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Greenhouse Gas Emissions Analysis Working toward Zero-Waste and Its Indication to Low Carbon City Development

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Abstract: Low carbon city development and greenhouse gas (GHG) emission mitigation in urban communities are urgent. There is great potential to improve the GHG inventory at the community level. Meanwhile, building zero-waste cities and improving waste treatment efficiency have been significant environmental issues due to the rapid increase of waste generation. This research aims to develop a community-scale GHG emission inventory of the waste sector and improve its accuracy and consistency through applying the bottom-up approach. This study covers both direct and indirect emissions categories of the waste sector with the goal of building a zero-waste community. Honjo Waseda community, located in Japan, was used as a case study community. Energy consumption waste treatment sectors were evaluated and calculated through first-hand field data. GHG emission estimation of the waste sector included waste incineration, residential wastewater, and waste transport. The highest emissions originated from Beisiagate supermarket due to the large waste amount produced, and the CO_2-biomass carbon emissions reached approximately 50% of the total emissions. Furthermore, a quantitative analysis of the implementation of new technologies was also conducted. This study created proposals for GHG emission reduction toward a zero-waste community through the comparison of three cases. Case 1 was business as usual; Case 2 proposed a combination of incineration bio-gasification (MBT); Case 3 introduced a combination of solid recovered fuel (SRF) and a bio-gasification system. SRF contributed the most to emission reduction, and Case 3 exhibited the highest energy recovery. Furthermore, comparing the GHG emissions produced by the use of SRF for power generation and heat supply revealed that using SRF as a heat supply reduced more GHG emissions than using SRF for power generation.

Keywords: greenhouse gas; community-scale; zero-waste; waste treatment; low carbon city

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1. Introduction

According to the Intergovernmental Panel on Climate Change [1], emission reduction at the city level is an inevitable requirement to ensure that GHG are reduced to national target levels [2]. To accurately report GHG emissions and to provide reliable data for both policymaking and recommendation formulation to achieve individual activity emission reduction, an accurate and complete city-level GHG emission inventory is necessary [3]. In fulfilling the Paris Agreement, city authorities should establish a GHG emission inventory such that they can monitor and design strategies to reduce GHG emissions [4,5].

With the rapid development of urbanization and industrialization, the Municipal Solid Waste (MSW) amount increasing rapidly in the world. The waste sector's GHG emission inventories are commonly supported by available estimation methodologies and accessible software and hardware. In the last decades, landfill, compost, thermal conversion methods (incineration, pyrolysis, gasification), and biological conversion method (anaerobic digestion) were the most common waste treatment methods [6]. A city-level GHG emission inventory of waste sector should possess the following features: (1) it must facilitate the development of appropriate global warming mitigation recommendations and enable urban planning involving efficient urban supply chains and low-carbon civil construction at the governmental level [7,8]; (2) it must support city designers in determining GHG emission sources and analyzing the accurate proportion of city emissions [9]; (3) it must be replicable and easily adaptable to different data sets [10]; (4) it must be timely in its approach through the application of the latest activity data and avoid double counting, thus ensuring data source consistency [11]. However, currently, most community-level inventories are limited by data availability and reporting consistency [2].

Previous studies have applied top-down [12–14] and bottom-up [15,16] methods in the development of a city-level GHG emission inventory. The bottom-up method divides and solves the problem based on small and practical parts, which considers a finer spatial scale [17]. In addition, studies on low-carbon community contains a variety of contents that includes industry, agriculture, waste, business, and carbon market [18,19]. There have been a variety of studies focusing on different contents of MSW, such as sludge [20,21], food waste [22], wastepaper, and social community trust [23]. In addition, the MSW treatment evaluation includes environment performances such as GHG emission reduction and economic impacts, technology and its application, integrated MSW treatment systems [24,25]. In addition, energy recovery from waste is a significant process of the treatment [26]. Waste-to-energy (WTE) processes recover the energy from the waste, that have been widely used in the MSW treatment. Therefore, the improvement of energy recovery efficiency from MSW has taken on great importance [27,28]. In addition, more and more researchers began to discuss the combination of system and integration with other industrial processes [29]. However, the scope framework and top-down method has not been suitably applied in previous studies, which are about analysis working toward waste in low carbon community.

The main objective of this study is to estimate the GHG emissions of the waste treatment sector using a bottom-up approach. This study considered the incineration, residential wastewater, and transport of the waste. The Honjo Waseda community in Japan, in which emissions are increasing, was used as a case study community. This study follows Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) guidelines [1], and quantity analyses were conducted through Statistical Product and Service Solutions (SPSS) software. After estimating the GHG emissions, mitigation reductions were analyzed for three case settings. Case 1 was a scenario in which all municipal solid waste (MSW) was incinerated. Case 2 was the combination of the incineration of combustible waste and the bio-gasification of food waste. In Case 2, automated sorting technology was applied to separate the two different types of waste. Case 3 was mechanical biological treatment (MBT), which combined refuse-derived solid recovered fuel (SRF) and the bio-gasification of food waste through the application of automated sorting technology.

This study comprises five sections. Section 1 provides an overview of the global trends in the GHG emission inventory development of waste treatment. Section 2 presents GHG emission accounting methods and data sources. Section 3 contains a demonstration of a waste sector GHG emission inventory outcome at the community level and offers proposals to reduce these GHG emissions. Section 4 contains the discussion. Section 5 contains the conclusion of the study.

2. Materials and Methods

2.1. Background Analysis of the Case Study Community

The estimation was conducted through a bottom-up methodology based on the waste treatment amount. The Honjo Waseda community, located in the Saitama Prefecture in Japan, was selected as a case study community. The GHG emissions of the case study community are increasing according to the Saitama government [30]. The GHG emissions were analyzed and illustrated in Figure 1. It is found that the emissions from 2014 to 2018 have been increased, with the increasing rate of 0.18%, 26%, 3.01% and 4.38%. In addition, we also found that the CGAR (compound annual growth rate) of the emissions during 2014–2018 was 6%. Hence, it is essential for Honjo city to draw attention to GHG reduction at community level as it is the basic unit for achieving the zero-emission goal in Japan.

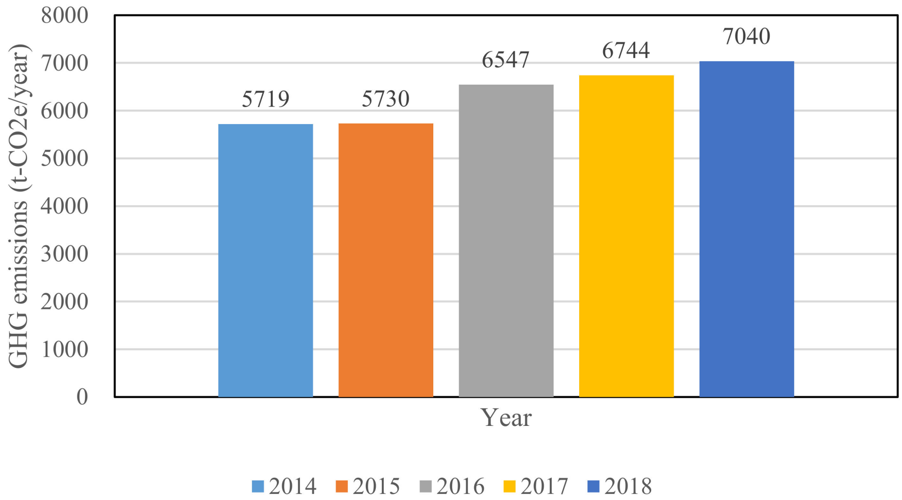


Figure 1. GHG emissions of Honjo city.

The waste produced per person per day in Honjo community is higher than the prefecture average. For example, in 2014, Honjo produced 1161 g/person/day and Saitama prefecture produced 897 g/person/day, and the population was 79,873 people. In 2015, Honjo produced 1154 g/person/day and Saitama prefecture produced 884 g/person/day, and the population was 77,881 people.

An analysis of the data provided by the Koyamagawa Clean Centre (Koyamagawa Clean Centre, 2018) revealed that the proportion of paper in the incinerated waste ranked the highest at around 40%, followed by plastic (27%), wood (13%), and food waste and unburnable waste. Details are illustrated in Table 1.

Table 1. Waste category and its percentage.

Waste Category	Percentage	Reference	Year
Paper	40%	Koyamagawa Clean Centre	2018
Plastic (Include Synthetic resin)	27%	Koyamagawa Clean Centre	2018
Wood	13%	Koyamagawa Clean Centre	2018
Food Waste	7%	Koyamagawa Clean Centre	2018
Unburnable waste	4%	Koyamagawa Clean Centre	2018
Others	9%	Koyamagawa Clean Centre	2018

2.2. Estimation of Emissions Originating from Incineration

This research estimated the GHG Emissions from the waste sector from three perspectives, which are emissions from incineration, sewage and transportation. In addition, each facility of the case study area (Honjo Waseda community) is calculated from those three perspectives. In addition, all the emissions calculated of the waste sector belongs to Scope 3 according to the Global Protocol for Community-Scale Greenhouse Gas Emission Inventories (GPC) guideline since the waste are treated outside the community and emitted without the community boundary; details are illustrated in Table 2.

Table 2. Estimation contents of inventory entries.

Calculation Contents	Location of Facilities	Scope
Incineration Sewage Transportation of waste	Cainz office	3
	JA office	3
	Beisiagate	3
	Honjo Campus	3
	Kanraku Hotel	3
	Honjo Senior high school	3
	Residents	3

Information pertaining to Honjo garbage treatment was collected from Honjo city [31]. The amount of waste recycled by the incineration facility was 6613 t/year. The amount of waste treated by the incineration facility was 228 t/day, of which the amount of human waste was 150 t/day. Furthermore, the resource recycling amount of utilization facilities was 1468 t/fiscal year. The estimation of emissions from incineration was conducted by analyzing the waste categories. The waste amount in each category in the facility was estimated by the number of people in the community. Then, following Equation (1), the emissions from paper, fiber, wood, food waste, unburnable waste, and plastic were estimated.

Paper, food waste, and other biomass waste (plant material and wood) were calculated in this study according to GPC guidelines [1], which include category i. According to the GPC, MSW is generally defined as waste collected by municipalities or other local authorities. MSW typically includes food waste, garden and park waste, paper and cardboard, wood, textiles, disposable diapers, rubber and leather, plastics, metal, glass, and other materials (e.g., ash, dirt, dust, soil, and electronic waste). Estimation of the no biogenic emissions originating from waste incineration of waste is described below.

$$E_{GHG} = \sum i(W_a \times P_{wc} \times I_w) \quad (1)$$

where E_{GHG} is GHG Emission, W_a is the fraction of waste amount of type i matter, P_{wc} is the parameter of waste amount in the type i matter, I_w is the fraction of waste index of type i matter, and i is the matter type of the solid waste incinerated such as paper, fiber, wood, food waste, unburnable waste, plastic.

The basic information on facilities in Honjo Waseda community were collected and analyzed through the application of the bottom-up method. First, in order to improve the data accuracy of waste amount, parameters of waste categories (e.g., paper, fiber, wood, food waste, unburnable waste, plastic) were collected according to governmental data accessibility based on city scale from small to big, which are Honjo city, Saitama city, Ichikawa city, and Tokyo city (see Table 3). Second, according to the above parameter and the waste amount of each facility (field data), the amounts in detailed waste category are estimated (illustrated in Table 4). Third, through applying the waste index as illustrated in Table 5, the GHG emissions of each waste category is calculated.

Table 3. Parameter of waste category in each facility.

Facility Category	Paper	Fiber	Wood	Food Waste	Unburnable Waste	Plastic	Others
Office **	47.20%	0.00%	0.00%	28.00%	19.80%	2.00%	-
Supermarket ****	4.00%	0.00%	0.00%	82.00%	-	1.50%	3.60%
Schools [32] *	59.32%	3.43%	1.76%	12.79%	7.27%	15.43%	3.43%
Hotel *	33.00%	0.00%	0.00%	37.90%	-	4.00%	29.50%
Residents ***	34.80%	7.60%	0.00%	36.80%	14.40%	13.60%	13.30%

* Honjo city data; ** Saitama city data; *** Ichikawa city government data; **** Tokyo city government data; - no data.

Table 4. Waste amount of each waste category for each facility (ton/year).

Facilities	Waste Amount	Paper	Fiber	Wood	Food Waste	Unburnable Waste	Plastic	Others
Cainz Office	2.12	22.96	0.00	0	0.00	0.00	0.00	0.00
JA Office	17.07	65.81	0.00	0	0.00	0.00	0.00	0.00
Beisiagate	0.00	105.91	0.00	0	2171.14	0.00	39.72	95.32
Waseda campus	0.00	39.73	2.30	1.18	8.57	4.87	10.33	2.30
Honjo senior high school	0.00	50.75	2.93	1.51	10.94	6.22	13.20	0.42
Kanraku Hotel	0.00	17.30	0.00	0	20.11	0.00	2.12	15.66
Residents	0.00	43.68	9.54	0	46.19	18.07	17.07	7.15

Table 5. Index applied in the study.

Category	Index	Unit	Reference
Paper	0.08	tCO2/t	IPCC guideline
Fiber	2.29	tCO2/t	IPCC guideline
Wood, bamboo	0.08	tCO2/t	IPCC guideline
Food waste	3.00	tCO2/t	IPCC guideline
Unburnable waste	0.08	tCO2/t	IPCC guideline
Plastic	2.77	tCO2/t	IPCC guideline

2.3. Estimation of Emissions Originating from Residential Wastewater

Residential wastewater includes CH_4 and N_2O emissions, according to IPCC guideline [1]. The estimated contents of both CH_4 and N_2O include residential wastewater treatment, urine, septic tanks, non-flush toilets, flush toilet wastewater purifiers, and combined processing. The equations applied for analysis are shown in Equation (2) [1]. In details, the treatment amount and reference are shown in Table 6. The units, emission factors (including units), and t-CO_2/year (exchanged) amounts are shown in Table 7, according to IPCC guideline [1] in which 1 ton equals 1000 kgs.

$$E_{GHG} = A_{ta} \times EF \tag{2}$$

where E_{GHG} is GHG Emission. A_{ta} means activity data of treatment amount, and EF stands for emission factor.

Table 6. Activity data of treatment amount and reference.

Items	Treatment Amount	Reference
The residential wastewater treatment	5.70	Field data
Urine	3.54×10^3	Saitama prefecture
Septic tank	3.30×10^4	Saitama prefecture
Merger processing	2.18×10^4	Saitama prefecture
Non-flush toilet	4.76×10^3	Saitama prefecture
Flush toilet wastewater purifier	1.60×10^4	Saitama prefecture

Table 7. Emission factors of CH_4 and N_2O.

Gas	Items	Treatment Amount	Emission Factors	Unit	t-CO_2e/Year (Exchanged)
CH_4	The residential wastewater treatment	5.70	8.8×10^{-7}	t-CH_4/m^3	1.05×10^{-4}
	Urine	3.54×10^3	5×10^{-6}	t-CH_4/kL	3.72×10^{-1}
	Septic tank	3.3×10^4	5×10^{-6}	t-CH_4/kL	3.46
	Merger processing	2.18×10^4	1.1×10^{-3}	t-CH_4/person	5.04×10^2
	Non-flush toilet	4.76×10^3	8.76×10^{-4}	t-CH_4/person	8.76×10
	Flush toilet wastewater purifier	1.6×10^4	8.76×10^{-4}	t-CH_4/person	2.95×10^2

Table 7. *Cont.*

Gas	Items	Treatment Amount	Emission Factors	Unit	t-CO_2e/Year (Exchanged)
N_2O	The residential wastewater throughput	5.7×10^0	1.6×10^{-7}	t-N_2O/m^3	2.83×10^{-4}
	Urine reason	3.54×10^3	7.83×10^{-6}	t-N_2O/kL	8.59
	Septic tank	3.3×10^4	1.68×10^{-6}	t-N_2O/kL	17.2
	Merger processing	2.18×10^4	2.60×10^{-5}	t-N_2O/person	176
	Non-flush	4.76×10^3	5.77×10^{-6}	t-N_2O/person	8.52
	Flush toilet wastewater purifier	1.6×10^4	5.77×10^{-6}	t-N_2O/person	28.7

2.4. Estimation of Emissions Originating from Waste Transport

For waste transport, we applied the data obtained from Honjo city government and Kodama Cleaning Company [33]. The annual number of collection time of vehicles was 96. The vehicle capacity per time was 2t, and there were 1231 vehicles per year. Furthermore, the travel distance of a vehicle per collection was 23.1 km.

The emissions included CH_4 and N_2O emissions, which were calculated following Equations (3) and (4), respectively. The routes of waste transport included those extending from the Kodama Cleaning Firm to the Honjo Waseda community, from the Honjo Waseda community to the Koyamakawa Cleaning Center, and from the Koyamakawa Cleaning Center to the Kodama Cleaning Firm.

$$tN_2O\ (round\ way) = T_d(km/vehicle/Ct)\ {}^*EF_n\ {}^*N_v{}^*Ct. \tag{3}$$

$$tCH_4\ (round\ way) = T_d\ (km/vehicle/Ct)\ {}^*EF_C\ {}^*N_v{}^*Ct. \tag{4}$$

where T_d is travel distance (km/vehicle/collection time), C_t means collection time in a year, N_v is the number of vehicles in a year, EF_n is emission factor of N_2O emission (tN_2O/km), and EF_C stands for emission factor of CH_4 emission (tCH_4/km).

3. Results and Proposals

3.1. Results

Beisiagate supermarket produced the most GHG emissions due to waste treatment because of its high garbage emissions. In details, as illustrated in Figure 2, the Beisiagate supermarket (1466 t-CO_2e/year) was followed by Honjo Senior High School (92 t-CO_2e/year), Kanraku Hotel (73 t-CO_2e/year), Waseda University (48 t-CO_2e/year), JA office (19 t-CO_2e/year), residents (13 t-CO_2e/year) and Cainz (7 t-CO_2e/year). Among all emissions, it was found that the CO_2-biomass carbon natural and CO_2 -non-biomass occupied around 49.4%, including food waste, paper, and wood, while CH_4 and N_2O occupied 0.2% and 1.0%, respectively.

With regard to incineration, Beisiagate supermarket ranked the highest (21.8t-CO_2e/day), followed by Honjo Senior High School, Waseda campus, and Kanraku hotel. As illustrated in Table 8, it was found that paper was the largest GHG emitter for Cainz office, JA office, Waseda campus, and Honjo Senior High School. Moreover, food waste was the largest emitter for Beisiagate supermarket and Kanraku Hotel.

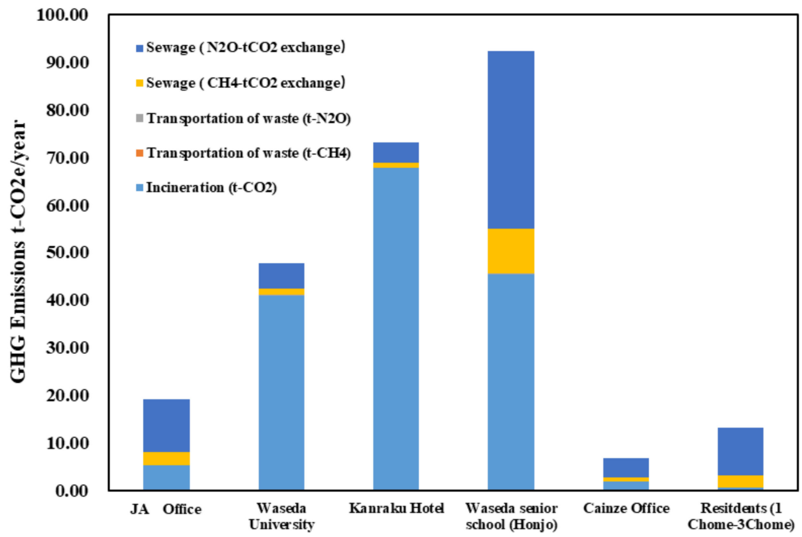


Figure 2. GHG Emissions of waste treatment sector in Honjo Waseda.

Table 8. GHG emissions of each building (t-CO_2e/day).

Category	Cainz Office	JA Office	Beisia-Gate	Waseda Campus	Honjo Senior High School	Kanraku Hotel
Paper	5.03×10^{-3}	1.44×10^{-2}	0.00×10^{0}	2.71×10^{-1}	3.46×10^{-1}	3.79×10^{-3}
Fiber	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	1.33×10^{-2}
Wood, bamboo	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	3.43×10^{-3}
Food waste	0.00×10^{0}	0.00×10^{0}	2.18×10^{1}	0.00×10^{0}	0.00×10^{0}	1.65×10^{-1}
Un-burnable waste	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	5.16×10^{-3}	6.60×10^{-3}	0.00×10^{0}
Others (Plastic)	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}	0.00×10^{0}
Total	5.03×10^{-3}	1.44×10^{-2}	2.18×10^{1}	2.76×10^{-1}	3.53×10^{-1}	1.86×10^{-1}

For residential wastewater, the annual CH_4 (890 t-CO_2e) emissions were higher than the annual N_2O (239 t-CO_2e) emissions. Combined processing produced the most emissions, accounting for 57% of CH_4 and 74% of N_2O; details are illustrated in Table 9.

For waste transport, it was found that the amount of CH_4 emissions for (round tripper vehicle per time) t-CO_2e conversion was 0.03 t-CO_2e. In addition, the amount of N_2O emissions for (round tripper vehicle per time) t-CO_2e conversion was 1.14 t-CO_2e.

Table 9. GHG emissions overview of residential water.

Waste Category	Emission Amount (CH_4)	Emission Amount (N_2O)
Merger processing	504.00	176.00
Flush toilet wastewater purifier	295.00	28.70
The residential wastewater treatment	87.60	8.52
Urine	0.37	5.69
Septic tank	3.46	17.20
Non-flush toilet	1.05×10^{-4}	0.00

3.2. GHG Reduction Proposal for the Waste Treatment Sector

This research evaluated waste treatments from the waste collection and recycling, transport, and treatment perspectives through a bottom-up method. Honjo Waseda community was used as a case study to offer proposals. A life cycle assessment (LCA) was applied for the assessment of CO_2 emissions and the primary energy consumption. Furthermore, a series of MSW processes were evaluated that ranged from collection and recycling to final use and disposal treatments. An environmental load evaluation database of incineration and melting (including the input and output amounts at different treatment scales and power generation efficiency) was compiled based on the plant maker's design and estimated values. This enabled the calculation of indices for the recycling rate, energy expended in the recycling process, and final disposal treatment for different evaluation scenarios.

In order to reduce GHG emissions generated by incineration and achieve zero-waste for building low carbon cities, this study proposed three cases for comparison and provided an overview of the current situation of MSW and food waste treatment in Honjo Waseda community. Case 1 was business as usual (BAU), in which it was assumed that there was no difference between Case 1 and the current waste treatment system. Case 2 proposed an option that combined the incineration of combustible waste and bio-gasification for food waste treatment. In this case, automated sorting technology was applied to separate two different types of waste.

This application was able to effectively connect a bio-gasification system and sewage treatment facilities in order to solve the following issues: (1) creating a connection between sewage treatment and the cement factory; (2) the collection of food waste in the areas with a centralized system; and (3) creating the heat supply from both biogas and waste plastic after waste treatment. Case 3 was the combination of SRF and bio-gasification in food waste treatment, namely an MBT system. In this case, the SRF was used to replace fossil fuel, such as coal, and the food waste was separated, collected, and treated using fermentation. The MBT system is a type of waste processing facility that combines a sorting facility with a form of biological treatment such as composting or anaerobic digestion. MBT plants are designed to process mixed household waste as well as commercial and industrial wastes. After separation and machine selection, food waste is used for power generation through fermentation, while other waste plastic becomes SRF for heat use in cement manufacturing factories. The generated electricity in these cases will be used in the city. Figure 3 describes the treatment processes for the four MSW treatment scenarios.

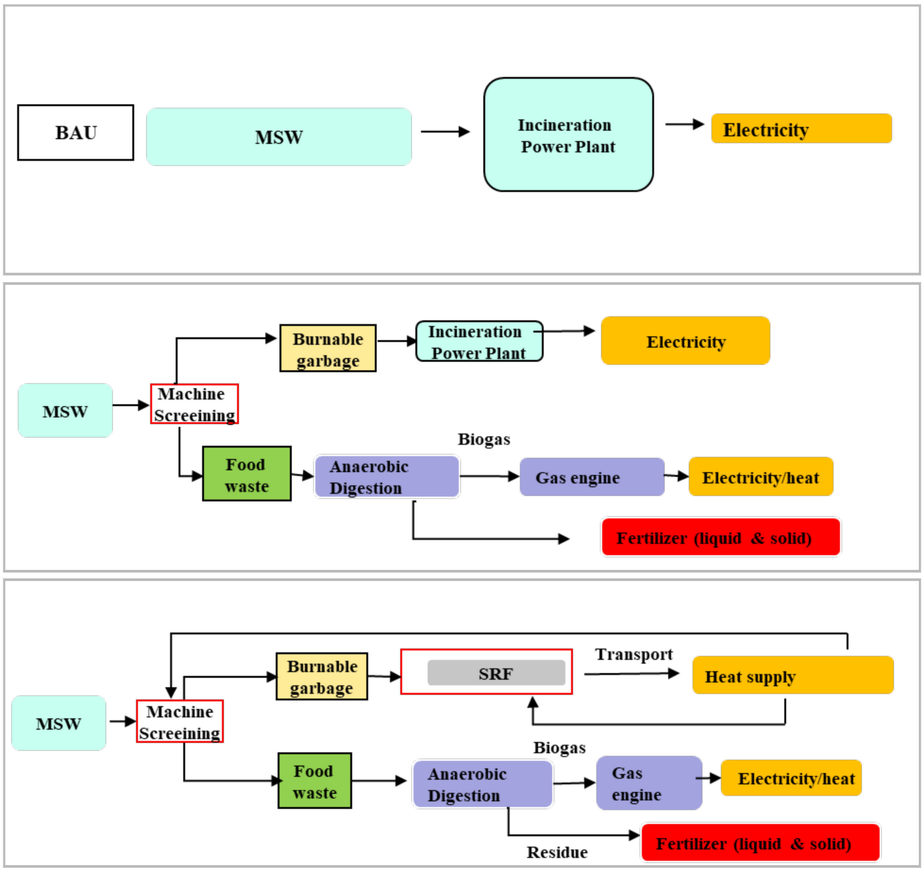


Figure 3. Case configuration.

3.3. Outcome of Proposals of Case Studies

The waste incineration amount and primary energy consumption were estimated using the LCA method. The details of the energy conversion index are illustrated in Table 9. For energy consumption, it was found that the SRF in Case 3 contributed the most for energy recovery. The energy conversion index and GHG factors, with references that were applied in this study, are applied in Tables 10 and 11, respectively. Furthermore, waste amount of each case in Honjo Waseda community and primary energy consumption are illustrated in Tables 12 and 13.

Table 10. Energy Conversion Index.

Item	Unit	Value
Electricity	MJ/kWh	9.75
Lamp oil	MJ/L	36.7
SRF	MJ/kg	17.4
Biogas	MJ/Nm^3	22.6

Table 11. GHG Emission factors.

Items	Factor	Unit	Reference
Electricity consumption	5.55×10^{-4}	tCO_2/kWh	MOE
kerosene	0.07	tCO_2/GJ	MOE
SRF	1.62	tCO_2/t	MOE
Biogas power generation	5.55×10^{-4}	tCO_2/kWh	MOE
Incineration power generation	5.55×10^{-4}	tCO_2/kWh	MOE
Incineration of waste (MSW)	2.75	tCO_2/t	MOE
A heavy oil	0.07	tCO_2/GJ	MOE
Heavy oil consumption for waste incineration	760.00	L/t waste of incineration	MOE
Calorific value of heavy oil	39.10	GJ/kl	MOE

Note: MOE means Ministry of the Environment (Japan).

Table 12. Waste amount of Case 1, Case 2 and Case 3.

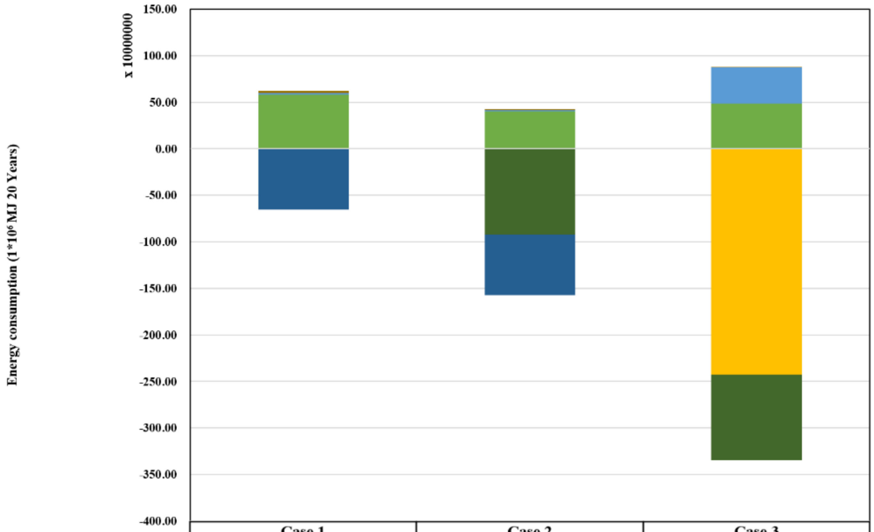
Item	Case1	Case 2	Case 3	Unit	Reference
Food waste	5.59	0	0	ton/day	Field data
Waste incineration amount	79.88	74.29	74.29	ton/day	Field data
Sewage treatment amount	0	0	46.58	ton/day	Field data
SRF	0	0	24.89	ton/day	Field data
Biogases	0	1300.02	0	Nm^3/ton waste	Field data

Table 13. Details of primary energy consumption.

Items	Case 1 (MJ/Year)	Case2 (MJ/Year)	Case3 (MJ/Year)
Electricity consumption	5.82×10^8	4.33×10^8	8.61×10^8
Kerosene	1.43×10^7	1.43×10^7	3.88×10^8
SRF	0	0	-2.61×10^9
Biogas power generation	0	-9.20×10^8	-9.20×10^8
Incineration power generation	-6.52×10^8	-8.10×10^8	0

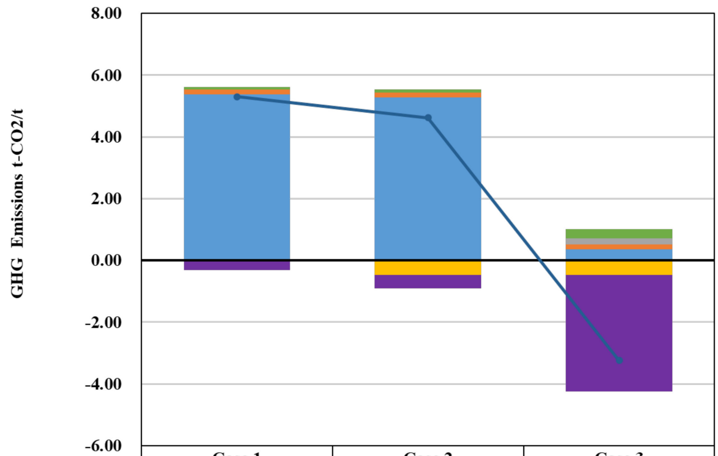
It was found that the incineration amount was largely reduced by applying the MBT (Case 2) system. In Case 1 (the BAU scenario), the electricity consumption was 582 GJ, the kerosene consumption was 14.3 GJ, the incineration power generation was −652 GJ, and the electricity consumption was 582 GJ. Details are illustrated in Table 10. In this study, the waste treatment facilities are assumed to operate 280 days/year and work for 20 years.

For the energy consumption outcomes, the output of Case 3 was the largest, and was generated mainly by the energy production of SRF (Figure 4). It was found that the energy input and output of current situation (Case 1) are almost equal. Regarding the GHG emissions, as shown in Figure 5, it was found that Case 3 contributed to GHG reduction most, while incineration accounted for a large proportion of the emissions in Case 1 and Case 2.



	Case 1	Case 2	Case 3
Sludge (residents)	2.42×10^{7}	8.60×10^{6}	8.60×10^{6}
Power generation (output)	-6.52×10^{8}	-6.52×10^{8}	0.00×10^{0}
Energy production (Biogas)	0.00×10^{0}	-9.20×10^{8}	-9.20×10^{8}
Energy production (SRF)	0.00×10^{0}	0.00×10^{0}	-2.42×10^{9}
Kerosene	1.43×10^{7}	1.33×10^{7}	3.88×10^{8}
Electricity consumption (input)	5.82×10^{8}	4.03×10^{8}	4.84×10^{8}

Figure 4. Primary energy consumption of each case.



	Case 1	Case 2	Case 3
Transport	0.09	0.09	0.29
power generation and heat supply	-0.32	-0.42	-3.77
Biogas	0.00	-0.48	-0.48
Incineration (SRF)	0.00	0.00	0.20
Incineration (Sludge)	0.16	0.16	0.16
Incineration	5.37	5.27	0.36
Total	5.30	4.62	-3.24

Figure 5. Outcome of GHG emissions of each case.

To improve energy efficiency and further reduce GHG emissions, this study also analyzed the changes in power generation efficiency. The estimation was based on applying the calorific value, energy conversion index, and GHG emission factor of waste. It was found that the GHG reduction ranged from 5% to 20% depending on power generation efficiency. When compared with heat supply, the GHG reductions generated from SRF power generation were higher than SRF heat supply when the efficiency changed (Table 14). Therefore, we recommend using SRF for heat supply rather than power generation.

After applying the bottom-up methodology in the case study area (Honjo community), it was found that the developed methodology filled the research gaps of the community GHG inventory. It is shown that the developed energy consumption-based methodology enabled calculation of GHG emissions within and without the community. Furthermore, it was proven that the developed bottom-up methodology is applicable for providing an essential basis and waste GHG emission outcome for policy making through proposals and performed case analyses toward zero-waste.

Table 14. SRF using for power generation and heat supply.

Power Generation Efficiency	GHG Emission Reduction (For Power Generation)	GHG Emission Reduction (For Heat Supply)	Unit
5%	0.13	3.77	t-CO_2e/t SRF
10%	0.26	3.77	t-CO_2e/t SRF
15%	0.39	3.77	t-CO_2e/t SRF
20%	0.52	3.77	t-CO_2e/t SRF

4. Discussion

In this study, we estimated GHG emission, which included waste incineration, sewage, and transport. Through applying the bottom-up method, it was found that the highest emissions were from Beisiagate supermarket and that the CO_2-biomass carbon neutral emissions reached approximately 50% of the total emissions. The Beisiagate supermarket emitted 21.8t-CO_2e/day for waste incineration. For waste transport, it was found that the emissions (round trip) for t-CO_2e conversion was 1.16 t-CO_2e/year, CH_4 was 0.0285 t-CO_2e (CO_2 conversion), and N_2O was 1.14 t-CO_2e (CO_2 conversion). In addition, for residential wastewater, the CH_4 emissions (890 t-CO_2e) were higher than the N_2O emissions (239 t-CO_2e) annually.

Different from relevant studies, this study estimates the GHG emissions of the waste treatment sector at a community level. In addition, compared with other studies that apply the top-down approach, this study estimated the wastes emissions from incineration, residential wastewater and waste transport through a bottom-up approach, which is more accurate and based on field data. Moreover, mitigation reductions were analyzed for three case settings in this study. Meanwhile, compared with other communities in Japan, the waste recycling rate of Honjo Waseda community was much lower, especially the food waste. Traditional solid waste treatment has formed a relatively complete recycling industry chain, and the wastepaper, waste plastic, and other varieties of domestic waste had a high recycling rate. However, waste glass [34,35], waste batteries [36,37], and other varieties of waste had a considerably lower recycling rate with low added value.

This study proposes the introduction of automated sorting technology in order to accelerate the MBT system. Therefore, machine screening as source sorting [38,39] and waste reduction are the first priorities. Increasing the rate of source sorting will also increase the classification and profitable recycling of waste materials. Furthermore, this research also suggests each community to adapt to local conditions and combine national special planning to further promote the reduction of MSW generation, reduce and control the environmental impacts of the MSW treatment process, and optimize the waste collection, transportation, and disposal process from the perspective of the entire life cycle. Moreover, this study recommends that municipalities consider other factors that influence decision making in planning as well as the zero-waste policy in future years. For instance, the financial situation of the current municipalities, the projected electricity sale price and population trends.

In addition, zero waste has been recognized as an essential strategy according to the Circular Economy Vision 2020 by the Ministry of Economy, Trade and Industry (METI, Japan, 2020) [40]. The virtuous cycle of the environment is significant for promoting the 3Rs (reuse, reduce, recycle) toward building zero-waste cities. In addition, five areas that need special attention in terms of the 3Rs are plastics, fibers, carbon fiber reinforced polymers, batteries, and solar panels. It is estimated that, by Japan's Ministry of Environment on Japan's environmental industry, this market has reached a record size of approximately 105.3 trillion JPY in 2017 [41].

Regarding building a zero-waste city, the policy implications of global carbon emission reduction, including applying renewable energy such as photovoltaic, wind, nuclear, hydropower, chemical energy storage, and carbon capture utilization and storage (CCUS), [42,43] are expected. Furthermore, the improvement of the incineration rate and the application of a centralized incineration system will increase the power generation efficiency and reduce GHG emissions in the community. Moreover, with the waste separation policy, food waste will contribute to the MTB (combined methane fermentation and SRF) system implementation in cities. Bio-gasification has improved, and the capacity is much higher than in some developed communities.

5. Conclusions

This study estimated and analyzed GHG emissions working toward zero-waste and its indication to low carbon city at a community level. Unlike existing studies, this study aimed to fill the research gaps from the following perspectives: (1) this research provided a variety of analyses and offered proposals for the development of GHG estimation at the community level in the waste sector through a bottom-up method; (2) this study designed estimation methods that included emissions within and without the community; (3) this study provided a detailed inventory and proposals for each building type through a bottom-up methodology and performed case analyses.

Through estimating and analyzing GHG emission from waste incineration, sewage, and transport, the outcome demonstrated that the highest emissions were produced by the Beisiagate supermarket, and the CO_2-biomass carbon neutral emissions reached approximately 50% of the total emissions. For incineration, the Beisiagate supermarket ranked the highest (2.18×10^1 t-CO_2e/day), and for residential wastewater, the CH_4 emissions (890 t-CO_2e) were higher than the N_2O emissions (239 t-CO_2e), annually. Moreover, for waste transport, it was found that the emissions (round trip) per time was 0.02 t-CO_2e, and annual emissions of the community was 2.33 t-CO_2e. Furthermore, because most waste was treated using incineration, this study conducted a case study and offered proposals for its reduction of incineration. In detail, case 1 was the current situation, case 2 was incineration + a bio-gasification system, and case 3 was SRF + a bio-gasification system (MBT). It was shown that the SRF contributed the most GHG reduction, and Case 3 resulted in the highest energy recovery.

To expand upon the results of this study, future research will include other communities with different characteristics in order to conduct comparative analyses and apply other technological options for GHG reduction. Furthermore, data visualization and database creation for software application and urban policy assessments will be conducted. Moreover, different local factors such as culture and resource endowments should be considered. Other topics, such as regional collaboration among surrounding communities, more detailed economic feasibility studies of innovative options, urban-industrial symbiosis, and the effect of consumer behavior on GHG emissions with the aim of zero waste, deserve further study. Furthermore, the cost–benefit perspective of waste treatment facility construction costs will be considered.

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