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Original Paper

Scenario Analysis on Greenhouse Gas Emission for Waste-to-Energy Alternatives in Japan

LE Hoang Son[1,2] & Yasuhiro MATSUI[1*]

[1] Graduate School of Environmental and Life Science, Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama, 700-8530, Japan

[2] Danang University of Science and Technology, University of Danang, 54 Nguyen Luong Bang, Lien Chieu, Danang, Vietnam

[*] Yasuhiro MATSUI, Yasuhiro MATSUI, Graduate School of Environmental and Life Science, Okayama University, 3-1-1 Tsushima-naka, Kita-ku, Okayama, 700-8530, Japan

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Abstract

This study focuses on Greenhouse Gas (GHG) emissions and reductions of Municipal Solid Waste (MSW) incineration. The authors aim to estimate the detailed composition of GHG emissions and reductions from the waste incineration facility and their influence factors using two Japanese databases on the operation of incinerators from Japan Ministry of the Environment (1,243 facilities) and Japan Waste Research Foundation (814 facilities). The databases cover detailed data on MSW amount and characteristics, specifications of the facility, annual utility consumption, and annual energy/material recovery. The authors analyze the correlations among them and develop predictive models for the detailed components of GHG emissions and reductions.

Japan Ministry of the Environment intended to group small municipalities for replacing small-scale incinerators to large-scale Waste-to-Energy (WtE) facilities with a higher energy recovery efficiency. Based on the abovementioned data and models, the authors estimate the expected effects of the block formation and major technological alternatives for GHG mitigation by the national level.

The current net GHG emission rate from 1,243 operating waste incineration plants in Japan in 2009 was estimated to be 653 kgCO_2*e/t. In the block formation, 1,007 plants were assumed to be closed; 236 kept operating; and 286 facilities would be newly built. The net GHG emission rate could be cut off to 454 kg*CO_2*e/t by applying the block formation and technological alternatives with a higher energy recovery efficiency (stalker furnace with power generation by extraction condensing turbine providing steam higher than 3MPa and 300 C). Ash melting caused a larger GHG emission by the increase in* *energy consumption. The GHG reduction by slag recycling was limited.*

Furthermore, the net GHG emission rate could be reduced to 242 kgCO_2e/t by applying the Best Available Technique (BAT) for combined heat and power plants. When compared with the current status, BAT can reduce 185 kgCO_2e/t by improving the power generation efficiency and 187 kgCO_2e/t by expanding heat utilization. At present, heat utilization is very limited in Japan, but heat utilization should be more focused and promoted for GHG mitigation decisions.

Keywords

Waste-to-Energy (WtE), waste incineration, Greenhouse Gas (GHG), turbine generator efficiency, multilinear regression model, Scenario analysis

1. Introduction

Along with the dramatic increase in population, change of consumption style, economic development, and rapid urbanization, Municipal Solid Waste (MSW) has become a large burden in Japan. Among the common methods used for treating MSW, waste incineration has received increased attention because of its properties of waste volume reductions and hygienic problem prevention (Psomopoulos et al., 2009). Since the introduction of the first waste incineration plant in Japan in 1924, the waste incineration technology has developed and expanded over the years.

In the past, the main benefits of waste incineration were to reduce the waste in mass and in volume to save the limited landfill site, as well as prevent sanitary problems (Gohlke & Martin, 2007). Nowadays, the technological improvement in the incineration field together with the increasing energy content in waste, affected by the change in the consumers' habits, has led to an additional attractiveness of energy recovery from waste incineration (Calabrò & Stehlók, 2012). With the goal of global warming prevention mission, Greenhouse Gas (GHG) mitigation has recently become one of the major objectives in the MSW management system. The national GHG inventory report of Japan for 2012 has stated that 20,874 thousand tons of CO_2e was emitted from the waste sector (accounted for 1.7% of Japan's total GHG emissions), of which 14,356 thousand tons of CO_2e was from waste incineration (represented 1.1% of the national total emissions) (*National Greenhouse Gas Inventory Report of Japan*, 2012).

As some studies confirmed, Waste-to-Energy (WtE) facilities reduced GHG emissions from the MSW treatment system by energy/material recovery processes (Murphy & McKeogh, 2004; Rand et al., 2000; Stehlók, 2012; Tabata, 2013). Japan Ministry of the Environment (JMOE) has intended to expand the introduction of the WtE facility and improve the energy recovery efficiency to establish the Sound Material-Cycle Society. JMOE has also promoted the introduction of the ash-melting process for material recovery and reductions of landfill amount.

However, the detailed breakdown of GHG emissions of the WtE facility and their influence factors, such as waste characteristics and specifications of the facility, have not been analyzed in detail. As Lombardi et al. mentioned the basic data on the waste incineration plant performance was still limited in the scientific literature about energy recovery from waste. They suggested that publication with real plant data should be encouraged (Lombardi et al., 2015).

In present study, the authors aimed to investigate the detailed composition of GHG emissions from the WtE facility and their relating factors using two Japanese databases on the operation of incinerators from JMOE and Japan Waste Research Foundation. The databases cover detailed data on the MSW amount and characteristics (annual treated waste amount, waste composition, calorific value, etc.), specs of the facility (scale, type of furnace, operation hours, type of ash melting, etc.), utility consumption (electricity, fuels and water), and annual energy/material recovery (annual power generation amount, annual heat recovery, annual slag amount, etc.). The authors analyzed the correlations among them and tried to develop predictive models for the detailed components of GHG emissions and reductions.

JMOE intended to group small municipalities for replacing small-scale incinerators to large-scale WtE facilities with higher energy recovery efficiency to promote GHG mitigation. All 47 prefectures have issued plans for block formation by small municipalities for MSW management. Based on the abovementioned data and models, the authors estimated the expected effect of the block formation for GHG emissions by a national level. The effects of major technological options were also discussed.

2. Methodology

2.1 System Boundary and Calculation Condition

This study focuses on the GHG emissions and reductions of the MSW incineration process. The authors included the following components of GHG emissions and reductions:

(1) direct CO_2 emissions from waste burning: CO_2 emissions from fossil plastic burning and synthetic textile burning

(2) direct CO_2 emissions from fossil fuels: CO_2 emissions from burning fossil fuels

(3) direct CH_4 and N_2O emissions from waste burning: methane gas (CH_4) and dinitrogen monoxide (N_2O) releasing from the combustion chamber

(4) indirect CO_2 emissions by utility consumption: CO_2 emissions from the production of electricity, fuels, and water used at the facility

(5) indirect CO_2 reductions by energy recovery: CO_2 reductions by saving energy by power generation and heat utilization at the facility

(6) indirect CO_2 reductions by slag recycling: CO_2 reductions by recycling slag from ash melting

The GHG emissions and reductions were calculated by the amount of each GHG component multiplied by the corresponding GHG emissions factors (Table 1). The GHG emission factors were extracted from the Japan Environmental Management Association for Industry, “2006 IPCC Guidelines for National Greenhouse Gas Inventories”, and “National Greenhouse Gas Inventory Report of Japan 2012” (Guendehou et al., 2006; *National Greenhouse Gas Inventory Report of Japan*, 2012).

The function unit was defined as the management of 1 ton of combustible waste.

2.1 Dataset on the Incineration Facility

The authors aimed to investigate the detailed composition of the GHG emissions from the WtE facility and their relating factors using two Japanese databases on the operation of incinerators from JMOE and Japan Waste Research Foundation (JWRF).

Regarding the former database, JMOE has conducted a survey of all the incineration facilities for MSW every year. The survey items included the MSW amount and characteristics (annual treated waste amount, waste composition, calorific value, etc.), specs of the facility (scale, type of furnace, operation hours, type of ash melting, etc.), and annual energy/material recovery (power generation amount, heat recovery).

Regarding the latter database, JWRF has conducted a detailed survey for a part of the incineration facilities for MSW every year until 2010. The survey items covered the annual treated amount, utility consumption (electricity, fuels and water), detailed technological parameters (scale, type of furnace, operation hours, type of turbine, steam condition, type of ash melting, etc.), and annual energy/material recovery (power generation amount, heat recovery, slag amount, etc.).

The authors analyzed the data in 2009, which is the data from the last survey year of the JWRF database. The numbers of facilities from the JMOE and JWRF databases were 1,243 and 814, respectively.

2.2 Analytical Process

The authors intended to clarify the influence factors for the GHG emissions and reductions.

Regarding the direct GHG emission components, the authors calculated the direct CO_2 emissions from waste burning (e.g., fossil CO_2 from plastic) based on the waste composition data for each facility in the JMOE and JWRF databases. The authors applied the emission factors for the direct CH_4 and N_2O emissions from waste burning (Table 1). The global warming potential from the IPCC AR4 was applied herein for methane and dinitrogen monoxide gases. The global warming potential for 100 years was applied to calculate the total GHG emissions by CO_2 equivalent. The authors did not consider the influence factors for the direct CO_2 emissions from waste burning and the direct CH_4 and N_2O emissions from waste burning. The direct CO_2 emissions from fossil fuels were calculated together with the indirect CO_2 emissions from fuels, as will be described later.

Regarding the indirect GHG emissions and reduction components, the authors estimated the indirect CO_2 emissions by utility consumption, indirect CO_2 reductions by energy recovery, and indirect CO_2 reductions by slag recycling by the amount of each GHG component multiplied by the corresponding GHG emission factors (Table 1). The authors also calculated the averages of the utility consumption rates and the energy/material recovery rates using the following major technological parameters: scale, type of furnace, operation hours, type of turbine type, steam condition, with/without ash melting, and with/without power generation. The analysis of variance (ANOVA) and rank correlation analysis by Spearman method were applied to judge whether significant differences existed. The needed data was extracted from the JWRF database that covered utility consumptions, energy/material recovery, and detailed technological parameters.

The mathematical modeling for the utility consumption rates and the energy/material recovery rates was then implemented through a multi-regression analysis. The significant influence factors by ANOVA were used as candidates for explanatory variables. The outliers were detected and excluded by Cook's distance criterion (D > 4/n (n is the sample size)) (Cook & Weisberg, 1982).

The R 3.3.0 program was applied for the statistical analyses.

Table 1. GHG Emission Factors Applied in This Study

Process	Component	Inventory	Direct emission factor	Indirect emission factor	Source
Operation	Fossil plastic burn	CO_2	Plastic burning: 2.69 tCO_2/t Synthetic textile: 2.29 tCO_2/t		JMOE
Operation	Fossil fuel burn	CO_2	Heavy oil: 0.0693 tCO_2/GJ Light oil: 0.0687 tCO_2/GJ Kerosene: 0.0679 tCO_2/GJ Coke: 0.108 tCO_2/GJ City gas: 0.0498 tCO_2/GJ LPG: 0.0595tCO_2/GJ Gasoline: 0.0671 tCO_2/GJ	Heavy oil: 0.0096 tCO_2/GJ Light oil: 0.008 tCO_2/GJ Kerosene: 0.0073 tCO_2/GJ Coke: 0.0206 tCO_2/GJ City gas: 0.0105 tCO_2/GJ LPG: 0.0149 tCO_2/GJ Gasoline: 0.0142 tCO_2/GJ	JEMAI
Operation	CH_4/N_2O from the combustion process	CH_4, N_2O	Continuous incinerator: 2.6 gCH_4/t Semi-continuous incinerator: 20.6 gCH_4/t Batch incinerator: 13.4 gCH_4/t Gasification: 7.0 gCH_4/t Continuous incinerator: 37.9 gN_2O/t Semi-continuous incinerator: 72.7 gN_2O/t Batch incinerator: 76.0 gN_2O/t Gasification: 11.2 gN_2O/t		JMOE
Operation	CH_4/N_2O from the combustion process	CH_4, N_2O	GWP (100-yr) of CH_4: 25 GWP (100-yr) of N_2O: 298		IPCC
Utility consumption	Power Water	CO_2		Power: 0.555 tCO_2/MWh Water: 0.99$kgCO_2/m^3$	JMOE
Energy/ material recovery	Power generation Heat utilization	CO_2		Power: −0.555 tCO_2/MWh Steam: −0.06 tCO_2/GJ	JMOE

Slag recycling		Slag: $-0.0044\ tCO_2/t$	JEMAI

JMOE: *Japan Ministry of the Enivronment: Reference material for calculating GHG emissions (In Japanese)*.

IPCC: Al., 2007.

JEMAI: JEMAI, 2014.

3. Results and Discussion

3.1 Outline of Incineration in Japan in 2009

The database of JMOE in 2009 showed that 1,243 operating facilities were among the 1,345 incinerators in Japan. Table 2 shows the number of waste incineration facilities in Japan in 2009 by capacity and applied technology.

Table 2. Outline of the Operating Incinerators in Japan (2009)

	Operation hours			Furnace type							
Capacity*(tons/day)	Continuous	Semi continuous	Batch	Stalker incinerator	Fluidized bed incinerator	Shaft gasification	Other gasification	Other	With power generation	With ash melting	Total
Cap ≤ 100	121	200	363	472	99	15	15	83	12	51	684
100<Cap≤150	140	32	-	117	31	15	8	1	35	23	172
150<Cap≤200	102	3	-	70	20	7	8	-	29	15	105
200<Cap≤300	131	-	-	104	13	3	11	-	81	36	131
300<Cap≤450	73	-	-	48	14	6	5	-	58	21	73
450<Cap≤600	57	-	-	52	2	2	1	-	57	24	57
600<Cap≤800	6	-	-	5	-	1	-	-	6	3	6
800<Cap≤1000	9	-	-	9	-	-	-	-	9	2	9
1000<Cap≤1400	4	-	-	4	-	-	-	-	4	1	4
1400<Cap≤1800	2	-	-	2	-	-	-	-	2	1	2
Total	645	235	363	883	179	49	48	84	296	177	1,243

*The category of the capacity follows the definition of JMOE for governmental support.

Source: Japan Ministry of the Environment database 2009 (In Japanese).

The incinerators with a capacity smaller than 100 tons/day accounted for more than half of the total number of MSW incinerators in Japan (n=684, 55%). Gohlke and Martin explained that the direct landfill was limited in Japan because of the lack of space. Thus, the municipal solid waste was incinerated in a high number of small plants (Gohlke & Martin, 2007). However, the treated waste amount by these small incinerators was 4,988 thousand tons, which is only 14% of the 35,523 thousand tons of total incinerated waste.

Regarding the operation hours, “Continuous (24-hour operation)” was 52% of the total facilities, followed by “Batch (8-hour operation)” and “Semi-continuous (16-hour operation)”. For the furnace type, “Stalker incinerator” was widely applied (71%), which could be explained by some of the advantages of the stalker incinerator (e.g., no need for prior sorting or shredding; the technology is widely used and thoroughly tested for waste incineration; meets the demands for technical performance; can accommodate a large variation in the waste composition and calorific value; and allows for an overall thermal efficiency of up to 85%) (Rand et al., 2000). Castaldi and Themelis also affirmed that the technology of the stalker incinerator with a mobile grate combustor has reached a high level of development (Castaldi & Themelis, 2010).

The incinerators with power generation were only 296 plants and especially limited for smaller facilities. Tabata mentioned that approximately 80% of the MSW in Japan was incinerated, but only 24.5% of the MSW incineration plants applied energy recovery (Tabata, 2013). Tanigaki et al. explained that one of the main objectives of waste management in Japan was reducing the buried volume at the landfill. They also mentioned that the treatment of the MSW incinerator bottom ash, such as melting, had higher priority before landfilling because of the strict regulation of environmental management in Japan (Tanigaki et al., 2012). The ash melting process was applied to 177 plants (9%).

3.2 Outline of Combustible Waste in Japan in 2009

MSW is a heterogeneous mixture of several materials. Its compositions and characteristics are affected by cultural differences, climate, socio-economic conditions, and the recycling policy (Bandara et al., 2007; Calabrò, 2010; Rand et al., 2000; Stehlók, 2012; Thanh et al., 2010).

According to the JMOE database in 2009, the combustible waste generation rate in Japan was 899 g/cap/day. “Paper and textile” was dominant in the waste composition (49.1%, n=1,095), followed by “plastic and leather” (20.2%, n=1095), and “biogenic waste” (15.4%, n=1,095). “Combustible”, “moisture”, and “ash” accounted for 42.3% (n=1,095), 47.9% (n=1,095), and 9.7% (n=1,095), respectively. According to the JWRF database in 2009, the “plastic” content was 18.5% (n=373), while the “synthetic textile” content was 13.1% (n=171).

The Lower Heating Value (LHV) of waste is the key parameter for the waste incineration operation. Komilis et al. mentioned that MSW can be incinerated without auxiliary fuels when its LHV exceeds 5–7 GJ/t (Komilis et al., 2014). Tanner suggested that the mass content of combustible waste must be higher than 25%, while moisture and ash must be lower than 50% and 60% for self-combustion, respectively (Tanner, 1965). Referring to these criteria, MSW in Japan was suitable for the incineration process. The LHV of the combustible waste was 8.5±1.9GJ/t (mean±standard deviation), which contained high calorific potential for the WtE facility.

3.3 Utility Consumption and Influence Factors

Using the JWRF database, the authors calculated the averages of the utility consumption rates through the major technological parameters. Table 3 summarizes the results of the energy consumption rate by technological options.

The power consumption rate of the MSW incineration plants was significantly different (F=24.9, $p<0.001$) among the types of furnace. “Shaft gasification” had the highest consumption rate with 371±125 KWh/t, followed by “other gasification” (343±106 KWh/t), “incineration with ash melting by electricity” (298±111 KWh/t), and “incineration without ash melting” (187±137 kWh/t). The BREF/Best Available Technique (BAT) reported that the process energy demand of incineration plants was60 to 700 kWh/t. The major power-consuming parts of the incinerator were the induced draught fan (30%), forced draught fan (20%), delivery and water pumps (20%), condenser (10%), and other equipment (20%). BREF/BAT also stated that the power consumption rate had a negative correlation with facility scale (Gabor Doka, 2005). Using the Pearson correlation analysis, the authors found a negative correlation between the power consumption rate and the facility capacity ($r= -0.121$; $p=0.013$; $n=424$).

The incineration plants also consumed some auxiliary fuels (e.g., diesel, heavy oil, gasoline, city gas, or liquefied petroleum gas). The authors calculated and presented the fuel consumption rate by GJ per ton of waste (GJ/t) based on the consumed amount and the calorific value of each fuel type. The fuel consumption rate of the MSW incineration plants was significantly different among the types of furnace (F=8.06; $p<0.001$). The gasification process consumed an additional amount of fuel to produce a syngas with the desired chemical composition and calorific value. Thus, the fuel consumption rates at the gasification facilities (2.25±0.28 GJ/t for “shaft gasification” and 1.03±0.20 GJ/t for “other gasification” plants) were much higher than those in the “incineration without ash melting” (0.07±0.01 GJ/t). “Incineration with ash melting by fuel” consumed 0.59±0.01 GJ/t of waste. The authors found a negative correlation between fuel consumption rate and scale ($r=-0.126$; $p=0.003$; $n=566$).

Table 3. Energy Consumption Rate by Technological Options

	Fuel consumption rate (GJ/t)		Power consumption rate (KWh/t)	
Technological options	n	Mean±SD	n	Mean±SD
Shaft gasification	35	2.25±0.28	25	371±125
Other gasification	36	1.03±0.20	27	343±106
Incineration with ash melting (fuel/electricity)	25	0.59±0.01	40	298±111
Incineration without ash melting	412	0.07±0.01	412	187±137
ANOVA (F value)		8.06***		24.9***

***$p < 0.001$.

Source: Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese), 2010.

The major water consumption in waste incineration plants was for flue-gas cleaning and steam production. The water consumption was reported to be 1 to 6 m^3/ton of waste and depended on the flue-gas cleaning system and re-circulating treated effluent of wastewater. The facilities without energy recovery consumed more water than the others (Gabor Doka, 2005). The authors used the data analysis and found a significant difference in the water consumption rate between the facilities with an energy recovery boiler (0.96±0.36 m^3/t, n=259) and those without (2.16±1.2 m^3/t, n=348) (F=200; p<0.001).

3.4 Energy/Material Recovery and Influence Factors

The possibilities of energy recovery depend on the local energy market conditions, including infrastructure for energy distribution (e.g., availability of a power grid, district heating network, and heat utilization facility nearby), price of various types of energy, and possible agreement with the consumer(s). According to the JMOE database, 296 incineration plants in Japan performed energy recovery, with a total electricity generation amount of 6,918,803 MWh. However, the power generation efficiency was still low with 10.9% of the national average.

Based on the analysis of the JWRF database, Table 4 shows the heat utilization rate from WtE incineration in Japan in 2009. The produced heat was used for the turbine generator for power generation, for onsite purposes (e.g., hot water, air condition, and road heating), and offsite purposes (i.e., heated pools and public facilities). The average percentage showed the allocated heat in the total heat for the target heat utilization. The results showed that the turbine generator at the facility with power generation consumed approximately 63.44% of the total input heat. Heat recovery was mainly used within the incineration plant (approximately 3.61% of the total input heat) because of the restrictions on the configuration and distance for supply. Moreover, as maller amount was provided to the local facility (approximately 1.75% of the total input heat). The heat supply for district heating was not common.

Using the JWRF database, the authors calculated the averages of the power generation rate and the power generation efficiency by utilizing the major technological parameters. Table 5 summarized the results. The Power Generation (PG) rate was found to be significantly different among the types of furnace through ANOVA (F=3.5; p=0.03). “Shaft gasification” was highest (347±243 kWh/t), followed by “other gasification” (347±243 kWh/t), “stalker incineration” (277±129 kWh/t), and “fluidized bed incineration” (206±90 kWh/t). The PG efficiency was also found to be significantly different among the types of furnace through ANOVA (F=5.5; p=0.007). Excluding the fluidized bed incinerator, the PG rates of the gasification plants were higher than that of the stalker incinerators. However, the turbine generator was similar among the three types of furnace. The reason for the difference in the PG rate would be the larger fuel consumption in the gasification plants.

Table 4. Heat Consumption by Heat Utilization

Heat utilization	Heat consumption rate (MJ/t)[a] n[b]	25% percentile	Mean	75% percentile	Average percentage of allocated heat in total heat (%)
Turbine generator	218	3,092	5,851	7,154	63.44
Onsite	542	141	332	877	3.61
Hot water	127	9	59	214	0.63
Air condition	47	6	31	128	0.34
Road heating	7	1	25	183	0.30
Others	59	17	77	426	0.84
Offsite	89	61	162	316	1.75
Heated pool	47	14	30	197	0.33
Public facility	5	23	90	460	0.81
Others	66	39	88	232	0.85

[a] Heat recovery from the incinerator boiler.

[b] Number of observed facility with available data.

Table 5. Power Generation Rate and Efficiency by Major Technological Parameters

Technological parameter	n	PG rate[a](KWh/t)	PG efficiency(%)	Turbine generator efficiency (%)
Furnace type				
Stalker incinerator	174	277±129	11.2±4.9	17.7±7.0
Fluidized bed incinerator	28	206±90	8.6±3.7	13.7±5.3
Shaft gasification	27	347±243	12.4±4.1	17.3±4.2
Other gasification	29	328±157	11.4±3.7	17.1±6.6
ANOVA (F value)		3.5*	5.5**	2.9*
Turbine type				
Back pressure	51	140±56	5.7±1.9	9.7±3.1
Condensing	120	271±138	10.8±3.5	16.7±4.5
Extraction condensing	87	386±119	11.2±4.8	22.0±6.0
ANOVA (F value)		107.0***	67.0***	90.6***
Steam condition				
Level 1 (≤2MPa)	94	186±85	7.8±3.7	12.8±5.2
Level 2 (>2MPa, >200 °C)	100	283±96	11.3±3.5	17.3±5.0
Level 3 (>3MPa, >300 °C)	64	423±175	15.7±3.7	23.7±17.1
ANOVA (F value)		90.7***	77.1***	78.1***

Rank correlation[b] (ρ)	0.538**	0.539**	0.517**

*p<0.05; **p<0.01; and ***p<0.001.

[a] PG: power generation and [b]rank correlation by the Spearman method.

Source: JWRF.

Table 5 also shows the averages of the PG rate and efficiency by turbine type. The PG rate of the "extraction condensing" turbine was highest (386±119 KWh/t), followed by the "condensing" turbine (271±138 KWh/t), and the "back pressure" turbine (140±56 KWh/t). Asignificant difference by turbine type was also found through ANOVA (F=107; p<0.001). This result was caused by different abilities of the turbine types. As regards the turbine design, the backpressure turbine was the simplest, and had the lowest cost compared to the other turbine types with the same scale. However, the backpressure turbine was not common at medium- and large-scale WtE plants in Japan because of its requirement of a stable inlet steam condition. In contrast, the condensing turbine is widely used for power generation facilities that want to supply electricity to consumers as much as possible. A vacuum condition occurring through the condensing process increases the turbine efficiency, thereby generating a high amount of electricity. However, the condensing turbine consists of many turbine stages and requires a large condenser, causing more construction activities and a higher maintenance cost. The extraction condensing turbine is a condensing turbine with two or more outlets for independently adjusting the electric power and the process steam flow. The extraction condensing turbine has features of both the condensing and backpressure turbines. It also has the capability of fulfilling the requirements of both electric power supply and process steam flow (Gabor Doka, 2005; *Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010; Rand et al., 2000; Tanuma, 2017). The extraction condensing turbine was applied for medium- and large-scale WtE plants in Japan. Kean et al. reported that the power generation efficiency of WtE incineration was affected by the turbine design (e.g., with/without condensing function). The same authors also stated that the condition of the supplied steam is one of the important factors in power generation. They noted that the greater the pressure and temperature drop through the turbine, the greater the amount of electricity that can be generated (Kean & Brickner, n.d.).

Figure 1 presents the distribution of the steam condition by turbine type using the JWRF database. The authors applied a cluster analysis for the data on steam pressure and temperature, then categorized the steam condition into three levels as follows:

- Level 1: the steam pressure is equal or less than 2MPa.
- Level 2: the steam pressure is from 2MPa to 3MPa, and the temperature is higher than 200 °C.
- Level 3: the steam pressure is higher than 3MPa, and the temperature is higher than 300 °C.

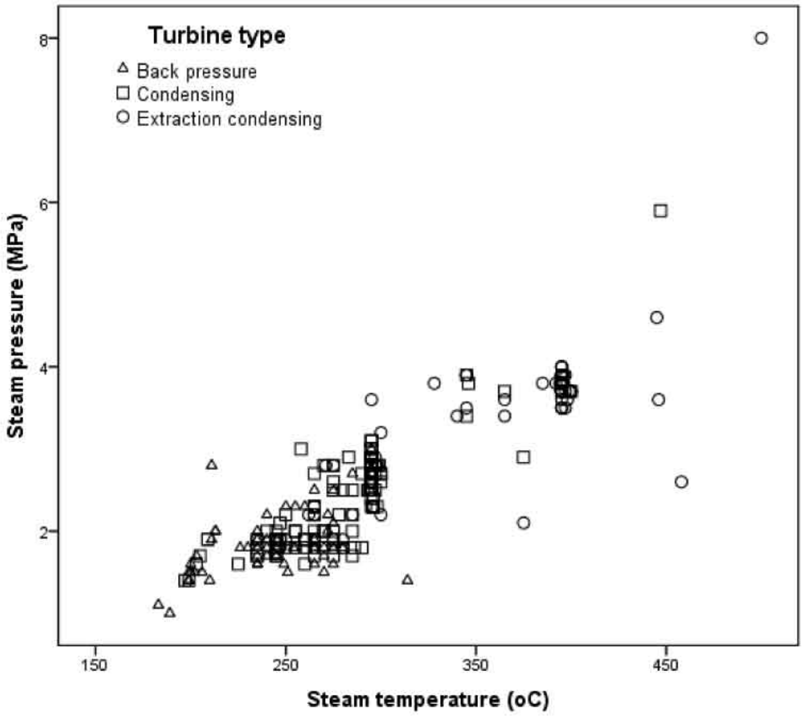

Figure 1. Distribution of Steam Condition and Turbine Type

As regards the steam condition, the PG rate at “Level 3” (423±175 KWh/t) was approximately two times higher than that at “Level 1” (186±85 KWh/t) and approximately 1.5 times higher than “Level 2” (283±96 KWh/t). These differences were found significant by ANOVA (F=90.7; p<0.001). According to the rank correlation analysis results by the Spearman method, the steam level and the PG rate had appositive correlation (ρ=0.538; p<0.01). The results were also similar to the PG efficiency by the steam condition.

The power generation efficiency is defined as the ratio between the useful electricity output from the generating unit in a specific time unit and the energy value of the primary energy source supplied to the unit within the same time. Different energy conversion processes have different thermodynamic limitations; hence, the power generation efficiency should not be compared with the energy sources that use different kinds of fuels (Rand et al., 2000; Stehlók, 2012; Tanuma, 2017). In the abovementioned energy consumption section, the “gasification” process consumed more fuels than the “incineration” process; thus, the PG efficiency at the “gasification” plants was significantly higher than that at the “incineration” plants. However, as regards the Turbine Generator (TG) efficiency, no difference was found between the “stalker incinerator” and the “gasification” plants.

Therefore, for further analyses, the authors would like to focus more on the technological parameters affecting the power generation by TG efficiency. The TG efficiency was significantly affected by the turbine type and the steam condition (p<0.001). Table 6 shows the turbine generator efficiency by turbine type and steam condition categories. The TG efficiency at “Level 2” (11.0±3.5%) for the “backpressure” turbine was higher than that at “Level 1” (9.7±3.4%). However, the authors could not find the significant difference (F=0.87; p=0.07). The TG efficiency for the “condensing” turbine was the highest at steam condition “Level 3” (19.6±4.0%), followed by “Level 2” (18.5±4.8%) and “Level 1” (14.4±4.2%). A significant difference was found (F=8.1; p=0.001). The rank correlation analyses by the Spearman method showed a positive correlation between the TG efficiency and the steam condition level (rank correlation=0.37; p<0.001). A positive rank correlation between the TG efficiency and the steam condition level (ρ=0.433; p<0.001) was observed for the “extraction condensing” turbine. At the same steam condition, the TG efficiency was the highest at the “extraction condensing” turbine, followed by the “condensing” and “backpressure” turbines. A significant difference was observed among the turbine types.

Table 6. Turbine Generator Efficiency (%) by Steam Condition and Turbine Type

	Steam condition						
	Level 1		Level 2		Level 3		ANOVA(F value)
Turbine type	n	Mean±SD	n	Mean±SD	n	Mean±SD	
Back pressure turbine	38	9.7±3.4	13	11.0±3.5	-	-	0.87
Condensing turbine	46	14.4±4.2	61	18.5±4.8	13	19.6±4.0	8.1**
Extraction condensing turbine	8	17.6±4.6	28	19.2±6.8	51	23.3±6.6	8.3**
ANOVA (F value)	20.3***		12.1***		4.9*		

*p<0.05; **p<0.01; and ***p<0.001.

Source: JWRF *Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010.

Regarding the ash melting function, the slag recycling rate by gasification (78 kg slag/ton of waste) was 53% higher than that of ash melting by electricity/fuel (51 kg slag/ton of waste). A significant difference was detected by ANOVA (F=8.3; p=0.044).

3.5 Mathematical Modeling for Utility Consumption and Energy Recovery

In reference to the results of the abovementioned analyses, the authors implemented mathematical modeling for the utility consumption and energy/material recovery rates using a multi-regression analysis. The significant influence factors by ANOVA were used as candidates for explanatory variables. Table 7 shows the definition of the objective and explanatory variables. Tables 8 and 9 present the multilinear regression models on the utility consumption and energy/material recovery rates.

As regards the fuel consumption rate of “gasification”, the dummy variables for “shaft gasification” and “power generation function” were selected as the explanatory variables. For the fuel consumption rate of “incineration”, the dummy variables for “ash melting by fuel” and “power generation function” were selected. Meanwhile, the dummy variables for "gasification furnace", "ash melting by electricity function", and "facility capacity" were selected as the positive predictors for the power consumption rate. "Capacity of facility" was selected as a negative predictor.

Regarding the TG efficiency, the authors separately developed two models for the "condensing" and "extraction condensing" turbines (Table 8). The dummy variables for the steam condition in both models (i.e., "Steam level 2" and "Steam level 3") and the capacities of the facility by steam condition (i.e., "Capacity of the facility with steam level 2" and "Capacity of the facility with steam level 3") were selected as predictors. The coefficients for the capacities of the facility were slightly larger at the models on the "extraction condensing turbine".

Table 7. Definition of Variables

	Variable	Factor	Range of variable
Response variable	Y_1	Fuel consumption rate (GJ/t)	
	Y_2	Power consumption rate (MWh/t)	
	Y_3	Water consumption rate (m^3/t)	
	Y_4	Turbine generator efficiency of the condensing turbine (%)	
	Y_5	Turbine generator efficiency of the extraction condensing turbine (%)	
Predictor variable	C	Constant	
	Cap	Capacity of facility (t/d)	0.1–1,000
	Gas	Gasification furnace	"Yes"=1; "No"=0
	Gas_{Shaft}	Shaft gasification furnace	"Yes"=1; "No"=0
	Gas_{Other}	Other gasification furnace	"Yes"=1; "No"=0
	AM_{fuel}	Ash melting by fuel	"Yes"=1; "No"=0
	$AM_{electricity}$	Ash melting by electricity	"Yes"=1; "No"=0
	PG	Power generation function	"Yes"=1; "No"=0
	St_2	Steam level 2 (>2MPa, >200 °C)	"Yes"=1; "No"=0
	St_3	Steam level 3 (>3MPa, >300 °C)	"Yes"=1; "No"=0

Table 8. Results of the Multilinear Regression Analyses for Utility Consumption

		Fuel consumption rate (gasification) (GJ/t)	Fuel consumption rate (incineration) (GJ/t)	Power consumption rate (kwh/t)	Water consumption rate (m^3/t)
Variable	Explanatory factor	β (Standard Error)			
C	Constant	1.214 (0.06)***	0.071 (0.01)***	216 (12)***	2.13 (0.05)***

Cap	Capacity of facility (t/d)			−0.14 (0.04)**	
Gas	Gasification furnace			155 (24)***	
Gas_{Shaft}	Shaft gasification furnace	0.222 (0.06)**			
AM_{fuel}	Ash melting by fuel		0.549 (0.002)***		
$AM_{electricity}$	Ash melting by electricity			236 (31) ***	
PG	Power generation function	1.261 (0.05)***	0.03 (0.001)**		−1.21 (0.08)***
n	Number of case	71	495	467	607
R^2	Coefficient of determination	0.885***	0.89***	0.371***	0.347***

* $p<0.05$, ** $p<0.01$ and *** $p<0.001$.

Table 9. Results of the Multilinear Regression Analyses for Energy Consumption and Recovery

		Turbine generation efficiency of the condensing turbine (%)	Turbine generation efficiency of the extraction condensing turbine (%)
Variable	Explanatory factor	β (standard error)	
C	Constant	14.7 (0.54)**	18.0 (0.8)***
St_2	Steam level 2 (>2MPa, >200 °C)	1.5 (0.7)**	0.6 (0.02)**
St_3	Steam level 3 (>3MPa, >300 °C)	2.9 (1.1)**	2.4 (0.9)**
Cap_{St2}	Capacity of facility with steam level 2	0.023 (0.002)***	0.028 (0.003)***
Cap_{St3}	Capacity of facility with steam level 3	0.031 (0.003)***	0.032 (0.002)***
n	Number of case	104	72
R^2	Coefficient of determination	0.551***	0.512***

*$p<0.05$; **$p<0.01$; and ***$p<0.001$.

3.6 Scenario Analysis for the GHG Emissions and Reductions

Based on the abovementioned analytical results on energy/material consumption and recovery, the authors intended to estimate the total GHG emissions by a national level and investigate the effects of some political and technological alternatives using a scenario analysis.

3.6.1 Scenario Definition

a) Scenario 1: business as usual (BAU) scenario

The authors estimated the current status of the GHG emissions and reductions from all the 1,243 operating facilities in 2009 as Scenario 1 ($S_{1\text{-BAU}}$): business as usual scenario.

b) Scenario 2: Block formation scenario

As a political alternative, the authors estimated the expected GHG emissions and reductions by block formation by small municipalities as Scenario 2: Block formation scenario. In 1997, Japanese government sent one official notice requesting municipalities to establish plans for promoting the block formation. The government intended to group small municipalities for replacing small-scale incinerators by large-scale WtE facilities with a higher energy recovery efficiency. All 47 prefectures in Japan issued plans for the block formation by small municipalities for MSW management (*Ministry of Health and Welfare, Japan: Notice for block formation for municipal solid waste management. (1997) (In Japanese)*, n.d.). Small-scale incinerators with a smaller than 100 t/day capacity were expected to be closed and replaced by a new larger-scale facility with 300 t/d capacity or more (*Japan Waste Research Foundation : Ledger on municipal solid waste incinerator in FY2009 (In Japanese)*, 2010).

The authors used the following conditions to design the blocks for estimation based on the plans for the block formation from the 47 prefectures: 1) close facilities without power generation, 2) facilities with 300t/day or more with power generation keeping the operation, and 3) integrate facilities in the designated block with a smaller than 300t/day capacity. In some specific blocks (e.g., isolated islands), the scales of the waste incinerators were smaller than 100 t/d. Table 11 shows the number of incineration plants in reference to the plans for the block formation (*Master plans of block formation for municipal solid waste management (issued by 47 prefectures in 1998-2017) (In Japanese).*, n.d.). A total of 1,007 plants among the 1,243 incineration plants operated in 2009 were assumed to be closed; 236 plants kept operating; and 286 facilities would be newly built.

The following four representative technological options for the 286 newly built facilities are defined by the predictive models in Tables 8 and 9: 1) stalker with minimum net GHG emissions ($S_{2s\text{-min}}$), 2) stalker with maximumnet GHG emissions ($S_{2s\text{-max}}$), 3) gasification with minimum net GHG emissions ($S_{2g\text{-min}}$), and 4) gasification with maximum net GHG emissions ($S_{2g\text{-max}}$).

c) Scenario3: Block formation scenario with BAT

The authors estimated the expected GHG emissions and reductions using BAT. According to the IPCC document on the BAT, the energy recovery efficiencies for combined heat and power plants are 22.5% for power generation and 37.4% for heat recovery (Gabor Doka, 2005) defined as Scenario 3-CHP ($S_{3\text{-CHP}}$): Block formation scenario with BAT for combined heat and power. As the maximum heat recovery condition, the energy recovery efficiency was defined as 74.3% for heat use only (Gabor Doka, 2005), which was defined as Scenario 3-H ($S_{3\text{-H}}$): Block formation scenario with BAT for heat use only.

Table 12 summarizes the definition and the technological condition of each scenario.

3.6.1 Methodology of the GHG Estimation

For GHG estimation, the authors applied the original data on the components of the GHG emissions and reductions from the JMOE and JWRF databases as much as possible. Table 13 summarizes the outline of the applied data for the scenario analysis.

Regarding the waste composition of each facility, the authors applied the percentages of plastic and synthetic textile from the JWRF database for the facilities with waste composition data. For the facilities without waste composition data, the corresponding prefectural average values calculated based on the JWRF database were used.

Regarding the utility consumption of each facility, the authors applied the original data on the utility consumption from the JWRF database that covered 814 facilities. For the remaining facilities without data on utility consumption, the authors calculated their amount by assigning the type of facility to the models in Table 8.

Table 11. Number of WtE Plants by the Integrated Waste Management System

Capacity range	Operating in FY2009	Status of operation after block formation			
		Stop operation	Upgraded	Newly built	Total
Cap≤100	684	644	40	47	87
100<Cap≤150	172	132	40	51	91
150<Cap≤200	105	82	23	39	62
200<Cap≤300	131	92	39	46	85
300<Cap≤450	73	39	34	73	107
450<Cap≤600	57	15	42	29	71
600<Cap≤800	6	0	6	3	9
800<Cap≤1000	9	0	9	0	9
1000<Cap≤1400	4	1	3	0	3
1400<Cap≤1800	2	0	2	0	2
Total	1,243	1,007	236	286	522

Table 12. Definition and Technological Condition of the Scenarios

Code	Scenario definition	Technological condition			
		Furnace	Turbine	Steam level	Ash melting
$S_{1\text{-BAU}}$	Business as usual	Current status			
$S_{2S\text{-Min}}$	Block formation with stalker furnace with minimum net GHG emissions	Stalker	Extraction condensing	Level 3	No
$S_{2S\text{-Max}}$	Block formation with stalker furnace with maximum net GHG emissions	Stalker	Back pressure	Level 1	Electricity
$S_{2G\text{-Min}}$	Block formation with gasification	Other	Extraction	Level 3	Gasification

	furnace with minimum net GHG emissions	gasification	condensing		
$S_{2G\text{-}Max}$	Block formation with gasification furnace with maximum net GHG emissions	Shaft gasification	Condensing	Level 1	Gasification
$S_{3\text{-}CHP}$	Block formation with BAT with combined heat and power	Stalker	BAT	BAT	No
$S_{3\text{-}H}$	Block formation with BAT with heat use only	Stalker	BAT	BAT	No

Regarding the power generation of each facility, for Scenario 1, the authors applied the original data from JMOE database that covered the power generation amount for all facilities with power generation. For Scenario 2, the authors calculated their amounts by assigning the type of facility to the models in Table 8 for the four representative technological options mentioned earlier. Meanwhile, the calculation for Scenario 3 was based on the condition mentioned in the “scenario” definition.

Regarding the heat utilization and slag generation, the authors applied the original data from the JWRF database that covered some of the facilities. For the facilities without data, the authors applied the national average rates calculated based on the JWRF database. The calculation for Scenario 3 was based on the condition mentioned in the “scenario” definition.

Table 13. Outline of the Applied Data for the Scenario Analysis

Component	Scenario	Target facility	Applied data	Reference
Direct CO_2 emissions from waste burning	All	Facilities with original data	Data on percentages of plastic and synthetic textile	JWRF
		Facilities without original data	Corresponding prefectural average of percentages of plastic and synthetic textile calculated based on the JWRF database	JWRF
Direct CO_2 emissions from fossil fuels	All	Same as indirect CO_2emissions by utility consumption		
Direct CH_4 and N_2O emissions from waste burning	All	All facilities	Emission factors for CH_4 and N_2O by type of furnace in Table 1	JMOE
Indirect CO_2	All	Facilities with original data	Data on utility consumption rate	JWRF

emissions by utility consumption			(electricity, fuel, water)	
		Facilities without original data	Calculated rate by assigning the type of facility to the models in Table 8	
Indirect CO_2 reductions by power generation	Practice 1	All facilities with power generation	Data on the power generation rate	JMOE
	Practice 2	236 facilities, which keep operation (300t/day or larger in 2009)	Data on the power generation rate	JMOE
		286 newly built facilities	Calculated power generation rate by assigning the designated technological parameters to the models in Table 8	
	Practice 3	236 facilities, which keep operation (300t/day or larger in 2009)	Data on the power generation rate	JMOE
		286 newly built facilities	Energy recovery efficiency for power generation: 22.5% for $S_{3\text{-CHP}}$	IPCC
Indirect CO_2 reductions by heat utilization	Practices 1 and 2	Facilities with original data	Data on the heat utilization rate	JWRF
		Facilities without original data	National average rate calculated based on the JWRF database	JWRF
	Practice 3	236 facilities, which keep operation (300t/day or larger in 2009) with original data	Data on the heat utilization rate	JWRF
		236 facilities, which keep operation (300t/day or larger in 2009) without original data	National average rate calculated based on the JWRF database	JWRF
		286 newly built facilities	Energy recovery efficiency for heat utilization: 37.4% for $S_{3\text{-CHP}}$, 74.3% for $S_{3\text{-H}}$	IPCC
Indirect CO_2 reductions by slag recycling	All		National average rate calculated based on the JWRF database	JWRF

3.6.2 GHG Emissions and Reductions by Scenario

Table 14 presents the results of the scenario analyses.

The net GHG emission rate for Scenario 1 ($S_{1\text{-BAU}}$) was estimated to be 653 kg-CO_2e/t, of which the total GHG emission rate was 758 kg-CO_2e/t, and the total GHG reduction ratewas−105 kg-CO_2e/t. The major GHG emission components were plastic burning (392 kgCO_2e/t), synthetic textile burning (225 kgCO_2e/t), and power consumption (108 kgCO_2e/t). The contributions of fuel consumption (21 kgCO_2e/t), CH_4 and N_2O (12 kgCO_2e/t), and water consumption (0.19 kgCO_2e/t) were less than 5%. These results were consistent with those of the past studies stating that the amount of CO_2 emissions from the waste treatment processes mainly depended on the waste compositions (Rand et al., 2000; Thanh & Matsui, 2013; Zaman, 2009). Power generation was dominant for the GHG reduction components (−103 kgCO_2e/t), and the contributions of "heat utilization" (−2.1 kgCO_2e/t) and "slag recycling" (−0.04 kgCO_2e/t) were relatively smaller.

In Scenario 2 (block formation with four technological alternatives), the results showed that Scenario $S_{2\text{-SMin}}$ had the lowest net GHG emission practice (454 kgCO_2e/t), followed by $S_{2\text{-GMin}}$ (542 kgCO_2e/t), $S_{2\text{-SMax}}$ (685 kgCO_2e/t), and $S_{2\text{-GMax}}$ (718 kgCO_2e/t). The stalker furnace showed a smaller net GHG emission rate than the gasification furnace.

For the stalker incineration furnace, the difference between $S_{2\text{-SMin}}$ (454 kgCO_2e/t) and $S_{2\text{-SMax}}$ (685 kgCO_2e/t) was 231 kgCO_2e/t. The turbine efficiency of $S_{2\text{-SMin}}$ (extraction condensing turbine with steam level 3) was higher than that of $S_{2\text{-SMax}}$ (back pressure turbine with steam level 1). Consequently, the GHG reduction of power generation for $S_{2\text{-SMin}}$ (239 kgCO_2e/t) was much larger than that of $S_{2\text{-SMax}}$ (93 kgCO_2e/t). The power consumption of $S_{2\text{-SMin}}$ (without ash melting) was smaller than that of $S_{2\text{-SMax}}$ (with ash melting by electricity). Consequently, the GHG emissions of the power consumption for $S_{2\text{-SMin}}$ (82 kgCO_2e/t) were smaller than that of $S_{2\text{-SMax}}$ (168 kgCO_2e/t). The GHG reductions of the slag recycling of $S_{2\text{-SMin}}$ and $S_{2\text{-SMax}}$ were 0.04 and 0.24, respectively. The GHG reduction by slag recycling was relatively smaller compared with the larger power consumption for ash melting. The difference of the net GHG emissions between $S_{2\text{-SMin}}$ and $S_{2\text{-SMax}}$ (231 kgCO_2e/t) came from the differences in the turbine condition (146 kgCO_2e/t), ash melting (85 kgCO_2e/t), and slag recycling (0.2 kgCO_2e/t).

For the gasification furnace, the difference between $S_{2\text{-GMin}}$ (542 kgCO_2e/t) and $S_{2\text{-GMax}}$ (718 kgCO_2e/t) was 176 kgCO_2e/t. The turbine efficiency of $S_{2\text{-GMin}}$ (extraction condensing turbine with steam level 3) was higher than that of $S_{2\text{-GMax}}$ (condensing turbine with steam level 1). Consequently, the GHG reduction of power generation for $S_{2\text{-GMin}}$ (274 kgCO_2e/t) was much larger than that of $S_{2\text{-GMax}}$ (106 kgCO_2e/t). Moreover, the fuel consumption of $S_{2\text{-GMin}}$ (other gasification furnaces) was smaller than that of $S_{2\text{-GMax}}$ (Shaft Gasification furnace). Consequently, the GHG emissions of fuel consumption for $S_{2\text{-GMin}}$ (98 kgCO_2e/t) were smaller than that of $S_{2\text{-GMax}}$ (107 kgCO_2e/t). Both gasification furnaces consumed a larger amount of fuel when compared with stalker furnaces, which resulted in a net GHG emission rate of the gasification furnace to be larger than that of the stalker furnace. The difference of the net GHG emission rate between $S_{2\text{-GMin}}$ and $S_{2\text{-GMax}}$ (176 kgCO_2e/t) came from the differences in the turbine condition (168 kgCO$_2$e/t) and the furnace type (8 kgCO$_2$e/t).

Regarding Scenario 3 ($S_{3\text{-CHP}}$ and $S_{3\text{-H}}$) (block formation with the BAT), the net GHG emission rate would be 242 kgCO$_2$e/t for combined heat and power ($S_{3\text{-CHP}}$), best in all the estimated scenarios. The total GHG reduction rate of $S_{3\text{-CHP}}$ was 483 kgCO$_2$e/t, of which the GHG reduction rate of power generation (288 kgCO2e/t) was 20% larger than that of $S_{2\text{-SMin}}$ (239 kgCO$_2$e/t), while that of heat utilization (189 kgCO$_2$e/t) was seven times larger than that of $S_{2\text{-SMin}}$ (27 kgCO$_2$e/t). The net GHG emission rate for Scenario $S_{3\text{-H}}$ would be 346 kgCO$_2$e/t.

The result in Table 11 shows that the current net GHG emission rate from 1,243 operating waste incineration plants in Japan was estimated to be 653 kgCO$_2$e/t in Scenario 1 ($S_{1\text{-BAU}}$). This rate could be cut off to 454 kgCO$_2$e/t by the block formation, as shown in Scenario $S_{2\text{-SMin}}$. This reduction would be achieved by (1) replacing the smaller facilities and the facilities without power generation by large-scale WtE facilities, and (2) applying technological alternatives with a higher power generation efficiency (stalker furnace and extraction condensing turbine with steam level. Ash melting had larger GHG emissions by the increase in energy consumption, and the GHG reduction by slag recycling was limited. Furthermore, the net GHG emissions would be reduced to 242 kgCO$_2$e/t if all the newly built facilities fulfill the energy recovery efficiency by BAT with combined heat and power (Scenario $S_{3\text{-CHP}}$). The results in Scenario $S_{3\text{-CHP}}$ also showed that GHG reductions by heat utilization played an important role in the total GHG reductions (189 in 483 kgCO$_2$e reductions per ton of waste). Based on the comparison of the GHG reduction components between the current status ($S_{1\text{-BAU}}$) and the status by BAT ($S_{3\text{-CHP}}$), BAT can reduce 185 kgCO$_2$e/t by improving the power generation efficiency and the comparable rate, 187 kgCO$_2$e/t, by expanding heat utilization. At present, heat utilization is very limited in Japan, but it should be more focused and promoted for GHG mitigation decisions.

The carbon emission reduction rates in the seven scenarios were in the range of 105 to 483 kgCO$_2$e/t, which were similar to the range of 100 to 350 kgCO$_2$e/reported by the World Energy Resources in 2016 (World Energy Council, 2013).

Table 14. Scenario Estimation Results of the GHG Emission and Reduction Rates (kgCO$_2$e/t)

	Scenario						
Components	$S_{1\text{-BAU}}$	$S_{2S\text{-Min}}$	$S_{2S\text{-Max}}$	$S_{2G\text{-Min}}$	$S_{2G\text{-Max}}$	$S_{3\text{-CHP}}$	$S_{3\text{-H}}$
GHG emissions	758	719	805	847	856	719	719
Plastic burn	392	392	392	392	392	392	392
Synthetic textile burn	225	225	225	225	225	225	225
Power consumption	108	82	168	125	125	82	82
CH_4, N_2O	12	11	11	7	7	11	11
Fuel consumption	21	9	9	98	107	9	9
Water consumption	0.19	0.13	0.13	0.13	0.13	0.13	0.13

GHG reductions	−105	−266	−112	−306	−138	−483	−373
Power generation	−103	−239	−93	−274	−106	−288	−71
Heat utilization	−2.1	−27	−27	−31	−31	−189	−302
Slag recycling	−0.04	−0.04	−0.24	−0.5	−0.5	−0.05	−0.05
Net GHG	653	454	685	542	718	242	346

4. Conclusion

(1) This study focused on the GHG emissions and reductions of MSW incineration. The detailed composition of GHG emissions from the waste incineration facility and their influence factors were investigated using two databases on the annual operation report from 1,243 facilities in Japan in 2009.

(2) The detailed energy/material consumption and recovery rates were analyzed by major technological factors. Gasification consumed more fuel and electricity than incineration. Incineration with ash melting also caused more consumption of fuel or electricity than incineration without it. The power generation rate/efficiency was significantly affected by the type of turbine and the steam condition.

(3) The multilinear regression models were developed on the fuel consumption rate, power consumption rate, water consumption rate, and turbine generator efficiency.

(4) Based on the abovementioned data and models, the current net GHG emission rate from 1,243 operating waste incineration plants in Japan in 2009 was estimated to be 653 kgCO_2e/t. The GHG emission and reduction rate from waste incineration in 2009 was estimated to be 758 kgCO_2e/t and 105 kgCO_2e/t, respectively. Plastic burning accounted for the majority part with 392 kg kgCO_2e/t, followed by synthetic textile burning (225 kg kgCO_2e/t) and power consumption (108 kg kgCO_2e/t). For the GHG reduction rate, power generation contributed the highest proportion of−103 kg kgCO_2e/t. The results showed that “plastic burn” and “synthetic textile burn” were the major contributors to GHG emissions, and “power generation” played an important role in reducing GHG.

(5) Japan Ministry of the Environment intended to group small municipalities for replacing small-scale incinerators to large-scale Waste-to-Energy (WtE) facilities with a higher energy recovery efficiency. The net GHG emissions could be reduced to 454 kgCO_2e/t by applying the block formation and technological alternatives with a higher energy recovery efficiency (the stalker furnace with power generation by the extraction condensing turbine, and the steam condition is higher than 3MPa and 300 °C). Ash melting caused larger GHG emissions by the increase in energy consumption. The GHG reduction by slag recycling was limited.

(6) The net GHG emission rate could be reduced to 242 kgCO_2e/t by applying BAT for combined heat and power plants. When compared with the current status, BAT can reduce 185 kgCO_2e/t by improving the power generation efficiency and 187 kgCO_2e/t by expanding heat utilization.

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