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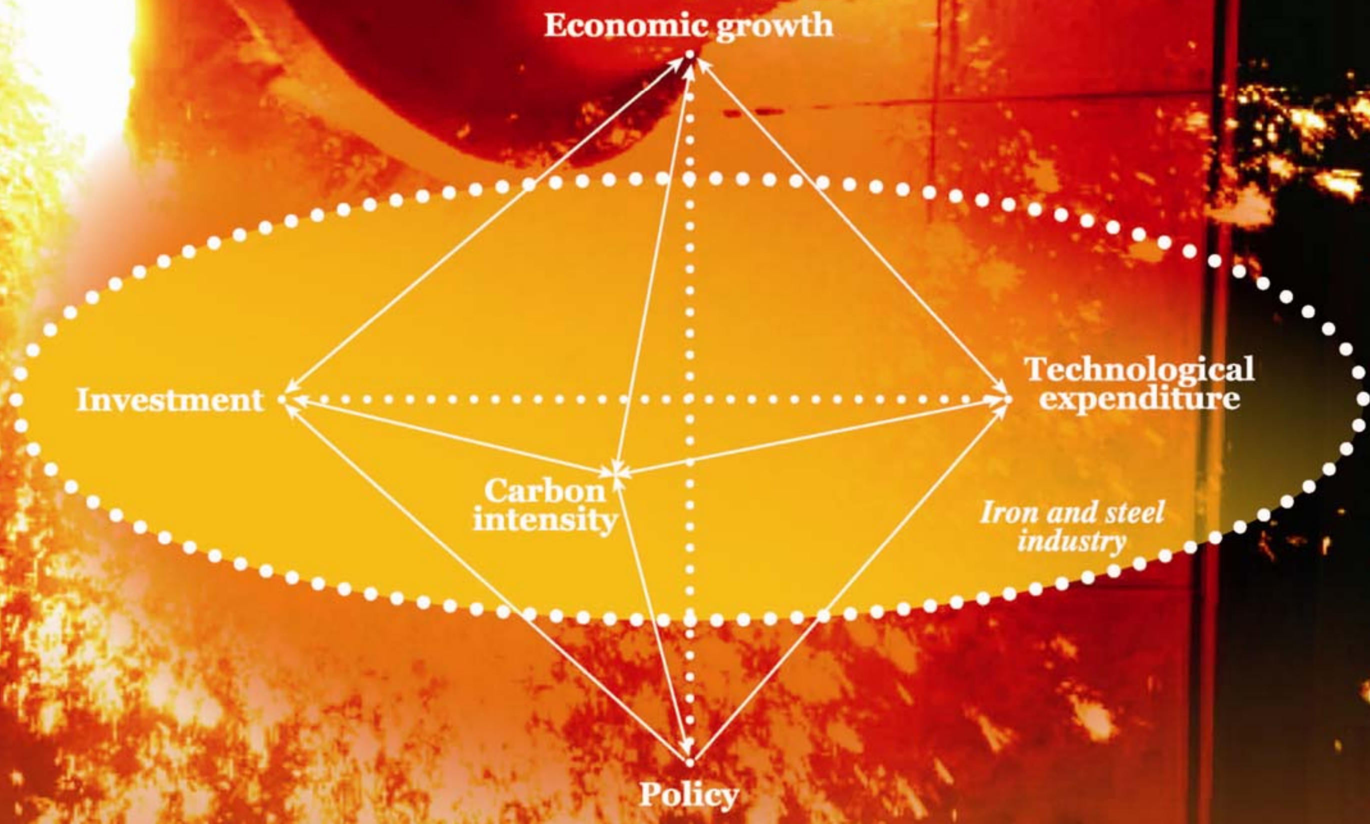

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Effects of introducing energy recovery processes to the municipal solid waste management system in Ulaanbaatar, Mongolia

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ABSTRACT

Currently, most developing countries have not set up municipal solid waste management systems with a view of recovering energy from waste or reducing greenhouse gas emissions. In this article, we have studied the possible effects of introducing three energy recovery processes either as a single or combination approach, refuse derived fuel production, incineration and waste power generation, and methane gas recovery from landfill and power generation in Ulaanbaatar, Mongolia, as a case study. We concluded that incineration process is the most suitable as first introduction of energy recovery. To operate it efficiently, 3Rs strategies need to be promoted. And then, RDF production which is made of waste papers and plastics in high level of sorting may be considered as the second step of energy recovery. However, safety control and marketability of RDF will be required at that moment.

Introduction

According to the fourth report of the Intergovernmental Panel on Climate Change (IPCC), the global contribution of waste and wastewater to greenhouse gas (GHG) emissions in 2004 was 2.8%. Majority of this was due to methane gas produced from landfill (Intergovernmental Panels on Climate Change working group III, 2007). In most developing countries, there has been remarkable increase in population, economic growth, accompanying urbanization and lifestyle changes. As a consequence, municipal solid waste (MSW) generations have rapidly increased and the composition of MSW has become more diverse. Mongolia is no exception to this which keeps rapidly growing with the development of mineral resources mining in recent years. Presently, Ulaanbaatar, which is the capital of Mongolia, is seeking to establish a new MSW management system. In the “Solid Waste Management Plan for Ulaanbaatar City, Mongolia” drawn up by the Japan International Cooperation Agency (JICA), a process of separating paper and plastic from waste, using them as raw materials for producing refuse derived fuel (RDF) and using the RDF as a coal substitute fuel in a coal

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fired power station is proposed (Japan International Cooperation Agency, 2007). The goals of this plan include recovering energy from waste in Ulaanbaatar's MSW and reducing landfill volumes.

Most developing countries in Asia have not set up MSW management systems with a view of using energy from waste or reducing GHG emissions. However, among the developed countries in Asia, Japan and South Korea are energetically working toward these goals. In Japan, about 70% of MSW are incinerated and electricity is generated by waste power generation plants in large municipalities. In the 1990s, the production of RDF from MSW attracted interest as a solution for local governments concerned with landfill volumes in MSW management. However, there were many accidents in the production of RDF and the demand for the RDF was low, so this interest has waned. On the other hand, in South Korea, incineration is not yet widely used and the emphasis has mainly been on recycling and landfill. With regard to energy recovery, methane recovery and power generation plant with a capacity of 50 MW (among the largest in the world), have started to operate at a landfill site in Seoul Metropolitan area. During interviews in Seoul Special City in September 2011, the authorities indicated that they would actively promote incineration and waste power generation for Seoul in the near future (Toshiki, 2012). Moreover, now RDF production has been introduced there. In 2011, we confirmed that RDFs were made using plastic and paper from household waste in a landfill site. And during interviews in the city in October, 2013, we confirmed that RDFs were made from sewage mixed with kitchen waste.

In regard to energy recovery processes in MSW management, the efforts of these two Asian developed countries in waste power generation, methane recovery and power generation deserve attention as showing the way for future MSW management systems in Asian developing countries.

After that plan was drawn up, JICA firstly addressed the reinforcement of MSW collection ability in Ulaanbaatar. Therefore, collection rate of household waste gradually improved. Currently, incineration has not been installed but a RDF production facility was built in 2011 by Korea International Cooperation Agency (KOICA). However, this facility has not operated in earnest so far. Therefore, MSW disposal depends on landfilling even now. When we went to the landfill sites in Ulaanbaatar and interviewed the administrator in 2012, it is said that the quantity of MSW brought to the landfill site was increasing. Ulaanbaatar city government newly built a small landfill site which has operated from 2012 to deal with the problem, although the landfill sites in the city are open-dumpsites with large environmental loads. Combustible gases generated from dumpsites catch fire and smokes always go up. In addition, there is the specific problem in Mongolia that domestic cattle of neighbor nomads often enter an open dumpsite to seek food. Therefore, MSW management that depends on landfilling is unpreferable. Accordingly, we have studied the likely effects of introducing the above energy recovery processes either as a single or combination approach in a future MSW management system in Ulaanbaatar.

The reason for having selected Ulaanbaatar as a case study is as follows: In order to examine the energy recovery processes from MSW, it is necessary to calculate the calorific value of the kinds of waste. Therefore, the composition data of MSW is required and the data of Ulaanbaatar had been investigated and released by JICA. Such data is usually unavailable except for the data of metropolises in developing countries. There are many local cities on a scale of a few million people in developing countries and the data of such rural cities is unavailable. Thus, having Ulaanbaatar as a case study is significant, when examining the directions of the future energy recovery in these cities.

1. Material and method

Firstly, on the basis of interviews and collected documents, we estimated population change, economic growth and other factors in Ulaanbaatar. MSW generation was then predicted. After that, we specified scenarios in which a number of energy recovery processes would be used in the MSW management system, such as RDF production, incineration and waste power generation, and methane recovery from landfill and power generation. Then we quantitatively evaluated their effects on energy recovery, GHG emissions and landfill volumes. Working from the results of this evaluation, we compared the attributes of the different scenarios.

1.1. *Assumptions for scenario analysis*

1.1.1. *Population changes in Ulaanbaatar*

There are roughly two residential areas in Ulaanbaatar. One is "the planned area" where residents live mainly in the apartment and infrastructure is maintained. The other is "the ger area" which spreads out to surround the apartment area. The ger area residents live in gers which are the Mongolian traditional yurt, or houses.

When predicting future MSW generation volumes in the SWMP, JICA used population change predictions shown in an urban master plan that was approved by Ulaanbaatar in 2001. However, there are two problems with this master plan. Firstly, many of the residents of the ger area did not register as citizens when they migrated to Ulaanbaatar from the provinces, so these people were not reflected in statistics published by the central government (National Statistical Office of Mongolia, 2002). Secondly, the master plan stated that the population of the ger area would be greatly reduced by subsequent housing policy. In reality, apartment construction has not kept up with the influx of people from the provinces and, because living in a ger is overwhelmingly less expensive; the population of the ger area is even now steadily increasing. The population change predictions in the master plan have already diverged greatly from the realities on the ground. For example, the master plan predicted that the population of Ulaanbaatar would be around 870,000 in 2005, of which around 52%, or 450,000 people, would be in the planed area and around 48%, or 420,000 people, in the ger area (Japan International Cooperation Agency, 2007). Hence, with the construction of apartments, the master plan estimated that in 2008 the population of the planned area would be around 610,000 and the population of the ger area around 310,000. However, according to a World Bank report, the population of Ulaanbaatar in 2007 was over 1 million, of whom around 60% were estimated to be living in the ger area. The report predicted that the population of Ulaanbaatar would be around 1.3 million in 2015 (Kamata et al., 2010).

Therefore, using the population change predictions in the World Bank report, we specified a population of Ulaanbaatar in 2015 of around 1.3 million and, taking account of the steadily increasing proportion of the population in the ger area, we specified the population changes of the respective areas in three steps as shown in Table 1. When this predicted population of Ulaanbaatar is compared with the population of Mongolia predicted by the Department of Economic and Social Affairs, United Nations (Department of Economic and Social Affairs Homepage, United Nations), we think that the predicted population in Table 1 is appropriate. In Mongolia, there is no big city except Ulaanbaatar, where industry is underdeveloped and employment is not enough in the provinces. There is a strong tendency to overconcentrate in Ulaanbaatar, and the factor which solves this problem is yet to be found.

1.1.2. Economic growth rate in Ulaanbaatar

As the economy grows, the waste generation rate of the citizens also grows. Therefore, to predict MSW generation volumes in Ulaanbaatar up to 2025, it is necessary to specify economic growth rates for the city. On the basis of economic growth rates from 2000 to 2003, the SWMP predicted economic growth rates for Ulaanbaatar averaging 5.5% up to 2020. However, a report of Asian Development Bank predicted economic growth of 7.0% from 2008 to 2010, 7.5% from 2011 to 2020, and a slowdown thereafter to about 6.8% around 2027 to 2030 (Wallack, 2009).

Focusing on the differences in population changes and household waste generation rates between the planned area and the ger area, we assumed economic growth rate for Ulaanbaatar to be 7.0%–7.5% from 2007 to 2025 in three steps as shown in Table 2. Then we specified that the economic growth rates of respective areas (weighted using the population proportions shown in Table 1) match the overall economic growth rate of Ulaanbaatar. The economic growth rates that we calculated are also displayed in Table 2.

Table 2 – Predicted economic growth rates of the areas of Ulaanbaatar used in our study.

Duration	Economic growth rate		
	Planned area	Ger area	Ulaanbaatar
2007–2015	7.5%	9.3%	4.7%
2016–2020	7.3%	9.0%	4.5%
2021–2025	7.0%	8.6%	4.3%

1.1.3. Predicted values for household waste generation volumes in Ulaanbaatar

Household waste generation rates in the respective areas in 2005 are shown in Table 3. These values were calculated on the basis of household waste generation per capita per day that had been obtained in survey by JICA in summer and in winter seasons of 2005 (Japan International Cooperation Agency, 2007), the summer season being 154 days and the winter season being the other 211 days. The 211-day winter season is the period during which the Ulaanbaatar city central heating system operates.

The generation growth rates of kitchen waste and other wastes such as containers and wrappings (paper, plastic, metal, bottle, and glass) have a strong correlation with the economic growth rate so that we used a proportionality coefficient of 0.55 calculated from records for Japan as described in the SWMP. In brief, when an economic growth rate is 1%, household waste generation will increase by 0.55%. We set the growth rate for textiles, leather and rubber, which currently have a very low generation rate, to half of the above mentioned 0.55. We assumed that the waste generation rates of yard waste, ceramic and stone, ash, and other incombustible waste do not change. We used basically the same waste generation rate calculation method as the method used in the SWMP. Using these specifications, we predicted household waste generation volumes in Ulaanbaatar from 2010 to 2025.

1.2. Scenario specification

We specified scenarios in which future processes for household waste management and energy recovery are incorporated beside the RDF production process proposed in the SWMP: incineration with waste power generation, methane gas recovery and power generation in single or combination approach. Table 4 shows the specified scenarios and the household waste management processes in each scenario.

We estimated energy recovery amounts, GHG emissions, and landfill volumes for the above seven scenarios, running from 2015 to 2025. In addition to the result of this quantitative analysis, we considered efficiency and practicability, and we draw up and compared the advantages and disadvantages of each of the scenarios.

1.3. Methods of calculating energy recovery amounts, GHG emissions, and landfill volumes

1.3.1. Calorific values of household waste

Equations for finding calorific values from chemical constitutions of waste include the Dulong equation, the Steuer equation, and the Scheurer Kestner equation. In our study, the Steuer equation was used because it is most suitable to MSW (Tanaka et al, 2003). However, the chemical constitutions of MSW in Ulaanbaatar were unclear, and only the data on the moisture content was available from a survey by JICA (Japan International Cooperation Agency, 2007). Therefore, firstly, the dry basis chemical constitution of each waste was calculated from the basis of chemical constitution surveys in Tokyo (Masuko et al, 2000; Oikawa et al, 2001). Then, taking account of the moisture contents of each waste in Ulaanbaatar provided by JICA survey, the wet basis chemical constitutions of each kind of waste in Ulaanbaatar was estimated. Using this data

Table 1 – Predicted population changes of the areas of Ulaanbaatar used in this study.

Year	Population growth rate		Population in Ulaanbaatar (proportion of respective areas)			Predicted population in Mongolia[a] (proportion of Ulaanbaatar population)
	Planned area	Ger area	Planned area	Ger area	Total	
2007	2.8%	3.6%	400,000 (40%)	600,000 (60%)	1,000,000 (100%)	2,612,900 (38%)
2015	2.5%	3.5%	498,890 (38%)	796,213 (62%)	1,295,103 (100%)	2,975,000 (44%)
2020	2.3%	3.3%	564,448 (37%)	945,651 (63%)	1,510,099 (100%)	3,186,000 (47%)
2025			632,415 (36%)	1,112,327 (64%)	1,744,742 (100%)	3,370,000 (51%)

[a] Source is from the Population Estimates and Projections Section, Population Division, Department of Economic and Social Affairs homepage (2012).

Table 3 – Household waste generation rate per capita in the areas of Ulaanbaatar in 2005.

Unit	Planned area			Ger area		
	Summer[a]	Winter[a]	Throughout the year	Summer[a]	Winter[a]	Throughout the year
	(g/capita day)	(g/capita day)	(kg/capita year)	(g/capita day)	(g/capita day)	(kg/capita year)
Combustible total	192.0	195.9	70.9	148.7	103.2	44.6
Kitchen waste	83.9	86.3	31.1	63.2	46.8	19.6
Paper	51.0	33.5	14.9	28.9	22.9	9.3
Textile	9.6	12.1	4.0	12.9	9.6	4.0
Plastics	34.1	59.1	17.7	33.9	21.0	9.6
Grass and wood	12.5	2.9	2.5	8.1	1.9	1.7
Leather and rubber	0.9	1.8	0.5	1.7	1.0	0.5
Incombustible total	43.0	68.1	21.0	59.3	852.8	189.0
Metal	4.2	10.6	2.9	13.3	5.7	3.3
Bottle and glass	22.3	32.7	10.3	26.8	28.7	10.2
Ceramic and stone	15.3	11.6	4.8	14.8	8.6	4.1
Miscellaneous	1.2	13.2	3.0	4.4	17.2	4.3
Coal ash	0.0	0.0	0.0	0.0	792.5	167.2
Total	235.0	264.0	91.9	208.0	956.0	233.6

[a] Source is from JICA (2007).

and the Steuer equation, a calorific value for each waste was calculated. The chemical constitutions and calculated calorific values of the household waste are presented in Table 5.

1.3.2. GHG emissions originating from household waste in each scenario

As the GHGs produced from RDF and waste incineration, carbon dioxide (CO_2) emissions originating from waste plastic were calculated. Since CO_2 emissions originating from other combustible waste such as kitchen waste are carbon neutral, they are not added to GHG emissions. Methane and nitrous oxide (N_2O) are also produced from waste incinerators and from RDF. However, the greenhouse effect of these gases is less than 1% of that of CO_2 so we disregarded them in this study. For CO_2 emissions from RDF and waste incineration, we assumed that all waste plastic is completely incinerated and took the carbon content in waste plastic, shown in Table 5, to be 64.9% for our calculation.

For landfill, the methane emitted from landfill site is calculated as GHG emissions. Where methane is recovered and used for power generation, the uncollected methane is calculated. The CO_2 produced by the combustion of methane at power generation is not added to GHG emissions, because it is carbon neutral. We calculated the methane emitted from landfill site using the calculation method given in “Guidelines on Calculating Greenhouse Gas Emissions from Businesses” (Global Environment Bureau, the Ministry of the Environment of Japanese Government, 2003). We converted the amount of

Table 4 – Specified scenarios and MSW management processes in the scenarios.

		Kinds of combustible waste			GHG emissions resources
		Paper & plastic	Other combustible waste	Kitchen waste	
Scenario	A: Baseline (current situation)	Sent directly to landfill (no methane recovery)			A1. Methane produced from the landfill site by decomposition of organic matter
	B. RDF Production (as in the SWMP)	Raw materials for RDF	Sent directly to landfill (no methane recovery)		B1. As A1 B2. Carbon dioxide produced from waste plastic by the incineration of RDF in a coal-fired power station
	C: Incineration & waste power generation	Incinerated (energy recovery by waste power generation)			C1. Carbon dioxide produced from waste plastic in an incinerator
	D: Methane recovery & power generation	Sent directly to landfill (methane recovery & power generation)			D1. Of A1, methane that cannot be recovered
	E: RDF production with methane recovery & power generation	Raw materials for RDF	Sent direct to landfill (methane recovery & power generation)		E1. As D1 E2. As B2
	F: Incineration & waste power generation with methane recovery & power generation	Incinerated (energy recovery by waste power generation)		Sent direct to landfill (methane recovery & power generation)	F1. As D1 F2. As C1
	G: RDF production with incineration & waste power generation	Raw materials for RDF	Incinerated (waste power generation)		G1. As B2

Table 5 – Estimated amounts of chemical constitutions and calorific value for different kinds of household waste in Ulaanbaatar.

	Moisture (%)	Ash (%)	Carbon (%)	Hydrogen (%)	Nitrogen (%)	Oxygen (%)	Combustible sulfur (%)	Volatile chlorine (%)	Calorific value (kJ/kg)
Kitchen waste	60.0	4.6	16.9	3.0	1.0	14.3	0.0	0.1	6109
Paper	25.0	7.7	31.3	4.5	0.1	31.2	0.0	0.1	11,478
Textile	14.0	0.6	43.7	5.0	5.4	30.7	0.1	0.6	16,629
Plastic	12.0	4.9	64.9	9.3	0.2	5.9	0.0	2.7	32,353
Yard waste	25.0	26.0	24.2	3.3	1.0	20.3	0.0	0.1	9051
Leather and rubber	1.0	4.0	57.0	7.4	1.3	20.6	0.1	8.7	25,754

methane to equivalent amount of CO_2 to calculate the GHG emissions' amount, taking the greenhouse effect of methane as being 21 times per unit weight as strong as that of CO_2.

1.3.3. RDF production and use as fuel in coal fired power station

RDF described in the SWMP is made of paper and plastic so that it is similar to refuse paper and plastic fuel. Therefore, we assumed that the drying process, which would require large amounts of energy for RDF production, would not be necessary. For when RDF is used as a substitute fuel in a coal fired power station, we used a thermal efficiency of 34%, the thermal efficiency of the number 4 coal fired power station that provides about 70% of electricity supplies to Ulaanbaatar (Japan External Trade Organization, 2007). This thermal efficiency value includes heat provision as well as electricity provision. The RDF will be used in existing power stations and hot water supply facilities, so we did not consider the amount of consumption within these existing facilities themselves. In regard to the ash when RDF has been burned in a coal fired power station, we used the ash contents of waste paper and plastic in Table 5 and assumed that the ash will be transported to a landfill site.

1.3.4. Energy recovery at incinerators

Incineration and waste power generation have become commonplace in Japan. Incinerators widely used are continuous stoker incinerators. Considering the prediction of combustible waste generation in the future, we assumed that a 450 ton per day class incinerator is required in Scenarios F and G, and two incinerators of the class are required in Scenario C (Appendix A). The average of energy recovery rate of waste power generation less than 1000 tons more than 100 tons that utilizes surplus heat for waste power generation in 2010 was around 14.3% (Ministry of the Environment of Japan Government, 2011). Moreover, considering the electricity consumption for incineration facility self, 160.21 TJ subtracted from 14.3% of calorific value of waste that incinerated left the quantity of electricity as new energy (Appendix B).

On the other hand, most of incineration facilities also utilize surplus heat for heat supply in Japan. It was thought that the incineration facilities which were in the cold region or in the area where there were many buildings such as apartment houses and public facilities in the neighborhood utilized surplus heat positively. In Ulaanbaatar, the demand of heat is high because winter season is long and very cold. Moreover, almost all apartments and buildings in the planned area are connected to the central heating system. If an incineration facility is installed, it has to recover and supply heat positively. Therefore, the incineration facilities in Japan where the heat that recovered was over 100 TJ were extracted and the average of energy recovery rate of these incineration facilities was around 37.7%. Moreover, considering that almost of the facilities which utilized surplus heat consumed 95.8% of the heat that recovered for itself, around 1.6% of calorific value of waste that incinerated can be considered to be new energy produced by incineration facility (Appendix C). In addition, amounts of ash produced in the incinerator were calculated from the ash contents of the different kinds of waste in Table 5 and it was assumed that the ash will be transported to a landfill site.

1.3.5. Methane recovery and power station generation at landfill site

According to a 2010 report from the United Nations Environment Programme, the recovery rate of methane produced from a landfill site is around 50%–80% in developing countries (United Nations Environment Programme, 2010). According to Japan's New Energy and Industrial Technology Development Organization, the power generation efficiency when recovered methane is used is 25%–35% in gas engines and gas turbines (New Energy and Industrial Technology Development Organization, 2010). According to the responses in interviews that we conducted on visits to a landfill site and a methane gas recovery and power generation facility in Seoul Special City in September 2011, the methane recovery rate there is 70%, of which 95% is combusted and contributes to power generation and the power generation efficiency is around 30%. Taking account of variations in methane gas recovery and energy usage amounts in power generation facilities such as gas engines, for this study we specified a methane recovery rate of 60% and a power generation efficiency of 25%. We assumed that the usable years of a methane gas recovery and power generation facility are for 20 years after 2015. Because of the use of gas engines and the distances from landfill sites to areas of dense housing, we assumed that the methane would not be used for heating schemes.

2. Results and discussion

2.1. Predicted values for household waste generation volumes in Ulaanbaatar

Household waste generation volumes in Ulaanbaatar from 2010 to 2025 were predicted. The results are shown in Fig. 1. For waste from business activities and public area cleaning waste, these generation rates are unclear and volumes are relatively small, so we performed our calculations only for household waste. The proportion of all MSW in Ulaanbaatar that is accounted for by household waste is 75.1% in the summer season and 91.6% in the winter season (Japan International Cooperation Agency, 2007).

The proportion of coal ash in waste from the ger area will be very high up to 2025. What it means is that, if an increasing population of the ger area is assumed as our study, the landfill volumes including coal ash will be very high and it can be assumed that the lifespans of landfill sites will be short. On the other hand, the proportion of combustible waste which was 33% in 2007 will be 44% in 2025. Of this, the proportion of kitchen waste, paper and plastic will be 20%, 10% and 11%, respectively.

With the assistance of JICA, Ulaanbaatar prepared the new Narangiin Enger landfill site to the north side of the Ulaanchuluut landfill site, which had been in use for a long time. The Narangiin Enger landfill started operation in 2009. Mongolia has a small population and a large area, so large amount of land is available. However, because Ulaanbaatar is located in a bowl and surrounded by mountains, there may not be sufficient land in the environs of the city that is suitable for landfill sites. In addition, the ger area is spreading at the fringes and has many unpaved roads. Selecting land for new landfill sites at locations that are moderately distant from the ger area, not distant from the city, and accessible by garbage trucks is not a simple matter. Therefore, the new landfill sites such as Narangiin Enger must be made to last for as long as possible. It is significant to reduce landfill volumes of this combustible waste and the coal ash.

2.2. Results in cases of each energy recovery process incorporated

Fig. 2 shows changes in energy recovery amount, GHG emissions, and landfill volumes respectively in the scenarios. Meanwhile, Table 6 shows cumulative values of these quantities, and calculated from these values, GHG emissions, and landfill volumes per unit megajoules of recovered energy. In addition, the duration of decomposition of kitchen waste, paper, textile, and yard waste is 8, 21, 21, and 103 years, respectively (Global Environment Bureau, the Ministry of the Environment of Japanese Government, 2003). That is, methane gases are produced after carrying in of waste to landfill site is stopped. Therefore, GHG emissions presented in Table 6 are cumulative values from 2010 to 2127. Moreover, energy recovery amounts by methane recovery for power generation in Table 6 are cumulative values from 2015 to 2035 as the usable years of a methane gas recovery and power generation facility. We assumed that RDF produced is used up within the year, so that energy recovery amounts of RDF, and incineration facility with waste power generation presented in Table 6 are cumulative values from 2015 to 2025. The above cumulative values mean the values originating from household waste generated from 2015 to 2025.

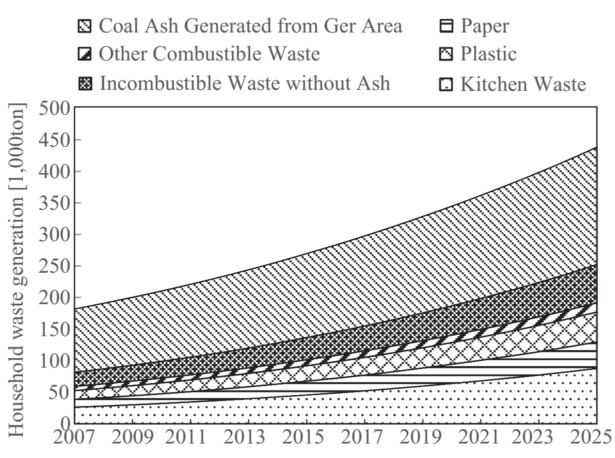

Fig. 1 – Household waste generation of Ulaanbaatar assumed in this study, predicted for 2007–2025.

2.2.1. Results in cases of each energy recovery process incorporated singly

We compared Scenarios B, C and D in which the RDF production, incineration and waste power generation, and methane recovery and power generation are individually incorporated. If the primary goal is energy recovery, the most effective scenario is Scenario B, with estimated energy recovery amounts of 5563 TJ. There is little energy recovery in Scenarios C and D compared to Scenario B. Comparing the efficiency of energy recovery relative to environmental impact in the scenarios, GHG emissions and landfill volumes per unit of energy recovered are both lowest in Scenario B. If the primary goal is a reduction of GHG emissions, the most effective scenarios are Scenarios C and D. For both these scenarios it is estimated that GHG emissions are reduced by over 50% compared to Scenario A, the current system. In contrast, GHG emissions of Scenario B are over the current system, because plastic, which would not be a source of methane in landfill, is incinerated in a coal fired power station. That is, methane gases originating from paper are decreasing while CO_2 emissions originating from plastic are increasing. If the primary goal is a reduction of landfill volumes, Scenario C is the most effective. In Scenario B, RDF is produced so landfill volumes are reduced by the amounts of paper and plastic used for the RDF, but the landfill volume reduction effect is not large.

To sum up, the scenario which can recover most energy most efficiently is the RDF production as Scenario B, while the scenario which can reduce quantity of both GHG emissions and landfill volumes with sufficient balance is incineration as Scenario C.

2.2.2. Results in cases of each energy recovery process incorporated in combination

We compared Scenarios E, F and G in which the RDF production, incineration and waste power generation, and methane recovery and power generation are incorporated in combination. From the view point of energy recovery, Scenario E is the most effective due to 6089 TJ of energy recovery amount, while from the view point of reduction of GHG emissions and landfill volumes, the most effective scenario is Scenario G. Comparing the efficiencies of energy recovery relative to environmental impact, Scenarios E and G are almost the same and lowest in the scenarios. In Scenario G, paper and plastic are used as raw materials for RDF and all other combustible waste goes to incineration facility with a process of energy recovery. Therefore, Scenario G includes a merit of Scenario B as energy recovery and a merit of Scenario C as reduction of environmental impact simultaneously. However, the energy recovery amount of waste

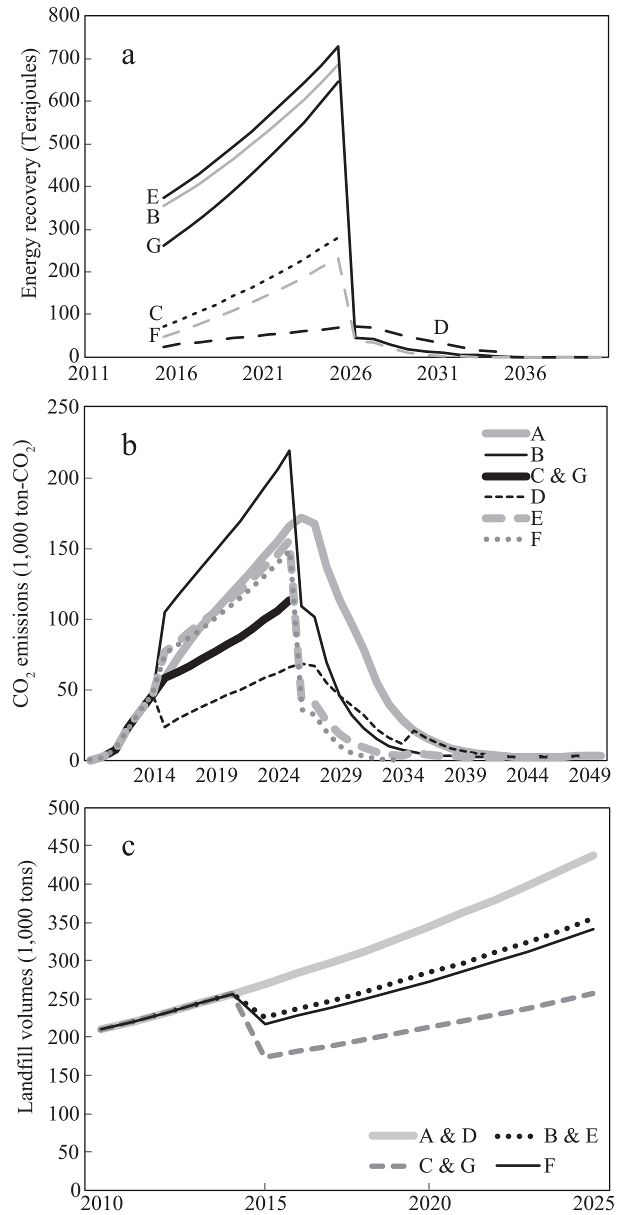

Fig. 2 – Changes in energy recovery amounts from 2015 to 2040 (a), GHG emissions from 2010 to 2050 (b), and landfill volumes from 2010 to 2025 (c).

power generation is not more than the energy consumption in the incineration facility itself as shown in Table 6.

Scenarios E and F can make some progress of reduction of GHG emissions, but they are not so good because drastic reduction of landfill volumes is not achievable.

2.3. Discussions and recommendations

Based on the above results of quantitative evaluation, we advance consideration as follows: From the viewpoints of environmental impacts and energy recovery, Scenario G is the most desirable in the future. However, because RDF is in competition with inexpensive coal, reliable supply of good quality, and low cost RDF would have to be ensured. In addition, a silo exploded in Mie Prefecture, Japan in August 2003 which resulted in the fatal injury of workers and firefighters. RDF made of MSW including kitchen waste has high fermentability and is easy to generate combustible gas. In this case, it was indicated that the unsuitable surveillance system and the irrelevant makeshift measures against initial ignition caused such severe accidents (Takeda, 2010). In Japan, introduction of RDF production in MSW management system declines at the moment because of little demand and severe accidents. The RDF proposed in SWMP for Ulaanbaatar will be made of paper and plastic so that it should have low fermentability and will be hard to generate combustible gas. However, in order to make high quality and stable RDF, papers and plastics must be finely sorted out from other wastes. Such high quality of sorting is not expected at present in Mongolia. Therefore, RDF production is difficult to manage from the viewpoint of safety control and demand reservation at present.

On the other hand, regarding incineration and energy recovery by waste power generation, safe technology is established and Japan has considerable experience of managing this technology. There is little energy recovery in Scenario C compared to Scenario B, but it is an appropriate quantity. Moreover, contribution to climate change mitigation and a lengthening of the life of landfill sites can be expected. Other advantages of incineration include the possibilities of detoxifying and mineralizing decomposing organic matter, pathogenic organisms, and harmful organic chemicals. Therefore, some effects of reducing damage to the health of waste pickers working in landfill site, and residents of the ger area or cattle of nomads close to landfill sites can be expected. In this case, collection of combustible wastes and incombustible wastes will be required separately. But it is possible for incineration to run when a few incombustible wastes are contained in combustible wastes, so that introduction of incineration is easy compared with RDF production. Moreover, the authorities are required to improve 3Rs (Reduce, Reuse, and Recycling) strategies of Ulaanbaatar. If MSW is continuously increasing as it is, it will become a big burden at MSW management and cost, because a large capacity of waste disposal facilities such as landfill site or incineration facility will be required. In this research, it is assumed that two incinerators of 450 tons per day class will be built in Scenario C. In this case, three furnaces of 150 tons per day class, for instance, will be installed in an incinerator so that 6 furnaces will be required eventually. If 3Rs strategies are improved and combustible waste generation is controlled, it may become possible to install at most 5 furnaces. Therefore, the improvement of 3Rs strategies is very important from the viewpoint of environmental impacts and costs. After 3Rs strategies promote smoothly, incineration process should be introduced firstly as shown in Scenario C. By introducing incineration and collecting combustible and incombustible wastes separately, it is desirable to give priority to sanitary disposal of wastes and reduction of environmental impact.

Then after management of separate collection and incineration is stabilized, the system may shift to Scenario G, where separate collection of paper and plastic as raw materials of RDF is further introduced as long as some criteria are met; paper and

Table 6 – Results of evaluation of each of the scenarios.

Quantity	Unit	A	B	C	D	E	F	G
GHG emissions[a]	1000 ton CO_2	2490 (100%)	2613 (108%)	1152 (48%)	964 (40%)	1736 (72%)	1581 (66%)	1152 (48%)
Landfill volumes[b]	1000 tons	4996 (100%)	4316 (86%)	3513 (70%)	4996 (100%)	4316 (86%)	4194 (84%)	3513 (70%)
Total energy recovery	Terajoules	0	5563	1855	895	6089	1570	4816
-RDF production		0	5563	0	0	5563	0	5563
-Waste power generation[c]		0	0	1855	0	0	1162	−849
-Methane recovery and power generation[d]		0	0	0	895	524	409	0
GHG emissions per unit of recovered energy	kg-CO_2/megajoules	–	0.470	0.621	1.077	0.285	1.007	0.239
Landfill volumes per unit of recovered energy	kg/megajoules	–	0.776	1.894	5.582	0.709	2.671	0.729

[a] Cumulative values from 2010 to 2127.
[b] Cumulative values from 2010 to 2025.
[c] Cumulative values from 2015 to 2025.
[d] Cumulative values from 2015 to 2035.

plastic can be sorted out from other wastes in high level, RDF has marketability compared with coal, and so on. At least, the quality should be prior to the quantity.

In addition, separate collection of coal ash which is generated from the ger area in winter should be considered. In the SWMP, and also in our research, it is assumed that coal ash is basically carried to landfill sites. If the population of the ger area increases as predicted, the concern is that large amount of coal ash will make the lifespan of landfill sites shorter. As shown in Fig. 1, it is predicted that the amount of discharge of coal ash from 2010 to 2025 will be a total of 2,344,000 tons, and the amount of annual discharge increases from 112,000 tons in 2010 to 168,000 tons in 2025. Most gers are not connected to a central heating system which supplies heat for households in Ulaanbaatar *via* hot water supply pipe network. Therefore, the residents of the ger area burn coal directly by stove, in order to warm themselves in cold season. Then, the generated coal ash is raked out from the stove and is temporarily kept with an outdoor drum or a bag. Such coal ash is usually carried by a garbage truck to a landfill site. However, illegal dumping on neighboring vacant land is also occurring frequently because there are a lot of high pitched and unpaved road in the ger area which are rendered impassable for garbage trucks. Thus, first of all, it is necessary to install household waste collection points on the sides of the roads on which garbage trucks pass by. Additionally, coal ash should be separately collected from other wastes. Coal ash which is collected separately will be recycled as the material for cement production. Although the cement industry in Mongolia does not have sufficient technical capacity and scale at the moment, considering recent economic growth and the boom in building construction, the demand for cement and the cement industry are expected to expand.

3. Conclusions

We have analyzed scenarios of future directions for the MSW management system of Ulaanbaatar in Mongolia with regard to energy recovery and environmental impact reductions. The results show that it is desirable to give priority to introduction of incineration process and separate collection compared with RDF production or methane recovery. Recently, reductions in environmental impacts are required internationally and improvement of public health is required in developing countries. In addition to that, the reduction of GHG emissions in a developing county may lead to technological and financial assistance from developed counties as part of the clean development mechanism project. Taking the above into consideration, we concluded that incineration process is the most suitable as first introduction of energy recovery. To operate it efficiently, 3Rs strategies need to be promoted. And then, RDF production which is made of waste papers and plastics in high level of sorting may be considered as the second step of energy recovery. However, safety control and marketability of RDF will be required at that moment.

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Appendix A. Supplementary data

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