Original Research

Energy and Environmental Indicators of Municipal Solid Waste Incineration: toward Selection of an Optimal Waste Management System

Ingrida Rimaitytė[1], Gintaras Denafas[1]*, Dainius Martuzevicius[1], Andrius Kavaliauskas[2]

[1]Department of Environmental Engineering, Kaunas University of Technology, Kaunas, Lithuania
[2]JSC "Kauno Švara", Kaunas, Lithuania

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Abstract

This work evaluates municipal solid waste (MSW) management options with respect to energy and environmental indicators. Two alternative scenarios have been analyzed: incineration of waste after mechanical biological treatment (MBT) and mass burning. The city of Kaunas, Lithuania, served as an object of the research. The calculations revealed that in the case of incineration of MBT-processed waste, only 2.4-2.8% of municipal heat energy requirements may be satisfied, while mass burning may provide up to 20% of integrated municipal heat energy requirements. The incineration of MBT-processed waste would result in 36% higher exhaust gas volume, 39% higher HCl emissions and 57% higher SO_2 emissions per ton of waste, compared to mass-burned waste. The presented approach may be applied to countries experiencing transitions of MSW management systems.

Keywords: municipal solid waste, waste incineration, mechanical biological treatment, national waste management strategy

Introduction

Landfilling currently is the main option for the utilization of municipal solid waste (MSW) in Lithuania. MSW can be landfilled despite its composition, calorific value, moisture, etc. However, landfilling needs to be limited, taking into account the hierarchy of waste management and other requirements of legislation. Furthermore, increasing costs and a lack of land suitable for landfills, disapproval of local communities to landfilling their neighbourhood, etc., makes it necessary to find a way to reduce the amount of landfilled waste.

*e-mail: gintaras.denafas@ktu.lt

The waste management strategy presented in the Lithuanian National Strategic Waste Management Plan (NSWMP) sets a target to minimize amounts of landfilled waste. This can be achieved either by mechanical-biological treatment (MBT) of MSW or by incineration of MSW. However, incineration is only permissible after recyclables (such as secondary raw materials and biodegradable fractions) are separated from the MSW stream. Thus, it is important to consider various options, alternatives, or scenarios of MSW management options with respect to impact on the environment and energy systems.

MBT consists of mechanical and biological processes and their combination depending on characteristic of waste. The mechanical stage includes separation of fractions for recycling, light fraction (high caloric fraction, HCF), and contaminants. The rest (low caloric fraction) is fed to the biological process [1]. The resulting HCF, which mostly consists of paper, textiles, plastic, and wood, can be used as an additional energy source in either a cement kiln, power plants or in a waste incineration plant [2, 3]. However, the implementation of MBT on waste management systems must be carefully evaluated. Special attention should be paid to economic indicators, technological capabilities to treat all collected waste, and the possibility of extracted secondary raw materials and HCF [4, 5]. Considering that 2,700-3,700 tons of MSW are generated in Kaunas city weekly (more than 150,000 t annually), the implementation of only MBT technology may be not feasible. On the other hand, the implementation of MBT is favourable in smaller areas of Lithuania due to a relatively low degree of household source separation. This would enable additional separations of recyclable fractions.

The incineration of unprocessed MSW is one of the most effective and fastest means to reduce the amount of landfilled waste. The volume of waste is reduced by 70% [6]. On the other hand, incineration is named as one of the most polluting technologies [7].

This article aims at analyzing two waste management alternatives with thermal energy recovery, with respect to energy and environmental aspects:
Alternative 1: MBT and incineration of produced HCF;
Alternative 2: mass burning without pre-treatment.

The results are expected to support decisions on waste management options in Lithuania, at the same time providing estimates and suggestions for planning and MSW management systems for the city of Kaunas. The methodology can also be applied to other countries with similar challenges experiencing transfers of waste management systems.

Methodology

Description of the Object of Research

Our research was based on weekly data of waste flows in Kaunas city. The data obtained from Kaunas municipal waste management company (JSC "Kauno švara") was utilized for analyses.

Kaunas is the second largest city in Lithuania, with total area of ca. 157 km^2 and 354,000 inhabitants.

Heating energy in Kaunas is mainly produced in a gas-fired heat and power plant. The integrated demand of heat energy of the Kaunas Heat and Power Plant is about 1,607 GWh per year [8].

In 2008 Kaunas generated 166,000 t MSW (460 kg/cap/yr). Currently, the main MSW disposal method is landfilling. Hazardous waste and a small part of recyclable materials are transferred for treatment.

Some of the most important problems that are being tackled currently include intensification of household separation and recycling of recyclable fractions from MSW. On the other hand, the current low degree of household separation provides an opportunity to consider MBT as a feasible alternative for MSW management in smaller towns.

Table 1. MSW composition in 2006 (as generated).

Paper and cardboard	11.0%
Glass	8.0%
Metals	2.0%
Plastics and composites	9.0%
Biowaste (waste from the kitchen: hulls, vegetable waste, feed waste, etc.)	43.0%
Other non-combustible fractions (construction waste, soil, etc.)	16.0%
Other combustible fractions (garden waste, wood, textiles, etc.)	11.0%
Total	100.0 %

The Effect of Separate Collection of Recyclables on MSW amount and Composition

Increasing source separation efficiency largely influences the composition and quantity of MSW, since the removal of recyclables decreases the overall quantity of MSW. Thus, the alternatives to MSW utilization (HCF vs. mass burning) were first evaluated by means of three scenarios with respect to different degrees of separate collection of recyclable materials. The MSW composition data of 2006 (Table 1) was selected as a starting point for data analysis.

The variation of the total MSW amount for the period of 2008-17 was calculated according to the trends of MSW quantity variation during 2000-07 by means of the LCA-IWM prognostic tool, as described below.

Scenario No. 1

This was considered as the most realizable scenario, which assumed that the amount of separately collected recyclables would increase insignificantly. Based on the data collected in other EU member states, the forecasted growth of quantity of separately collected recyclable fraction per capita was assumed to grow gradually from 4 kg in 2008 to 6 kg in 2017. For separately collected fractions, this quantity was calculated according to social-economic indicators using the "LCA-IWM prognostic tool" that supports the prediction of future amounts of generated waste for cities and regions with rapidly growing economies [9, 10]. The results of forecasted quantity of separately collected recyclable fractions are presented in Table 2.

Scenario No. 2

Optimistic scenario: the waste would be sorted as in EU member states having highly developed separate collection systems of recyclables. In such a case, the amount of sepa-

Table 2. The yearly increase of separately collected recyclable fractions (kg per capita) in Scenario No. 1.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Paper and cardboard	2.2	2.7	2.7	2.9	3.0	3.3	3.2	3.2	3.3	3.3
Glass	0.8	0.6	0.6	0.8	0.8	0.8	0.8	0.9	1.1	0.8
Metals	0.1	0.2	0.3	0.1	0.0	0.3	0.2	0.4	0.0	0.6
Plastics and composites	0.2	0.7	0.6	0.6	0.7	0.6	0.8	0.8	0.7	0.7
Biowaste	0.8	0.6	0.8	0.4	0.7	0.8	0.8	1.0	0.9	1.0
Total	4.1	4.7	4.9	4.8	5.1	5.8	5.8	6.3	6.0	6.3

Table 3. The yearly increase of separately collected recyclable fractions (kg per capita) in Scenario No. 2.

	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Paper and cardboard	14.4	17.1	19.8	22.7	25.7	29.0	32.2	35.4	38.8	42.1
Glass	9.1	9.7	10.2	11.0	11.8	12.6	13.3	14.2	15.3	16.1
Metals	2.7	2.9	3.2	3.3	3.3	3.7	3.9	4.3	4.3	4.9
Plastics and composites	9.1	9.8	10.3	10.9	11.6	12.1	12.9	13.7	14.3	15.0
Biowaste	29.8	30.3	31.1	31.5	32.2	33.0	33.8	34.8	35.7	36.7
Total	65.1	69.8	74.7	79.4	84.5	90.3	96.1	102.4	108.4	114.8

rately collected recyclables would grow gradually from 65.1 kg in 2008 (assuming that separation efficiency had already reached Western European levels) to 114.8 kg in 2017, as indicated in Table 3. Although this scenario seems unrealistic, it serves the purpose of identifying of the impact of high separation levels on energy and environmental aspects of waste incineration.

Scenario No. 3

Pessimistic scenario: the waste management system remains similar to the one that existed in 2006. The composition of MSW would also remain similar, since no recyclables would be separated from the entire MSW amount.

The Effect of MBT on Waste Amount and Composition

In the case of MBT treatment, the MSW (after source separation in households) is treated mechanically, with the aim of additionally separating recyclables and biodegradable matter. For the purpose of this analysis, described methodology is based on results of a study on the performance of MBT plant technology in Germany [2]. The following sequence of the MBT process has been selected: MSW is first sorted by a manual system (glass and other inert fractions are separated manually, the ferromagnetic metallic fraction is separated by a magnetic separator). This type of waste management system is capable of separating

Table 4. The amounts of various waste components remaining in HCF after screening (80 mm mesh size) [11, 12].

Paper and cardboard	13.0%
Glass	0.0%
Metals	30.0%
Plastics and composites	34.0%
Biowaste	5.0%
Non-combustible fraction	15.0%
Combustible fraction	36.0%

Table 5. The effectiveness of secondary metal separator and air classifier [11, 12].

Paper and cardboard	97.2%
Glass	56.3%
Metals	4.87%
Plastics and composites	88.1%
Biowaste	95.9%
Non-combustible fraction	85.3%
Combustible fraction	56.3%

Table 6. The variation of MBT-processed waste composition (scenario No. 1).

Fraction. kg/1000 kg MSW and %	Initial composition	After first stage sorting	After screening by 80 mm screen	After metal separator and air classifier
Year	2008			
Paper and cardboard	107 (10.7)	107 (12.3)	14 (11.4)	14 (13.6)
Glass	80 (8.0)	40 (4.6)	0 (0.0)	0 (0.0)
Metals	21 (2.1)	13 (1.5)	4 (3.3)	0 (0.0)
Plastics and composites	91 (9.1)	91 (10.4)	31 (25.2)	27 (26.2)
Biowaste	432 (43.2)	432 (49.5)	22 (17.9)	21 (20.4)
Non-combustible fraction	109 (10.9)	109 (12.5)	40 (32.5)	34 (33.0)
Combustible fraction	160 (16.0)	80 (9.2)	12 (9.8)	7 (6.8)
Total:	1,000 (100.0)	872 (100.0)	123 (100.0)	103 (100.0)
Year	2017			
Paper and cardboard	64 (6.4)	64 (7.4)	8 (6.6)	8 (8.0)
Glass	74 (7.4)	37 (4.3)	0 (0.0)	0 (0.0)
Metals	19 (1.9)	11 (1.3)	3 (2.5)	0 (0.0)
Plastics and composites	88 (8.8)	88 (10.1)	30 (24.8)	26 (26.0)
Biowaste	460 (46.0)	460 (53.0)	23 (19.0)	22 (22.0)
Non-combustible fraction	120 (12.0)	120 (13.8)	44 (36.4)	37 (37.0)
Combustible fraction	175 (17.5)	88 (10.1)	13 (10.7)	7 (7.0)
Total:	1,000 (100.0)	868 (100.0)	121 (100.0)	100 (100.0)

Table 7. The variation of MBT-treated waste composition (scenario No. 2).

Fraction. kg/1000 kg MSW and %	Initial composition	After first stage sorting	After screening by 80 mm screen	After metal separator and air classifier
Year	2008			
Paper and cardboard	91 (9.1)	91 (10.5)	12 (9.6)	12 (11.4)
Glass	70 (7.0)	35 (4.1)	0 (0.0)	0 (0.0)
Metals	17 (1.7)	10 (1.2)	3 (2.4)	0 (0.0)
Plastics and composites	82 (8.2)	82 (9.5)	28 (22.4)	25 (23.8)
Biowaste	424 (42.2)	424 (49.1)	21 (16.8)	20 (19.0)
Non-combustible fraction	128 (12.8)	128 (14.8)	47 (37.6)	40 (38.1)
Combustible fraction	188 (18.8)	94 (10.9)	14 (11.2)	8 (7.6)
Total:	1,000 (100.0)	864 (100.0)	125 (100.0)	105 (100.0)
Year	2017			
Paper and cardboard	42 (4.2)	42 (4.9)	6 (4.9)	6 (5.8)
Glass	64 (6.4)	32 (3.7)	0 (0.0)	0 (0.0)
Metals	15 (1.5)	9 (1.0)	3 (2.4)	0 (0.0)
Plastics and composites	80 (8.0)	80 (9.3)	27 (22.0)	24 (23.1)
Biowaste	458 (45.8)	458 (53.3)	22 (17.9)	22 (21.2)
Non-combustible fraction	138 (13.8)	138 (16.0)	50 (40.7)	43 (41.3)
Combustible fraction	203 (20.3)	101 (11.7)	15 (12.2)	9 (8.7)
Total:	1,000	860 (100.0)	123 (100.0)	104 (100.0)

Table 8. The variation of MBT-treated waste composition (scenario No. 3).

Fraction. kg/1000 kg MSW and %	Initial composition	After first stage sorting	After screening by 80 mm screen	After metal separator and air classifier
Paper and cardboard	111 (11.1)	111 (12.7)	15 (12.2)	14 (13.6)
Glass	82 (8.2)	41 (4.7)	0 (0.0)	0 (0.0)
Metals	21 (2.1)	13 (1.5)	4 (3.3)	0 (0.0)
Plastics and composites	91 (9.1)	91 (10.4)	31 (25.2)	27 (26.2)
Biowaste	430 (43.0)	430 (49.3)	22 (17.9)	21 (20.4)
Non-combustible fraction	108 (10.8)	108 (12.4)	39 (31.7)	34 (33.0)
Combustible fraction	158 (15.8)	79 (9.0)	12 (9.8)	7 (6.8)
Total:	1,000 (100.0)	873 (100.0)	123 (100.0)	103 (100.0)

50% of glass, 41% of metals, and 50% of other inert materials of low calorific value [11, 12]. After first-stage sorting, waste is reduced in a shredder and screened. Screen mesh size is selected according to desired amounts and properties of highly calorific fractions. Often a mesh size of 100 mm is used. In such cases, however, smaller quantities of HCF are obtained. Thus, according to this consideration, a screen mesh size of 80 mm was selected as a reference for further calculations. The amounts of various waste components remaining in HCF after screening are presented in Table 4.

After screening, the remaining waste is diverted to a secondary metal separator and sorted by air classifier, separating the heavy fraction [11, 12] (Table 5).

The comparison of composition of MSW and MBT-processed waste in the years 2008 and 2017 is presented in Tables 6-8. In the case of Scenario No. 3, the amounts of separated waste remain constant throughout the entire year.

During mechanical treatment, moisture content in waste is reduced, and glass and metals are separated. At the same time, the share of plastics, paper, and other combustibles is increased, consecutively increasing the calorific value of the waste.

The Energy Indicators of MSW Incineration

The main parameter of any combustible matter is its calorific value. Not all waste is suitable for combustion. The waste may be too humid or of low calorific value due to the low concentration of organic fractions. The calorific value for incinerated waste should not fall lower than 6.5 MJ·kg^{-1} [13]; otherwise, additional fuel is necessary to maintain efficient combustion.

Calculations of calorific values were performed according to the elemental composition of waste fractions [14]. It was assumed that the fraction of plastics and composites is composed of plastics, packaging composites, and other composites; biodegradable fraction is composed of kitchen and garden wastes; other combustible fraction is composed of textiles, diapers, wood, and leather. The calculated calorific values of various waste fractions are presented in Table 9.

Environmental Indicators of MSW Incineration

The MBT treatment of waste not only affects its composition, but also the composition of exhaust gases forming in the incinerator. In order to estimate and compare the effect of MBT to the environmental indicators, the total produced exhaust gas volume as well as amounts of SO_2 and HCl generated from 1 ton of incinerated waste were calculated [15]. The volume of exhaust gas was calculated according to the emitted amounts of CO_2, H_2O, and N_2 (these depend on the elemental composition of the waste), as well as the concentrations of O_2, N_2, and H_2O present in the combustion air [16].

Results

Two alternatives of the waste management system consisting of waste incineration with thermal energy recovery were researched.

Alternative No. 1

Waste is incinerated after MBT. The calculated variation of calorific values in cases of various scenarios according to HCF composition from Tables 6-8 is presented in Fig. 1.

Table 9. Calculated calorific values of various waste fractions.

	MJ kg^{-1}
Paper and cardboard	9.3
Glass	-0.1
Metals	-0.3
Plastics and composites	20.6
Biowaste	6.3
Non-combustible fraction	-0.3
Combustible fraction	8.5

It is evident that the calorific value of incinerated waste has an insignificantly decreasing trend. During a ten-year period, the calorific value of HCF may decrease up to 1.8% (Scenario 1) and up to 1.2% (in Scenario 2; the difference between scenarios 1 and 2 is 4%). This is attributed to increasing effectiveness of household separation of recyclable fractions. Although the share of other combustible waste in the MSW content will increase, it will not compensate the decrease of calorific value. In Scenario 3, when the MSW composition remains constant, the calorific value of waste after mechanical treatment remains the same.

The calculations suggest that even with a gradual decrease of calorific value of waste, the overall calorific value will be greater than the minimum value for waste incineration. Such waste may be incinerated without additional fuel.

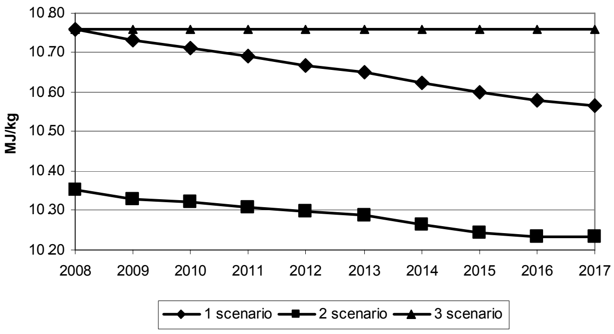

Fig. 1. The variation of calorific values of highly calorific fractions in cases of various scenarios.

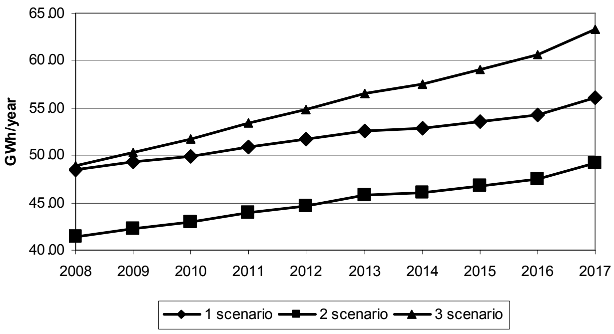

Fig. 2. The amount of produced energy in cases of the 1st alternative.

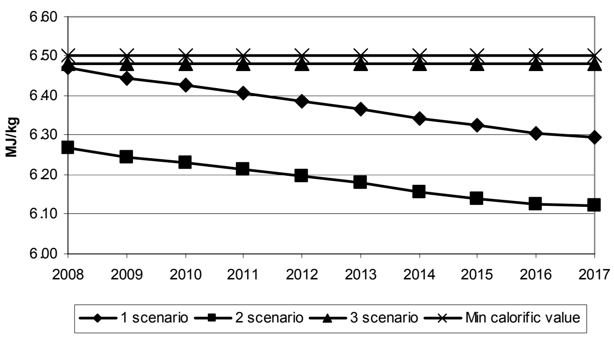

Fig. 3. The calorific value of MSW after household source sorting.

The treatment of MSW according to suggested MBT technology would reduce the amount of incinerated waste by 90%. The calculated yearly energy generation of incinerated waste fuel (without accounting for incineration efficiency) is presented in Fig. 2.

Heat generation efficiency of the modern waste incineration boilers is approximately 80% [16]. Assuming that only waste collected in Kaunas city would be incinerated, this alternative would yield only 2.4-2.8% of the heat distribution network's capacity of Kaunas Heat and Power Plant in the case of Scenario 1, and 2.1-2.4% and 2.4-3.2% in scenarios 2 and 3, respectively.

Alternative No. 2

In this case, the waste generated in Kaunas city would be incinerated by mass burning without pre-treatment. In order to maximize the amount of incinerated waste and, consecutively, the amount of produced energy. This alternative was designed assuming that the only treatment of waste happens in the households as source sorting.

The variation of calculated calorific value of the waste is presented in Fig. 3.

In Fig. 3, the value of minimal required calorific value is also presented. It is evident that the calorific value of MSW collected in Kaunas city is lower than the minimum value. The calorific value is decreasing with increasing sorting efficiency. Even in case of Scenario 3, it may not be recommended to incinerate waste without additional fuel. In this perspective, the incineration of HCF obtained in neighbouring regions mixed with MSW collected in Kaunas may be considered.

The calculated produced amount of energy is presented in Fig. 4. This alternative would yield 15.4-17.7% of the heat distribution network's capacity in the case of Scenario 1, 13.1-15.4% and 15.6-20.0% in cases of scenarios 2 and 3, respectively.

It is evident that the incineration of MBT-concentrated waste produces higher amounts of exhaust gases per 1 ton of waste, and (51-58% higher in comparison to mass burning, Table 10). On other hand, the amount of flue gas per energy unit (kWh) for mass burning is 5.5-6% higher in comparison with HCF incineration.

The exhaust volume could be reduced by increasing efficiency of household sorting. In the case of low improve-

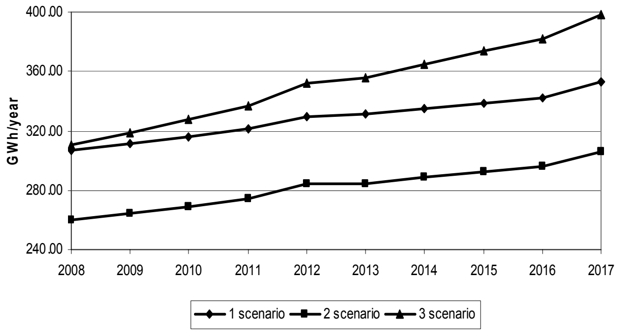

Fig. 4. The amount of produced energy in the case of the 2nd alternative.

Table 10. Volume of exhaust gas (m^3) per 1 ton of waste and per kWh of heat energy.

Years	The volume of exhaust gas											
	Scenario 1 after MBT		Scenario 1 without MBT		Scenario 2 after MBT		Scenario 2 without MBT		Scenario 3 after MBT		Scenario #3 without MBT	
	m^3 t^{-1}	m^3 kWh^{-1}	m3 t^{-1}	m^3 kWh^{-1}	m^3 t^{-1}	m^3 kWh^{-1}	m^3 t^{-1}	m^3 kWh^{-1}	m^3 t^{-1}	m^3 kWh^{-1}	m^3 t^{-1}	m^3 kWh^{-1}
2008	4,745	198.29	3,017	209.65	4,577	198.78	2,930	210.21	4,745	198.29	3,019	209.46
2009	4,713	197.48	3,007	209.78	4,558	198.44	2,922	210.36	4,745	198.29	3,019	209.46
2010	4,725	198.36	2,999	209.88	4,565	198.84	2,916	210.45	4,745	198.29	3,019	209.46
2011	4,717	198.40	2,992	210.00	4,559	198.87	2,910	210.58	4,745	198.29	3,019	209.46
2012	4,708	198.43	2,984	210.11	4,556	198.89	2,903	210.68	4,745	198.29	3,019	209.46
2013	4,701	198.46	2,976	210.22	4,551	198.91	2,897	210.80	4,745	198.29	3,019	209.46
2014	4,690	198.50	2,967	210.35	4,541	198.95	2,888	210.93	4,745	198.29	3,019	209.46
2015	4,680	198.54	2,960	210.46	4,533	198.98	2,882	211.05	4,745	198.29	3,019	209.46
2016	4,672	198.57	2,953	210.57	4,530	199.00	2,877	211.15	4,745	198.29	3,019	209.46
2017	4,667	198.59	2,949	210.64	4,530	199.00	2,875	211.21	4,745	198.29	3,019	209.46

Table 11. Amount of HCl in exhaust gas (2008-17).

	Scenario 1 after MBT	Scenario 1 without MBT	Scenario 2 after MBT	Scenario 2 without MBT	Scenario 3 after MBT	Scenario 3 without MBT
kg per 1 ton of waste	2.39	1.47	2.36	1.45	2.39	1.47
kg per 1 kWh	0.080-0.082	0.082-0.084	0.082-0.083	0.083-0.085	0.080	0.082
mg/m^3	504-513	488-496	516-524	496-503	503	488

Table 12. Amount of SO_2 in exhaust gas (2008-17).

	Scenario 1 after MBT	Scenario 1 without MBT	Scenario 2 after MBT	Scenario 2 without MBT	Scenario 3 after MBT	Scenario 3 without MBT
kg per 1 ton of waste	3.01	1.29	3.02	1.28	3.01	1.29
kg per 1 kWh	0.101-0.103	0.072-0.071	0.105-0.106	0.074-0.072	0.101	0.071
mg/m^3	635-647	426-420	660-669	438-428	634	427

ment of household separation efficiency (Scenario 1), the volume of exhaust gas may decrease 2% per 10 years (for both 1 ton of incinerated waste and 1 kWh of energy produced). In cases of treating waste by MBT and improving household sorting efficiency, the decrease of the exhaust gas volume would be slower.

The incineration of MBT-processed waste yields 63% higher emissions of HCl per 1 ton of waste, but 1-2% less per kWh compared to that from mass-burned waste. The improving efficiency of household sorting would also produce higher HCl emissions, although this increase would not be significant (1% per 10 years, Scenario 1). On the other hand, in the case of mass burning, the improving household sorting efficiency would yield lower amounts of HCl, especially after minimizing paper and plastic content in waste (Table 11).

The amount of SO_2 in the exhaust gases is twice as high per 1 ton of incinerated waste and 40-47% higher per produced kWh for the MBT-processed waste compared to that from mass-burned waste. Similarly to HCl, SO_2 emissions would insignificantly increase with improving household sorting efficiency (1% per 10 years). In the case of mass burning, the emissions of SO_2 would decrease with improving household sorting efficiency (Table 12).

It must be noted that the above-presented values do not directly provide information about the environmental impact of these systems. However, they provide an indication on the effort needed for the treatment of flue gases.

Table 13. The consumable materials demand for flue gas treatment, t/year.

Years	The consumable materials demand for flue gas treatment, t/year					
	Scenario 1 after MBT	Scenario 1 without MBT	Scenario 2 after MBT	Scenario 2 without MBT	Scenario 3 after MBT	Scenario 3 without MBT
$Ca(OH)_2$	184-216	915-1054	162-195	791-933	185-239	923-1183
Coke	53-61	334-387	45-54	283-335	54-69	337-432
NH_4OH	21-25	134-154	18-21	113-134	21-28	135-173

For example, assuming the exhaust limit values of 10 mg/m^3 for HCl and 50 mg/m^3 for SO_2, the effectiveness of the flue gas treatment system of the mass burning process should reach 98% for HCl, 89% for SO_2 after mass burning, and 93% for SO_2 after HCF incineration. HCF incineration requires less consumable materials for flue gas treatment because of the smaller amount of incinerated waste (calculations according to [15], Table 13).

Discussion

This study presents an application of an algorithm for the assessment of various policy measures and technologies on energy and environmental indicators of MSW utilization with energy recovery. Based on this algorithm, other options of the MSW management may be chosen. For example, different schemes for MBT of MSW may be chosen, resulting in different composition of HCF.

The presented estimates may serve as substantial contributions to the selection of an optimal MSW system. However, they do not strictly suggest the best system in terms of environmental pollution. The comparison of the incineration of unprocessed MSW and MBT-processed MSW shows that the indicators are contrary if calculated per 1 ton of waste or per 1 kWh of produced energy. The HCF has lower volume and higher calorific value, thus producing more exhaust per 1 t of waste, but less exhaust per 1 kWh of produced energy. Emissions from the MBT process may be also be included in the overall evaluation of the system.

It must be stated that economic factors, which were not discussed in this paper, are also equally or even more important in the selection of appropriate waste management options. By utilizing results presented in this article, each of the scenarios and alternatives must be assessed from the economics perspective in order to establish a monetary mechanism of waste management. Moreover, the scenarios of entire waste management systems should be analyzed from the life-cycle standpoint, accounting for benefits and burdens from all steps of the waste management process.

The calculations also revealed that the requirement of incineration of only MBT-processed waste, set in the Lithuanian National Strategic Waste Management Plan, poorly satisfies the needs of the city heating network. This suggests that the national strategy should be reviewed with the aim of loosening requirements for mass burning of waste. Another option is incineration of waste collected in several regions, providing higher amounts of HCF available for incineration.

The presented principles of calculations may be applied for several regions, combining their efforts in MSW management. Even more scenarios and alternatives may be researched with the aim of finding an optimal solution with respect to the environmental, energy and economic indicators. The methodology can also be applied to other countries with similar challenges experiencing transfers of waste management systems.

Conclusions

Several waste management incineration-based options were analyzed with the aim of presenting possible indicators of waste management systems (based on the data of Kaunas, Lithuania). The energy and environmental indicators were compared for different scenarios of household sorting and incineration technologies.

In the case of utilization of MBT-processed waste, the calorific value of produced HCF would be sufficient for incineration without additional fuel (higher than 6,5 MJ/kg). However, a rather small amount of waste would be available for incineration. At the same time, such incineration would not be able to significantly contribute to the heating sector of the city (only up to 4%).

In the case of mass burning of MSW, incineration of additional fuel may be necessary, since the calculated calorific value of unprocessed waste may be less than 6.5 MJ/kg. Due to relatively high amounts of produced MSW, the heat energy amount from such incineration could satisfy up to ¼ of total heat energy demands of the Kaunas Heat and Power Plant.

The calculated amount of exhaust gas volume per 1 ton of incinerated waste is 57% higher in the case of HCF incineration, compared to mass burning, at the same time emitting 63% more of HCl and 50% more of SO_2. The improved efficiency of household sorting would reduce the volumes and concentration of pollutants in exhaust gases. Calculation of indicators per energy unit showed that mass incineration would release 5.5-6% more exhaust gas, 1-2% more HCl and 40-47% less SO_2 in comparison with HCF incineration.

In order to optimize selection of a future waste management system, several actions may be performed.

The national strategy should be reviewed with the aim of loosening requirements for mass burning of waste. In the case of the selection of MBT, incineration of waste collected in several smaller regions should be considered, providing higher amounts of HCF available for incineration. The environmental and energy scenarios and alternatives must be assessed from an economical perspective in order to establish a financial mechanism for MSW management.

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