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Waste Input-Output Analysis on "Landfill Mining Activity"

Kazuyo Yokoyama[1], Takashi Onda[2], Shunsuke Kashiwakura[1] and Tetsuya Nagasaka[1]

[1]*Graduate School of Environmental Studies, Tohoku University, Sendai 980-8579, Japan*
[2]*Dowa Mining Co., LTD, Tokyo 101-0021, Japan*

New environmental assessment model based on the Waste Input-Output analysis has been developed and applied for the "Landfill mining activity" for the recovery of valuable materials and energy resources and the saving of landfill site.

In this study, the landfilled wastes are assumed to be treated by the gasification/melting processes. Two kinds of reactors, the fluidized bed type and the shaft furnace type, have been considered in this work as the typical gasification/melting processes adopted in Japan. Both processes generate electric power by the recovered heat and fly ash as waste to be landfilled. It has been found in this study that the both processes can reduce the total volume of waste and save the available landfill space. The shaft furnace type seems to have higher potential for decreasing volume of wastes because of less emission than the fluidized bed type. The results of scenario analysis have also indicated that the landfill mining activity is effective for sustainable management of landfill sites. [doi:10.2320/matertrans.47.2582]

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1. Introduction

Waste disposal with production and consumption activities is transformed into environmental emission after appropriate treatment. In Japan, most of municipal wastes are separated and sent to incineration system. Incineration residue is mainly landfilled.

With respect to geographical condition of Japan, the total land area is approximately 380,000 km^2 based on 4 main islands which lie nearly 3,000 km from north to south, and 127 Million people are living and highly concentrated economic activities are carried out.

Under such conditions of Japan, we have narrow space for final disposal site, and it is difficult to find new one. Figure 1 shows residual capacity of landfill site in Japan. The residual years of final disposal site is increasing because of the reduction of waste generation by depression and enforcement of recycling. However the situation around us about limited capacity of final disposal space is still serious. It is, thus, important for us to reduce quantity of final disposal and to save existing final disposal space, whereas more conservation of landfill site seems to be difficult only with existing treatment. Under these conditions, recovering of material and energy from final disposal space is promoted by material industry, which plays a key role. Recently, new technology of "Landfill mining activity" is being paid attention.2) "Landfill mining" implies the digging up of the landfilled wastes, the recovery of valuable materials and energy resources and, thus, the reuse of the saved space as a new landfill site. Landfill mining activities have actually been examined in some local governments of Japan3) and they have employed the gasification melting furnace system, where it receives waste including municipal waste, incinerator ash and landfilled waste. Metals contained in the waste like aluminium, copper and iron, can be recovered as mixed metal and slag after the treatment.

Waste is generated from the production activities of industries, and the consumption activities of household economies. The wastes generated in industrial sectors are managed in waste treatment sectors. However, the goods produced by industrial sectors are indispensable to the activity of waste treatment sectors. Therefore, we must consider the interdependence between production sectors and waste treatment sectors. The Waste Input-Output analysis (WIO)4) enables the quantitative evaluation on the relations of such interdependence.

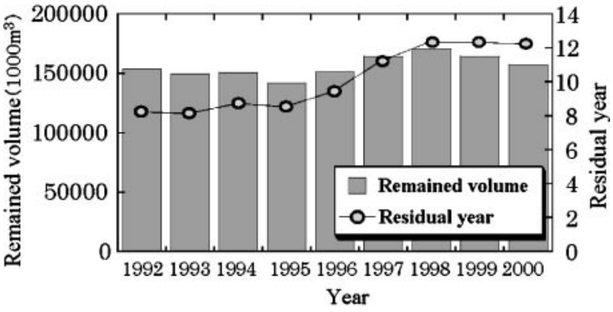

Fig. 1 Remained capacity of landfill in Japan.1)

However, in many methods of environmental assessment by using input-output model, the material recovery from final disposal site such as "Landfill mining activity" is not taken into account. The purpose of this study is the development of method to evaluate environmental burden and to analyze economic effects with landfill mining activity.

2. The Model

The well-known input-output model proposed by W. Leontief5) is very useful in the analysis of economic activity based on the scenarios. The traditional input-output model can be described by

$$(x_1)_{i:t} = \sum_{j=1}^{N}(a_{11})_{ij}(x_1)_{j:t} + (f_1)_{i:t} \quad (i = 1, 2, \cdots, N) \quad (1)$$

where $(x_1)_{i:t}$ is the total output of goods i in time period t, $(a_{11})_{ij}$ is the technical coefficient that represents the intermediate input of goods j required to produce a unit of goods i, $(f_1)_{i:t}$ is the final demand of goods i in time period t. In algebraic form, we can rewrite Eq. (1) as the following equation.

$$\boldsymbol{X}_{1:t} = \boldsymbol{A}_{11}\boldsymbol{X}_{1:t} + \boldsymbol{F}_{1:t} \tag{2}$$

where $\boldsymbol{X}_{1:t}$ is the total output vector, $\boldsymbol{A}_{11}$ means technical coefficient matrix, and $\boldsymbol{F}_{1:t}$ is the final demand vector.

Although Equations (1) and (2) describe the interdependence of economic activities, the joint products such as waste are not dealt with considered. Here let us assume that M industrial wastes are generated by N ordinary economic activities and treated by K waste treatment activities. Since the waste treatment activities require the additional goods such as materials, energy and services in order to treat and recycle the waste, Equations (1) and (2) can be rewritten as

$$(x_1)_{i:t} = \sum_{j=1}^{N}(a_{11})_{ij}(x_1)_{j:t} + \sum_{k=1}^{K}(a_{12})_{ik}(x_2)_{k:t} + (f_1)_{i:t} \quad (i = 1, 2, \cdots, N). \tag{3}$$

In algebraic form,

$$X_{1:t} = A_{11}X_{1:t} + A_{12}X_{2:t} + F_{1:t} \tag{4}$$

where $(x_2)_{k:t}$ is the activity level of waste treatment k in time period t, $(a_{12})_{ik}$ is the technical coefficient that represents the intermediate input of goods i required to treat a unit of waste treatment k.

Equations (3) and (4) express the material balance relating to goods productions and waste treatment. Subsequently, it is necessary to formulate the waste generations after the waste treatment activities.

$(\bar{a}_{21})_{ij}$ is defined as the waste generation coefficient representing waste i generated by unit production of goods j and $(\bar{a}_{22})_{ik}$ is defined as the waste residue coefficient representing waste i generated by unit activity of waste treatment k. Waste input-output table is a hybrid type of conventional input-output table, that is formed of both monetary based information and physical based data about waste generation and recycling. Hence, note that $(\bar{a}_{21})_{ij}$ and $(\bar{a}_{22})_{ik}$ are derived on quantity based data.

We have the following waste generation equation,

$$(x_2)_{i:t} = \sum_{j=1}^{N}(\bar{a}_{21})_{ij}(x_1)_{j:t} + \sum_{k=1}^{K}(\bar{a}_{22})_{ik}(x_2)_{k:t} + (\bar{f}_2)_{i:t} \quad (i = 1, 2, \cdots, M) \tag{5}$$

or

$$\bar{X}_{2:t} = \bar{A}_{21}X_{1:t} + \bar{A}_{22}X_{2:t} + F_{2:t}. \tag{6}$$

Here, $F_{2:t} = (f_2)_{i:t}$ denotes the net waste generations mainly by household and government consumption.

Rearrangement of Eqs. (5) and (6) yields

$$\begin{bmatrix} \boldsymbol{X}_{1:t} \\ \bar{\boldsymbol{X}}_{2:t} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{11:t} & \boldsymbol{A}_{12:t} \\ \bar{\boldsymbol{A}}_{21:t} & \bar{\boldsymbol{A}}_{22:t} \end{bmatrix} \begin{bmatrix} \boldsymbol{X}_{1:t} \\ \boldsymbol{X}_{2:t} \end{bmatrix} + \begin{bmatrix} \boldsymbol{F}_{1:t} \\ \bar{\boldsymbol{F}}_{2:t} \end{bmatrix}. \tag{7}$$

Since Equation (7) is the rectangular model, it is necessary to transform it into the square model. The waste allocation matrix $S = (s_{ij})$ represents the share of waste j treated by waste treatment i. We can formulate the following square system.

$$\begin{bmatrix} \boldsymbol{X}_{1:t} \\ \boldsymbol{X}_{2:t} \end{bmatrix} = \begin{bmatrix} \boldsymbol{A}_{11:t} & \boldsymbol{A}_{12:t} \\ \boldsymbol{A}_{21:t} & \boldsymbol{A}_{22:t} \end{bmatrix} \begin{bmatrix} \boldsymbol{X}_{1:t} \\ \boldsymbol{X}_{2:t} \end{bmatrix} + \begin{bmatrix} \boldsymbol{F}_{1:t} \\ \boldsymbol{F}_{2:t} \end{bmatrix} \tag{8}$$

In algebric form,

$$\boldsymbol{X}_t = \boldsymbol{A}_t\boldsymbol{X}_t + \boldsymbol{X}_{f:t} \tag{9}$$

with

$$\boldsymbol{A}_{21} = \boldsymbol{S}\bar{\boldsymbol{A}}_{21},\ \boldsymbol{A}_{22} = \boldsymbol{S}\bar{\boldsymbol{A}}_{22},$$
$$\boldsymbol{B}_{21} = \boldsymbol{S}\bar{\boldsymbol{B}}_{21},\ \boldsymbol{B}_{22} = \boldsymbol{S}\bar{\boldsymbol{B}}_{22},\ \boldsymbol{F}_2 = \boldsymbol{S}\bar{\boldsymbol{F}}_2.$$

This system of equations can be solved for production and waste treatment sectors, where the technology coefficient and final demand are given.[4)]

In environmental emission, landfill consumption $\boldsymbol{E}_{l:t}$ is defined as the quantity calculated by deduction of $\boldsymbol{E}_{q:t}$ from the sum of $\boldsymbol{E}_{p:t}$ and $\boldsymbol{E}_{r:t}$. $\boldsymbol{E}_{q:t}$ is the quantity of landfill waste dug up, $\boldsymbol{E}_{p:t}$ is landfill consumption with production activity, and $\boldsymbol{E}_{r:t}$ is landfill consumption with material and energy recovery activity.

$$\boldsymbol{E}_{l:t} = \boldsymbol{e}_{l:t}\boldsymbol{X}_t + \boldsymbol{E}_{r:t} - \boldsymbol{E}_{q:t} \tag{10}$$
$$= \boldsymbol{e}_{l:t}[\boldsymbol{I} - \boldsymbol{A}_t]^{-1}\boldsymbol{X}_{f:t} + \boldsymbol{E}_{r:t} - \boldsymbol{E}_{q:t}. \tag{11}$$

Here the coefficient of environmental emission $\boldsymbol{e}_{l:t}$ refers to the 3EID.[6)]

Considering the environmental effects of landfill mining activity, we applied not bottom-up type environmental assessment but the WIO approach. The use of Input-Output approach can significantly reduce the arbitrariness with regard to the definition of the relevant system boundary. Thus we discuss about the environmental effects about landfiill mining activity by WIO approach.

3. Conditions for Scenario Analysis

3.1 Extension of waste input output table

The conventional WIO table is extensively modified to meet the objective of the present work. Two activities of “Landfill mining” and “Gasification melting furnace” are first added in waste treatment sector. Secondly, we added eight kinds of wastes: “Iron waste from landfill site”, “Aluminum waste from landfill site”, “Recovered metal”, “Slag”, “Landfill mining waste”, “Waste soil”, “The waste sent to the gasification melting furnaces” and “Tiles and stones” (Fig. 2).

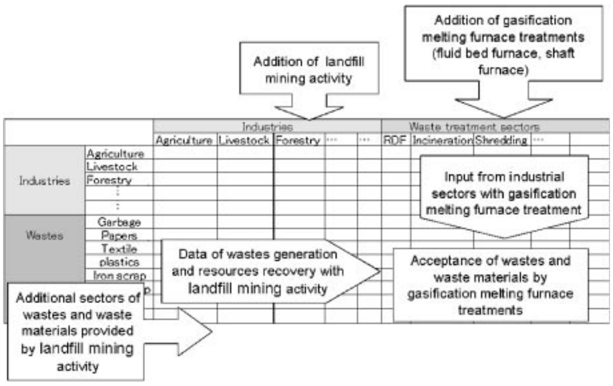

Fig. 2 Extension of Waste Input Output Table.

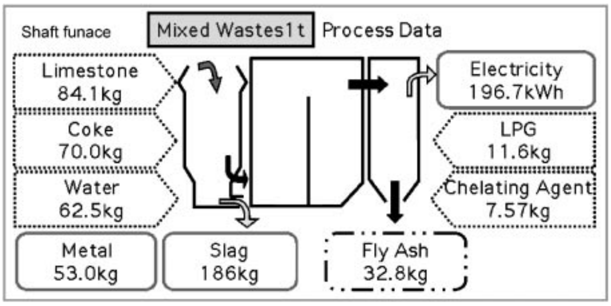

Fig. 3 Inventory data of shaft furnace type (Based on the interview).

In Japan, 40,633,227 t of waste are incinerated and 9,949,281 t of waste are landfilled in 2001.1) According to preliminary investigation of Japan Environmental Sanitary Center (JESC),3) we have assumed that 994,928 t of waste are relandfilled, which equals to 10 wt% of landfilled waste in 2001. Components of landfilled wastes are as follows; a half of components is soil, a quarter is impropriety wastes for incineration, residue is waste to re-treated according to the reports of JESC.

Landfill mining activity needs additional materials, energy and resources for the digging up, transportation, operation of the furnace, final waste treatment and so on. For example, insufficient calorie of wastes in fluidized bed funace (FB) type gasification process requires heavy oil input as an assistant fuel, while the calorie shortage of watses makes the rate of coke cosumption larger in shaft furnace (SF) type gasification process.

The dewatered and dried sludge is melted in SF process by exposing it to the high temperature combustion gas and converted to the metal and the slag. Therefore, the volume of the waste is markedly reduced and the most of heavy metals are dissolved into generated metal bath or stabilized in the slag. Thus, the slag can be safely recycled.

Most existing landfill mining activity treats mixed waste which is a mixture of the landfilled waste and municipal solid wastes, by a ratio of 1:9. Thus, here let us assume that SF and FB treats the mixed waste.

Figure 3 shows the inventory data of mixed waste treated by SF. The waste treatment by SF requires coke, limestone, water, LPG and chelating agent, and generates electric power by residual heat. Metal and slag are recovered from treated wastes and fly ash is generated as waste to landfill.

Figure 4 shows the material flow of mixed waste treated by FB. In this process, the sludge is reacted in the sand which is fluidized with the hot air and the generated gas is treated in the subsequent reactors with limestone, activated carbon, heavy oil, chelating agent, cement and water to recover energy and stabilize fly ash.

3.2 Selected landfill sites

Considering landfill mining activity, it is required to select landfill sites which have a certain amount of volume with environmental incentive for landfill mining activity.

Thus the landfill sites which satisfy following 5 conditions have been selected for the present investigation.

1. The landfill sites for the municipal solid wastes.
2. The landfill sites which are already fully occupied.

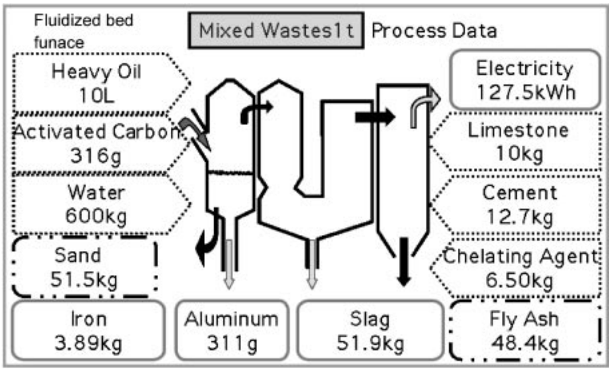

Fig. 4 Inventory data of fluidized bed type (Based on the interview).

3. The sites with insufficient leachate treatment and water shielding.
4. The sites of the capacity larger than 100,000 m^3.
5. The sites with inappropriate treatment judged by Ministry of Health, Labour and Welfare.

According to these 5 conditions, 43 final disposal sites in Japan are selected.

3.3 Classification of landfilled waste

Contents of landfilled wastes generally vary strongly depending on the local conditions, such as industrial structure, consumption patterns and the waste treatment. In Japan, the shortage of landfill capacity makes it impossible to accept the waste without pre-treatment. In the past, some local governments landfilled a part of plastics, because the insufficient refractory capacity of their incineration facilities could not accept too much plastics which generated high temprature during incineration. Therefore, the content of plastics in the watses landfilled on such period would be relatively high. On the other hand, the recent progress of incineration technologies and the improvements of their facilities make it possible to incinerate plastics in the furnace. Thus, in the present landifll site, the contents of incineration ash in landfilled waste are high.

Table 1 shows the classification of landfilled wastes, which are investigated by Environmental Bureau of the Tokyo Metropolitan Government. Waste A has high ratio of ferrous metal but with the low ratio of plastics. On the other hand, majority of waste D is plastics and its calorie is high in comparison with other 3 types of landfilled wastes. Here, we classified the waste as metal rich waste or plastic rich one, depending on the metal/plastic ratio.

Table 2 shows the change of inventory data associated with landfill mining activity about 4 types of waste weighing 1 t, which reflects the difference of waste to be re-treated and the furnace type. Inventory data of landfill mining activity, such as energy and material input and the generated residue, changes with the composition of waste.7) Composition of fly ash is affected by the input ratio of limestone, coke and chelating agent in SF, and that of activated carbon, limestone, cement and chelating agent in FB. The contents of ferrous or non-ferrous metal reflect on the recovery ratio of mixed metal in SF, and recovery of Fe and Al in FB. Electric power sale depends on calorie contents of wastes, and the contents of nonflammables cause the residue from FB increase.

Table 1 Classification of Landfilled Waste (Based on the Interview about investigation of Chubou landfill site in Tokyo Pref.).

	A	B	C	D
Paper	5.70	3.49	0.55	0.31
Textile	0.08	2.38	0.28	0.42
Garbage	—	—	0.24	—
Plant · Wood	1.59	13.38	0.42	0.35
Other flammables	—	—	3.87	8.72
Plastics	7.64	18.10	15.54	32.99
Rubber and Leather	—	0.38	0.24	0.09
Ferrous metal	7.21	5.14	1.99	0.99
Non-ferrous metal	—	—	0.36	0.59
Glass	0.67	6.69	1.25	0.98
Stones · Ceramics	17.59	8.39	0.62	—
Other Nonflammable	59.52	42.05	74.64	54.56
Total (%)	100	100	100	100
Calorie (kcal/kg)	225	716	1,238	2,369
Bulk Density (t/m^3)	0.82	0.46	0.23	0.22
Ash Content (%)	91.86	76.05	72.28	57.93

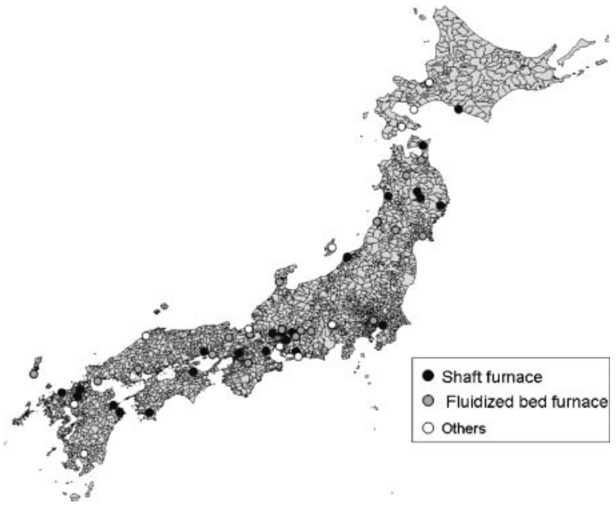

Fig. 5 Geographical conditions.

3.4 Geographical conditions

Figure 5 shows the location of the gasification melting furnace plants (SF and FB) in Japan.[8] Here we assume the one-to-one relationships of final disposal site for landfill mining and gasification melting furnace plant. Some examples of such one-to-one relationship in north area of Japan are demonstrated in Fig. 6.

The waste for landfill mining is trasported through the principal road between landfill sites and gasification furnace plants, and the distance is estimated by ArcGIS.[9] According to such procedure, average distance of transportation is evaluated as 60.6 km (min 3.9-max 123.2 km). Then, it is assumed that the waste is transported by truck of which loading capacity is 4 t and fuel efficiency is 4 km/diesel oil L, total transportation frequency including a return trip is 45,420(= 90,840 t ÷ 4 t × 2). Thus it can be calculated that total transportation is 2,752,452 km(= 60.6 km × 45,420), and total consumption of diesel oil is 688,113 L (= 2,752,452 km ÷ 4 km/L).

Table 2 Change of inventory data associated with landfill mining activity for 4 types of landfilled waste weighing 1 t.

			Shaft furnace type			
			Waste A	Waste B	Waste C	Waste D
Input	Limestone	(kg)	+21.28	+11.86	+1.06	+9.61
	Coke	(kg)	16.95	+9.45	+0.86	+7.66
	Water	(kg)	—	—	—	—
	LPG	(kg)	−0.33	−0.86	−1.43	−2.65
	Chelating agent	(kg)	+0.67	+0.37	+0.03	+0.30
Recovery	Mixed Metal	(kg)	+20.44	+11.40	+1.04	+9.24
	Slag	(kg)	+56.76	+31.46	+2.46	+25.43
	Electricity	(kwh)	−17.90	−14.1	−10.10	−13.00
Output	Fly ash	(kg)	+3.08	+1.72	+0.16	+1.39

			Fluidized bed type			
			Waste A	Waste B	Waste C	Waste D
Input	Heavy oil	(kg)	—	—	—	—
	Activated carbon	(kg)	−0.22	−0.14	−0.04	−0.12
	Water	(kg)	—	—	—	—
	Limestone	(kg)	−3.29	−2.00	−0.51	−1.69
	Cement	(kg)	+1.99	+1.13	+0.14	+0.92
	Chelating agent	(kg)	+1.05	+0.61	+0.10	+0.51
Recovery	Ferrous metal	(kg)	+0.72	+0.45	+0.14	+0.38
	Aluminum	(kg)	+0.16	+0.11	+0.05	+0.09
	Slag	(kg)	−23.63	−15.14	−5.41	−13.12
	Electricity	(kwh)	−11.30	−8.10	−4.70	+2.70
Output	Sand	(kg)	−7.98	−16.57	−26.42	−18.60
	Fly ash	(kg)	+2.56	+1.58	+0.45	+1.30

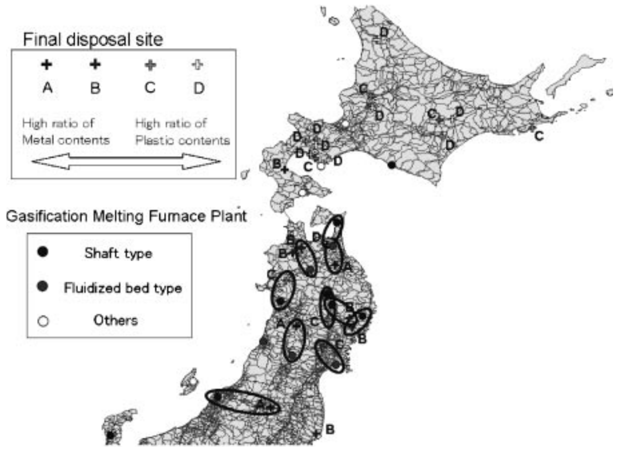

Fig. 6 One to one relations of final disposal site and gasification melting furnace plant.

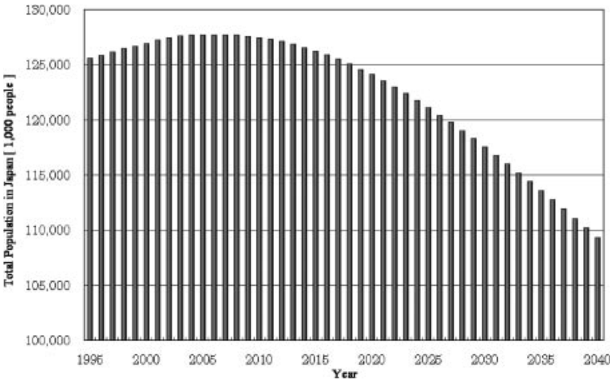

Fig. 7 Prediction of total population in Japan.

3.5 Scenarios

Based on the conditions mentioned above, 3 scenarios are considered. The case without landfill mining activity (present situation) is considered in Scenario 1. In scenario 2, landfill mining activity is carried out by the two types of gasification melting furnaces, FB and SF existing in 2000. Scenario 3 corresponds to the case with landfill mining activity by gasification melting furnaces which are newly constructed by every year from 2000 to 2040, and finally 80 plants assumed to be constructed. Thus in 2040, 1,051,400 t of landfilled waste, which is 10 wt% of landfill waste in 2000, is assumed to be treated by gasification melting furnaces. The ratio of newly constructed SF and FB is set as same as that in 2000, with a ratio of SF to FB, 25:17.[8)]

For the estimation of effects of landfill mining activity for 40 years, it is assumed that the final demand is in proportion to domestic population. Domestic population is refered to the prediction by National Institute of Social Security and Population Problems in Japan[10)] (Fig. 7).

4. Results and Discussions

4.1 The amount of waste sent to the final disposal site

It is assumed that the landfill mining activity has started since 2000. Figure 8 shows the evaluated results on the amount of waste sent to the final disposal site and the difference from the present situation (scenario 1). In this figure, the x-axis, left y-axis and right y-axis denote year, the amount of waste sent to the final disposal site and different ratio, respectively. The plots of scenario 1, 2 and 3 are on the left y-axis and difference 1 and 2 is on the right y-axis. Comparison of Scenario 1 with others indicates that the reduction rate of the amount of waste sent to the final disposal site in Scenario 2 is 0.35–0.39% and that in Scenario 3 is about 4% (in 2040). Landfill mining activity and recovery of resources such as slag, ferrous metal and plastics reduce the amount of waste sent to landfill for final disposal.

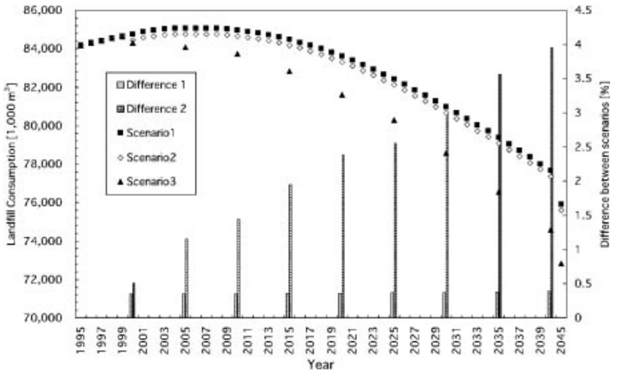

Fig. 8 The results on the amount of waste sent to the final disposal site.

Considering the result of Scenario 2 in 2000, reduction of landfill volume is 301,333 m^3, which requires the volume of landfill mining by 2.3 times, and 21% of the reduction of landfill volume is caused by recovery of slag. On the other hand, sand and rubble as backfill wastes which are discharged in the separation process of landfill mining waste, and cover soil cause inefficiency for landfill saving. Sand and rubble are generated by 112 and 29% of total reduction amount of landfill volume, respectively.

Considering the results of Scenario 3 in 2000, similar effects can be seen. The difference of the results of scenario 2 and 3 mainly comes from the replacement of the gasification furnace plants. However the amount of wastes discharged by the replacement of the gasification furnace plants are much smaller than the one of discharged by digging up/separation of landfill mining waste, so it doesn't have a big effect on scenario results of landfill consumption.

4.2 CO_2 emission

Figure 9 shows the difference between the results compared with scenario 1 in terms of CO_2 emission per year. It should be noted that the increase of CO_2 emission in 2021-22 depends on the reconstructing of facilities. It can be shown from the figure that the amount of CO_2 emission has been evaluated to be less in scenario 2 and 3. It is mainly because in scenario 1, most of municipal waste is treated by existing incineration plants which have ineffective electric power generation. Thus the reduction rate of CO_2 emission compared with Scenario 1 is 15.78% (Scenario 2) and 24.56–24.80% (Scenario 3). However, SF needs much energy and input for operation, mainly due to the consumption of coke, so that SF would emit more CO_2 than FB.

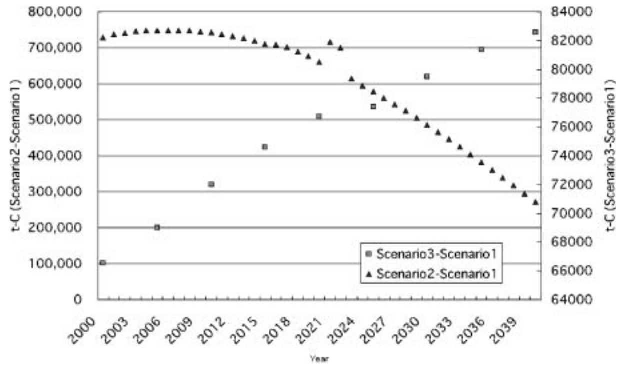

Fig. 9 The comparison between Scenario 1–2 and Scenario 1–3 in terms of CO_2 emission.

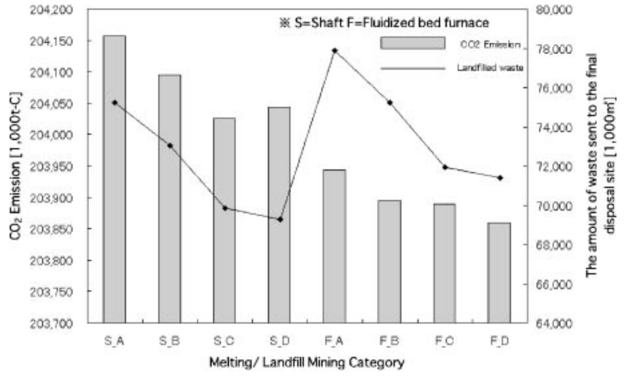

Fig. 10 Comparison of scenario results.

4.3 Comparison of scenario results

Here we will discuss based on the results which are assumed to treat landfill mining waste A $\sim$ D respectively by SF or FB. Landfill mining waste, 960,000 t/year is assumed to be treated as scenario 3 in 2040.

Scenario results of the amount of waste to landfill and CO_2 emission are dependent on melting furnace type and the composition of landfill mining wastes as shown in Fig. 10. In this figure, the bar graph indicate CO_2 emission and line graph indicate the amount of waste sent to be landfilled with the x-axis, left y-axis and right y-axis which denote the combination of furnace and waste type, CO_2 emission and the amount of waste sent to be landfilled, respectively.

Higher the ratio of plastics included in the landfill mining waste, smaller the landfill consumption, and CO_2 emission shows the same trend. It mainly comes from bulk density of plastic rich waste is smaller than the metal rich waste, and calorie of landfill mining waste D is higher than that of A (about CO_2 emission). A comparison between furnace types gives the implication that plastic rich wastes are to be treated by FB from the viewpoint of landfill saving. Giving the weight of CO_2 emission, one can derive the opposite implication.

5. Conclusion

In this work, we have extended the WIO model for environmental assessment on the landfill mining activity, which means digging up landfill wastes; recovery of resources and energy by the gasification melting furnace, and saving remaining landfill capacity. Landfill consumption and CO_2 emission have been estimated based on three kinds of scenarios with two types of melting furnaces of fluidized bed furnace type and shaft furnace type, and four types of landfilled wastes.

In the view point of landfill consumption, each gasification melting furnace can decrease the volume of waste and save the existing landfill space. The results indicate SF seems to have more potential for decreasing volume of wastes because of less emission than FB.

In this work, we have indicated that landfill mining activity is effective for sustainable management of landfill sites. However, due to limited assessed landfilled waste components, we need to extend the present model to other landfilled wastes which have various components for a future work.

There are currently more than 300 waste incineration plants in operation in Japan with a total capacity exceeding 50 million tons/unit. The recovery of energy for heat and power production is dependent on local conditions and in particular on the national waste management strategy and landfill policy.

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