438.

Thinkstep, 2015. Gabi 6 Software-System and database for Life Cycle Engineering. Copyright, TM. Stuttgart, Echterdingen.

Turner, D.A., Williams, I.D., Kemp, S., 2016. Combined material flow analysis and life cycle assessment as a support tool for solid waste management decision making. J. Clean. Prod. 129, 234–248.

Zhang, D.-Q., He, P.-J., Shao, L.-M., 2009. Sorting efficiency and combustion properties of municipal solid waste during bio-drying. Waste Manag. 29, 2816–23.

Zhang, D.Q., Tan, S.K., Gersberg, R.M., 2010. Municipal solid waste management in China: Status, problems and challenges. J. Environ. Manage. 91, 1623–1633.

Zhao, W., der Voet, E. Van, Zhang, Y., Huppes, G., 2009a. Life cycle assessment of municipal solid waste management with regard to greenhouse gas emissions: Case study of Tianjin, China. Sci. Total Environ. 407, 1517–1526.

Zhao, Y., Wang, H.-T., Lu, W.-J., Damgaard, A., Christensen, T.H., 2009b. Life-cycle assessment of the municipal solid waste management system in Hangzhou, China (EASEWASTE). Waste Manag. Res. 27, 399–406.

Zhao, W., Huppes, G., van der Voet, E., 2011. Eco-efficiency for greenhouse gas emissions mitigation of municipal solid waste management: a case study of Tianjin, China. Waste Manag. 31, 1407–15.

5. Supplementary material

5.1. SI1 Waste transport

Table SI1.1 Transportation distances of MSW, fly ash and cement for ash treatment.

	MSW	Fly ash	Cement
Truck capacity (t)	5	5	5
Lvneng (km)	31	78	75
Qiaosi (km)	32	38	32
Yahang (km)	43	78	78
Xiasohan (km)	65	118	116
New plants (km)	43	78	78
Tianziling (km)	51	-	-
Liugongduan (km)	102	-	-

5.2. SI2 Landfill of MSW

Table SI2.1 Emissions of bulldozer in landfill (VTT, 2012).

Emission	kg/kg diesel
CO	0.01065
HC	0.00367
NOx	0.02367
PM	0.00154
CH4	0.00017
N2O	0.00008
SO2	0.00002
CO2	3.08521

5.3. SI3 Incineration of MSW

Table SI3.1 Hangzhou MSW incineration plant information (Hangzhou Municipal Solid Waste Disposal center, 2014).

Name	Lvneng	Qiaosi	Yuhang	Xiaoshan
Technology	grate	fluidized bed	fluidized bed	fluidized bed
Capacity (t/d)	450	800	600	1200
Fly ash disposal	solidification and landfill	solidification and landfill	solidification and landfill	solidification and landfill
Starting operation	2004	2002	1998	2007

Table SI3.2. Metal recycling emission credits (Thinkstep, 2015).

	GWP $kg_{CO2,eq}/t$	Acidification $kg_{SO2,eq}/t$	Eutrophication $kg_{Phosphate\ eq}/t$
Steel	1 500	4	0.10
Aluminum	7 900	45	2

The CO_2 emissions from incinerating waste resulting from the fossil carbon in waste are accounted in life cycle assessment. The CO_2 emissions from biogenic carbon of biodegradable waste is not included as it is considered to be carbon neutral. The fossil carbon in the waste was calculated using the data in table SI3.3 and MSW composition in Hangzhou.

Table SI3.3. Data used for calculating fossil carbon content of MSW in Hangzhou (Bjarnadóttir et al., 2002; Finnveden et al., 2000).

		Plastic	Textile	Food waste	Paper	Wood
Moisture content		1 %	10 %	70 %	10 %	1 %
Carbon content (CC)	of TS	59 %	56 %	50 %	43 %	50 %
Fossil carbon (FC)	of C	100 %	50 %	0 %	0 %	0 %

$$w_{FC} = \sum_{i}^{N} m_i * (1 - w_{H2O,i}) * w_{CC,i} * w_{FC,i}$$

, where

w_{FC} share of fossil carbon in waste (%)
m_i share of waste fraction i in waste (%)
$w_{H2O,i}$ moisture content of waste fraction i (%)
$w_{CC,i}$ share of carbon of waste fraction i (%)
$w_{FC,i}$ share of fossil carbon content of waste fraction i (%)

5.4. SI4 Mechanical treatment

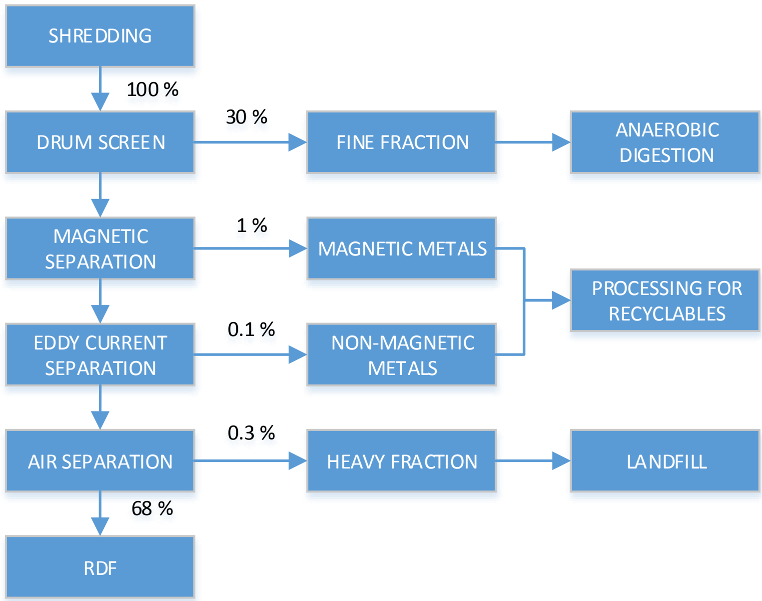

Figure SI4.1. Mechanical treatment line used for RDF production.

Table SI4.1. Recovery rate of RDF line (calculated from Nasrullah et al., 2015).

	Pre-screen	Metal	Eddy	Air separation
Food waste	48 %	0 %	0 %	0 %
Paper	3 %	0 %	0 %	0 %
Plastic	7 %	1 %	0 %	1 %
Textile	4 %	0 %	0 %	0 %
Wood and bambu	7 %	1 %	0 %	1 %
Metal	8 %	56 %	19 %	13 %
Glass	83 %	0 %	0 %	0 %
Mixed	12 %	0 %	0 %	0 %

Table SI4.2. Calculated RDF and organic reject composition.

	RDF (%)	Organic reject (%)
Food waste	43	88
Paper	16	1
Plastic	26	4
Textile	1	0
Wood and bamboo	4	1
Metal	0	0
Glass	0	3
Mixed	10	3

5.5. SI5 Organic reject treatment

5.5.1. SI5.1 Biodrying of organic reject.

Table SI5.1. LCI data of biodrying process, input and output properties (Ragazzi et al., 2007; Zhang et al., 2009).

Biordying process		
Energy use	0.153	MJ/kg reject
Organic degredation	35	% of organic
Water evaporation	68	% of water
Input: wet organic reject		
Moisture content	63	%
Organic content	69	% of TS
Output: dried organic reject		
Moisture content	42	%
Ash content	13	% of TS
Fossil C content	0.050	kg /kg dried reject

5.5.2. SI5.2 Anaerobic digestion of organic reject.

Table SI5.2. LCI data of anaerobic digestion, biogas utilization and digestate dewatering (Angelidaki et al., 2006; Berglund and Börjesson, 2006; Davidsson et al., 2007; Havukainen et al., 2014; Møller et al., 2002; Nielsen et al., 2008).

Anaerobic digestion		
Electricity use	0.07	MJ/kg
Heat use	0.09	MJ/kg
CH_4 yield	0.34	m3/kg VS
Moisture content in reactor	90	%
Gas motor		
Electric efficiency	40	%
Heat efficiency	40	%
Emission CH_4	0.323	g/MJ
Emission N_2O	0.0005	g/MJ
Dewatering digestate		
Electricity use	0.0162	MJ/kg
TS separation to dried fraction	80	%
TS content of dried fraction	30	%
N separation to solid fraction	26	%

Table SI5.3. LCI of pile composting of dewatered digestate (Boldrin et al., 2009; Brown and Subler, 2007; Brown et al., 2008; Bustamante et al., 2013).

Input properties		
TS	30	%
N	1.4	% of TS
C	48	% of TS
Composting		
Diesel use	5	l/ t MSW
Organic degradation	58	%
Compost water content	60	%
Emissions		
CH_4	2.5	% of degraded C
N_2O	0.7	% of input N

Table SI5.4 Emissions of front end loader used at the composting plant (VTT, 2012).

Emission	kg/kg diesel
CO	0.0092
HC	0.0030
Nox	0.026
PM	0.0013
CH4	0.00018
N2O	0.00008
SO2	0.00002
CO2	3.1

5.5.3. SI5.3 Ethanol production from organic reject.

Table SI5.5. LCI data used in calculating ethanol production from organic reject (Kim et al., 2011; Koike et al., 2009).

Input properties		
Sugar content	35.9	% of TS
Ethanol production		
Alpha-amylase	0.0003	kg/kg sugar
Glucoamylase	0.001	kg/kg sugar
Electricity use	0.56	MJ/ kg EtOH
Heat use	8.3	MJ/ kg EtOH
Ethanol yield	0.45	kg/kg sugar
Stillage	0.59	kg/kg food waste

Table SI5.6 Alpha amylase and glucoamylase production emissions (Nielsen et al., 2007).

	Alpha-amylase	Glucoamylase	
Global warming	1	7.5	kg CO_2,eq./kg
Acidification	0.00500	0.024000	kg SO_2,eq./kg
Nutrient enrichment	0.00150	0.02200	kg PO_4,eq./kg

Table SI5.7. LCI data of dry anaerobic digestion of stillage (Bolzonella et al., 2006; Koike et al., 2009).

Input properties		
Moisture	67	%
Organic content	69	% of TS
Anaerobic digestion		
Methane yield	0.4	m^3/kg VS
Electricity use	0.259	MJ/kg