Current MSW Management and Waste-to-Energy Status in the Republic of Korea

By

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EXECUTIVE SUMMARY

Rapid industrialization and urbanization have resulted in an accelerated rate of waste generation, adding to the environmental challenges on the relatively small land mass of the Republic of Korea ("South Korea"). Since the early 1990s, securing landfills for the country's waste output has become more and more difficult because of the congestion of land space and the public concern for a cleaner environment. In order to move towards a sustainable future, the government of the Republic of Korea has set periodic environmental plans and implemented several waste management policies.

The objective of this study was to examine the management of municipal solid waste (MSW) in the Republic of Korea, from generation to final disposal, in the light of the generally accepted hierarchy of waste management. The study also investigated the status of waste-to-energy (WTE) in Korea and the potential for improvement.

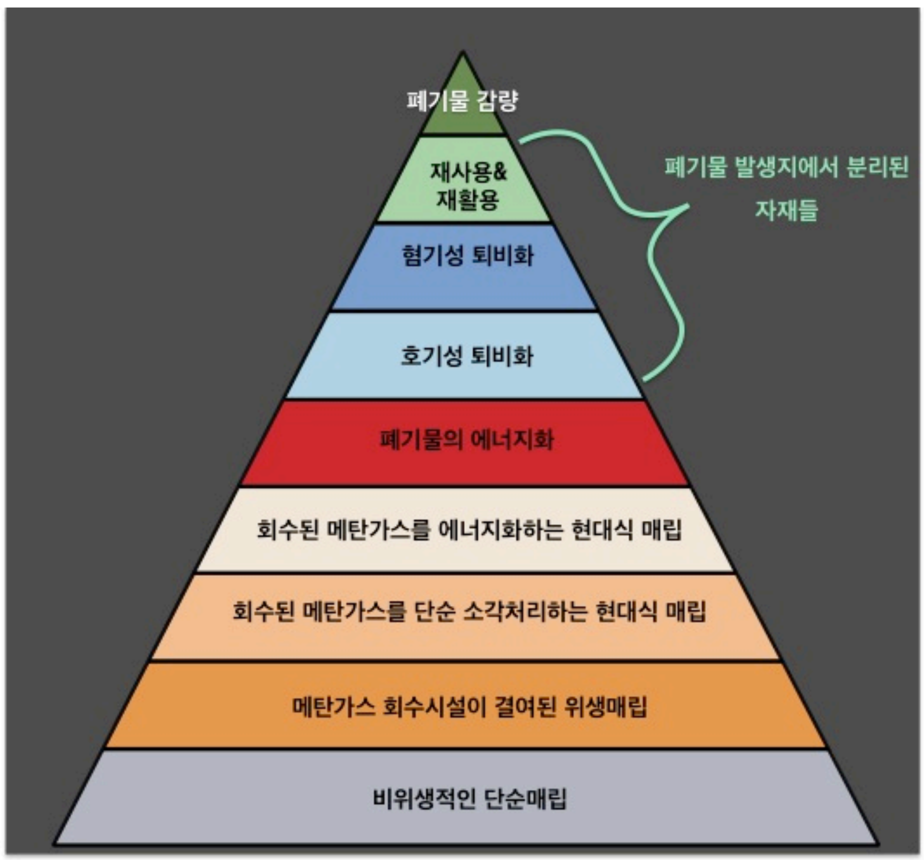
Despite of in-between growth of per capita GDP of nearly 50%, the generation of MSW decreased from 0.39 tons per capita in 1995 to 0.37 tons in 2009. Also, as a result of the implementation of national waste management policies, such as the Volume Based Waste Fee (VBWF) system, the Republic of Korea has made great progress in the area of waste management by drastically reducing the MSW landfilled from 12.6 million tons (72%), in 1995, to 3.5 million tons (19%) in 2009. This was achieved by increasing recycling and composting from 4.1 million tons (24%), in 1995, to 11.4 million tons (61%) in 2009; and increasing capacity of combustion with and without energy recovery from 0.7 million tons (4%), in 1995, to 3.8 million tons (20%) in 2009.

The priority in waste management is the reduction of waste followed by the recovery of recyclable materials through recycling and composting. Since not all wastes can be recycled, energy recovery from the non-recyclable materials is the next best waste management option. WTE is highly desirable versus landfilling in countries such as the Republic of Korea where land is scarce and energy dependence on outside sources high (96.4% in 2009). Of the total of 172 incinerators in the Republic of Korea, only 35 WTE large plants, most in metropolitan areas, are supplying energy, mostly in the form of heat. The rest are incinerators with small capacities that use the energy produced for their own needs. The 2010 capacity of the 35 WTE facilities was 3.1 million tons, accounting for 90% of the total amount of controlled incineration in Korea.

However, unlike the Republic of Korea's great success in MSW recycling, the current WTE capacity is relatively low in comparison to northern E.U. nations and Japan. In 2009, the thermal energy input to the 35 WTE plants was 8.3 million MWh of which 4.5 million MWh (1.45 MWh/ton) was provided to the nation, mostly in the form of district heat, corresponding to only 0.24% of the total primary energy supply. Since the Republic of Korea is ranked tenth in energy consumption worldwide and over 95% of its energy is imported, it is imperative that additional WTE capacity be implemented to reduce the current landfilling rate and recover energy.

Utilizing the R1 factor as specified in the European legislation, this study determined that only 22 of the 35 Korean WTE plants have R1 factors to qualify as energy recovery plants (R1>0.61), rather than waste disposal plants. By increasing their R1 efficiency factor, WTE plants can contribute to the national energy supply and CO2 emission reduction. From an emissions standpoint, all Korean WTE plants are excellent performers, with very low air emissions levels for the six most objectionable air pollutants examined. It is recommended that the Korean government adds heavy metals, such as mercury and lead, to its annual report of air emissions from WTE plants.

During the course of her Columbia studies, the author is proud to have made a small contribution to the formation of WTERT-Korea, headed by Prof. Yong-Chil Seo of Yonsei University and President of the Korea Society of Waste Management (KSWM).



Korean Hierarchy of Waste Management (by Yoonjung Seo)

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1.1 Definition of Solid Waste

1.1.1 What is Municipal Solid Waste?

Municipal Solid Waste (MSW) is commonly known as trash or garbage, and includes items that we use every day and then discard [31]. However, it is not simply trash, as it contains valuable commodities such as paper, cardboard, aluminum, steel and energy [37]. Examples include packaging material, yard waste, furniture, newspaper, cans and bottles, and food scraps. MSW generators include homes (*domestic waste*), schools and hospitals (*institutional waste*) and businesses (*commercial waste*) [36]. MSW excludes industrial waste, agricultural waste, and sewage sludge [39]. Waste collection is handled by each municipality. The collected material is transported to a processing facility, a transfer station, or a landfill.

The rate of MSW generation has been shown to increase with rising incomes [32]. One study found that in developing nations, the per capita waste generation rate ranged from 0.45 to 1.3 kg/capita/day while in developed nations, the per capita waste generation rate ranged from 0.8 to 2.0 kg/capita/day [36]. Uncontrolled dumping can lead to problems such as contaminated ground water, pests, and greenhouse gases, making solid waste management critical to human health and the protection of the environment [32].

1.1.2 What is Integrated Solid Waste Management?

Integrated Solid Waste Management covers the generation, reuse, recycling, composting, waste-to-energy and landfilling of waste, with the goal of a reduction in the amount of waste generated as well as the safe disposal of waste with the minimization of impact to human health and the environment [32].

The modern landfill is not a dump. It is a facility designed to contain solid wastes without creating hazards to public health or safety, or harming the environment [40].

The success of any waste management program depends on public awareness, long-term sustainability and technical feasibility [36].

1.2 Hierarchy of Waste Management

The hierarchy of waste management is a coordinated set of actions that classify waste management strategies from the most preferred to least preferred waste disposal method. Figure 1 shows the structure of the hierarchy of waste management.

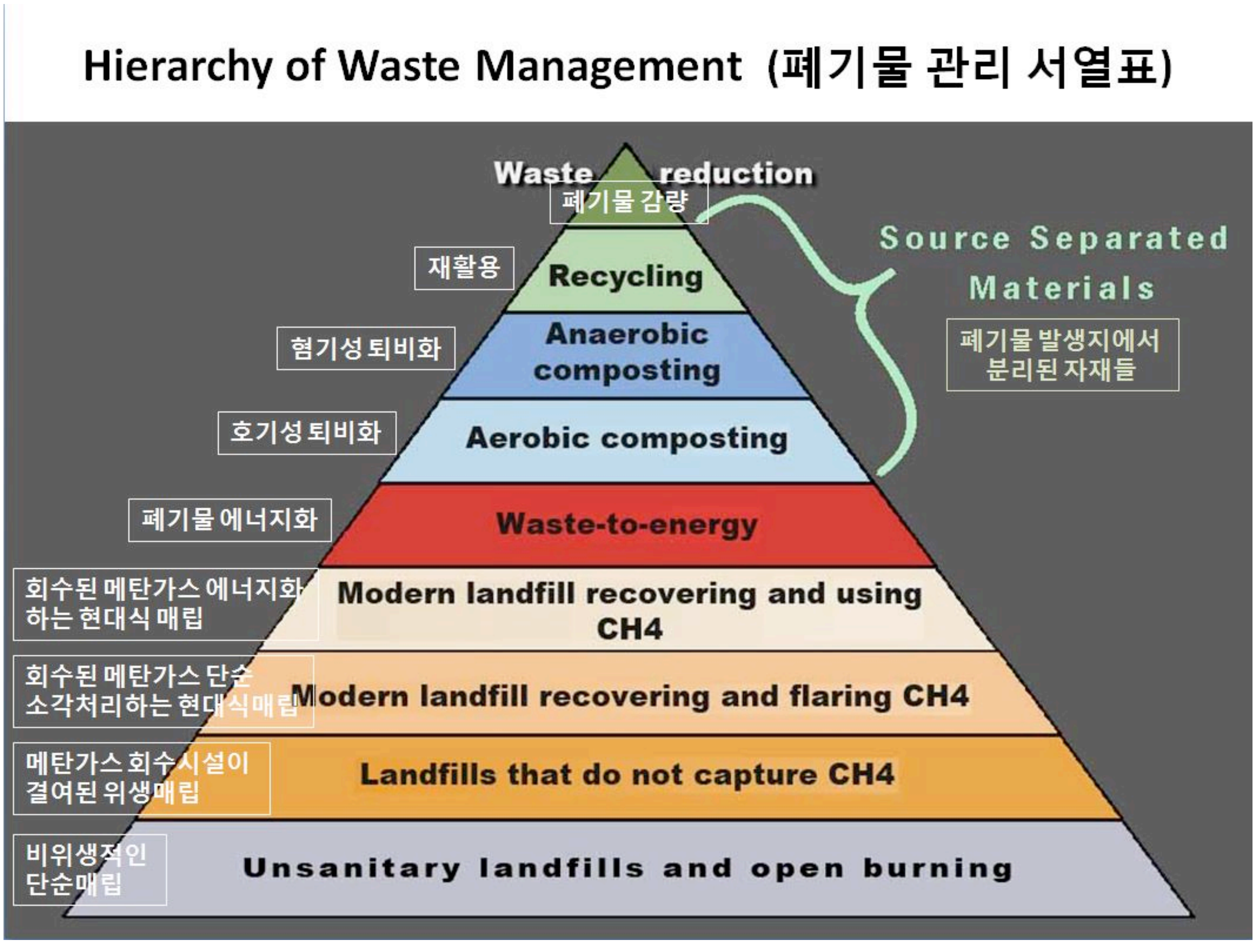


Figure 1: Hierarchy of Waste Management (WTERT, 2010; Korean translation by author)

1.2.1 Waste Reduction

Waste reduction and prevention includes the reduction in the use of packaging materials, the use of reusable items rather than disposable, and the designing of products that last longer [32]. The reduction in the amount of waste generated is a reduction in costs arising from the handling, transport, treatment and disposal of wastes as well as a reduction in the amount of methane generated [32]. Making new products requires the extraction of raw materials from the earth, the energy to process and turn those raw materials into products, and the fuel to transport those products to the consumer. Thus, reusing saves on natural and economic resources and protects the environment as well [33].

Items that are no longer desirable in affluent societies may have value in the developing world [36]. For example, food wastes from hotels are auctioned off as feed to poultry and pig farmers in India [36]. Materials of all types – construction wastes, paper, cardboard, glass, plastics, and metals – can all be utilized by the Asian countries [36]. Unwanted household items – used clothes and goods – may be gifted to the needy through charities [36]. Thus, many things need not end up in the landfill.

1.2.2 Recycling

Recycling is the recovery of certain materials that can be reprocessed and reused [32]. Examples of recyclable items include glass, metals, plastics and paper. Recyclable items may be collected at the curbside, at drop-off centers or through deposit or refund programs [34]. The recycled items are then brought to a processing facility to be sorted, cleaned, and made into a form that can be used in manufacturing. Common items that are made from recycled materials include newspapers, paper towels, and drink containers [34].

1.2.3 Anaerobic digestion and aerobic composting

Composting is the recycling of materials that are rich in nutrients for fertilizer [32]. Aerobic digestion of organic matter, such as food scraps, will result in humus, a soil-like material that can be used to enrich soil [32]. Composting may be aided by the addition of air, water, carbon and nitrogen [42, 43].

Anaerobic digestion of organic matter takes place in a landfill and results in the production of methane, a potent greenhouse gas. With the right technology, methane can be recovered and burned for energy [32, 45].

According to the EPA, food scraps and yard waste make up 20 to 30 percent of MSW [35]. Composting at home keeps these materials out of the landfills where they take up space and release methane [35].

1.2.4 Waste-to-Energy (WTE)

Through incineration, energy can be recovered from waste before it goes to the landfill. Steam and water are produced from incineration that can be used to generate energy. In addition to recovering energy, incineration reduces the volume of waste that reaches the landfill [32].

At the MSW combustion facility, MSW is loaded into a combustion chamber and burned. The heat released from this burning is used to turn water into steam, which is sent to a turbine generator to generate electricity. The ash that remains is brought to the landfill to be used as a covering [38].

In Japan, Europe and other countries, waste-to-energy incineration has been used to reduce the volume of waste by 80 to 90 percent [44].

Environmental protection agencies have placed strict standards on dioxin and mercury emissions from WTE facilities. Modern WTE facilities are equipped with sophisticated pollution-control devices that scrub, precipitate and filter acid, heavy metal and fly ash from an incinerator’s emissions [44]. As a result, the levels of these pollutants have been reduced drastically [41].

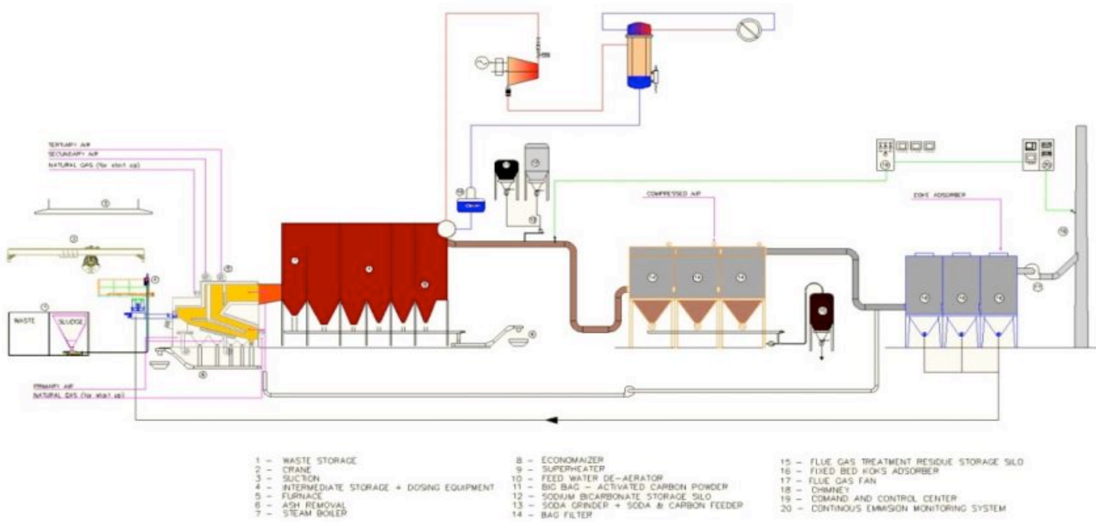


Figure 2: Schematic presentation of WTE plant [46]

1.2.5 Landfilling

Landfilling is the least favorable method for waste disposal from a sustainable perspective. However, it is evident that waste that cannot be prevented or recycled ends up in the landfill. A properly designed landfill can safely contain the waste with a liner system and other safeguards to prevent pollution to the groundwater [31]. Liners may be made of compacted clay or plastic. Liners prevent the filtration of liquids, or "leachate," from a landfill. Leachate has the potential to pollute surface or ground water, which is the source of most drinking water [45]. Drains may be installed at the bottom of a landfill to collect the leachate before contamination of surrounding water and soil can occur. Leachate recovered from drains is pumped to wastewater collection points for treatment. Landfills are closely monitored for their environmental impact by environmental protection agencies [45].

In a landfill, the waste is spread into layers, compacted to reduce the volume, and covered daily with clay, ash or soil to minimize odor and deter insects and vermin [32, 45].

CHAPTER 2: WASTE MANAGEMENT IN THE REPUBLIC OF KOREA

2.1 Republic of Korea: Geography, Administration and Population

The Republic of Korea (hereafter "Korea"), commonly called South Korea, occupies the southern part of the Korean Peninsula. Politically, the country is divided into nine provinces and seven metropolitan cities including the capital city, Seoul (Figure 3). The provinces include Gyeonggi-do, Gangwon-do, Gyeongsangnam-do, Gyeongsangbuk-do, Chungcheongnam-do, Chungcheongbuk-do, Jeollanam-do, Jeollabuk-do , Gyeongsangnam-do, and Gyeongsangbuk-do. The seven metropolitan cities are Seoul, Incheon, Busan, Gwangju, Daegu, Daejeon, and Ulsan.

Figure 3: Political administration map of Korea [1]

With a population of about 50 million people in an area of 99,720 square kilometers, Korea is one of the most densely populated countries in the world (2010 population density: 509 persons per square kilometer [2]). The national capital, Seoul, has a population of about ten million people and the total urban population in 2010 was 82% of total (Figure 4).

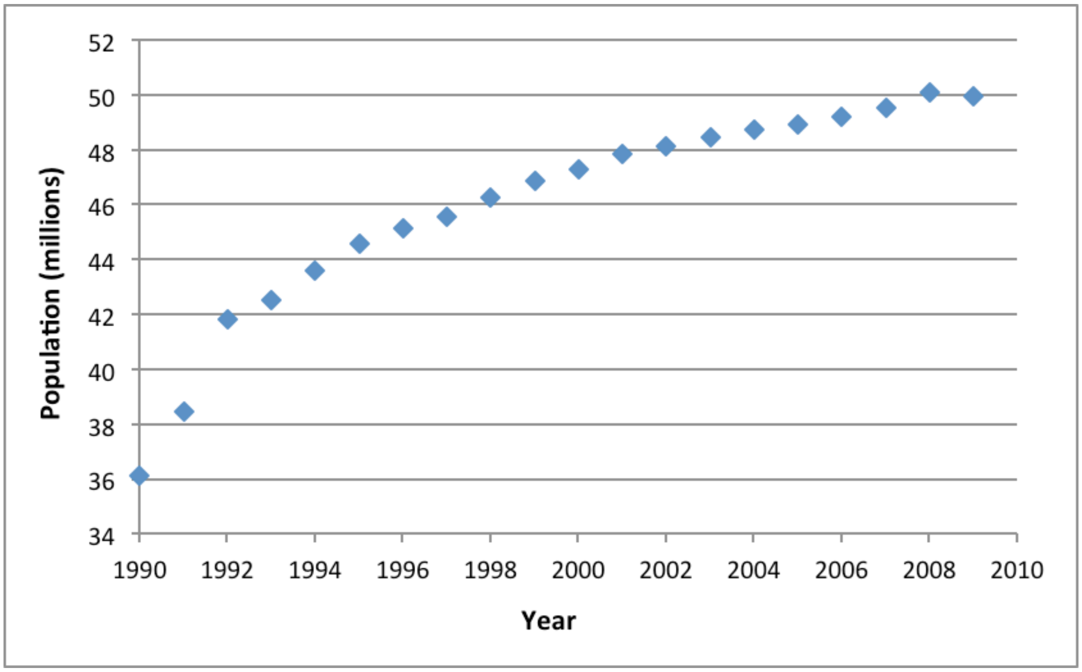


Figure 4: Population change in Korea, 1990-2009 (millions)

2.2 Background

A change in the lifestyle and consumption patterns of the population due to rapid industrialization and urbanization has brought about a rapid increase in the flow of goods and services in Korea. The rate of waste generation has accelerated as people pursue more convenient and luxurious lifestyles that result in higher consumption and shorter lifespan of materials. In view of the relatively small land mass, the generation of wastes has added to the environmental challenges that Korea has to face [3]. Since the early 1990s, securing landfills for the country's waste output has become more and more difficult. Most of the existing landfills were nearly full, while some were discovered to be poorly designed and/or operated and in need of serious remediation [4]. Furthermore, it was problematic to find new sites for landfills, because of the congestion of land space and public concern for a cleaner environment in their municipality. The Korean government's Ministry of Environment (MOE), together with a group of non-governmental environmental organizations, the automobile and recycling industries, and local governments, started to concentrate on reducing waste generation at the source and maximizing waste recycling [5], by implementing several waste management policies, as described in the next section.

The central government of Korea promulgates periodic national waste management plans and provides the technical and financial support to local governments, while local municipalities are in charge of the collection, transport, recycling, and treatment of MSW. The current waste management process in Korea can be represented by the flow diagram shown in Figure 5.

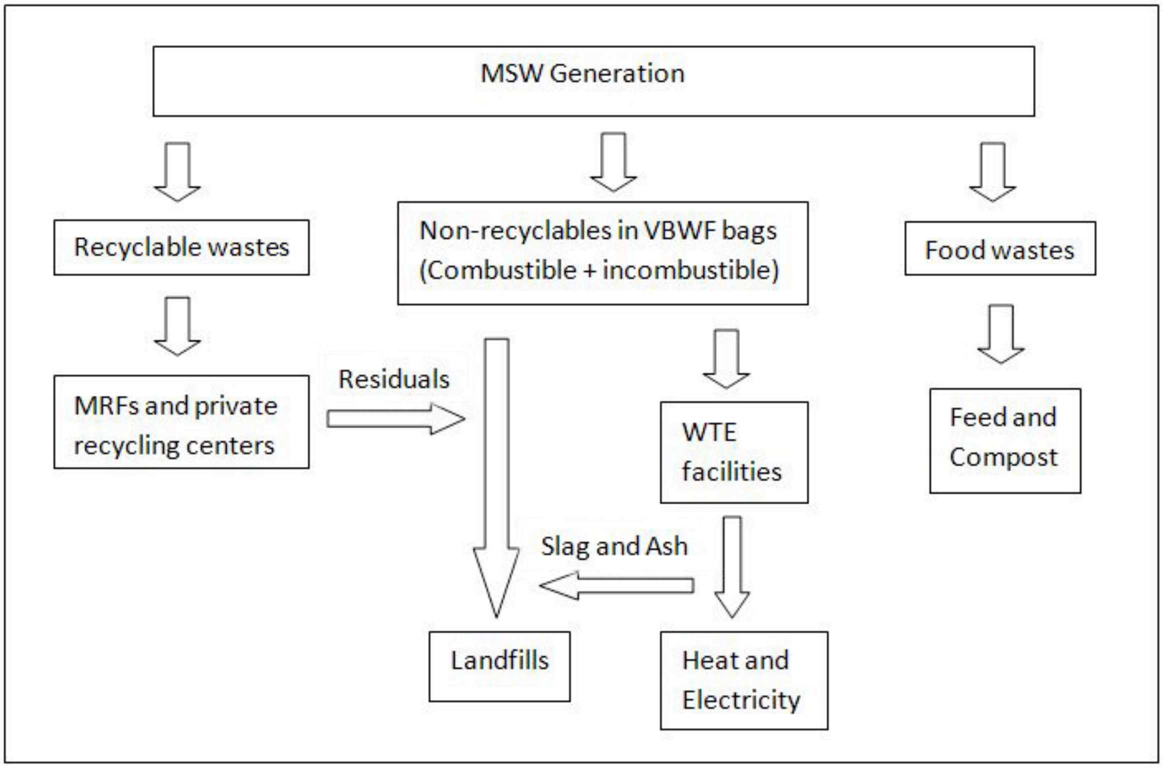


Figure 5: MSW flow system in Korea

2.3 MSW Generation in the ROK

2.3.1 Current and 1990-2009 Trend of MSW Generation

According to "National Waste Generation and Treatment" published by the MOE annually, the total MSW generation in 2009 was 18.6 million tons and the average MSW generated per capita 0.37 tons [9]. As shown in Figure 4, the total MSW generation had fluctuated with an overall increase in the subsequent 14 years. In comparison to the 17.4 million tons generated in 1995, the volume of total MSW generation in 2009 increased by 7%. On the other hand, the per capita MSW generation was decreased from 0.39 tons per capita in 1995 to 0.37 tons per capita in 2009 [6,7,8,9].

The controlled increase rate of total MSW generation and the reduction of the per capita MSW generation occurred during a period of population growth (Figure 6) and economic development were due to the efforts of the Korean government. Some important regulations and policies adopted by the

MOE were the “Waste Deposit Refund System (1991)”, the “Act on the Promotion of Saving and Recycling of Resources (1992)”, the “Volume-Based Waste Fee (VBWF) system (1995)”, the “Extended Producer Responsibility initiatives (2003)”, and the “Mandatory Food Waste Separation (2005)” act [10, 11].

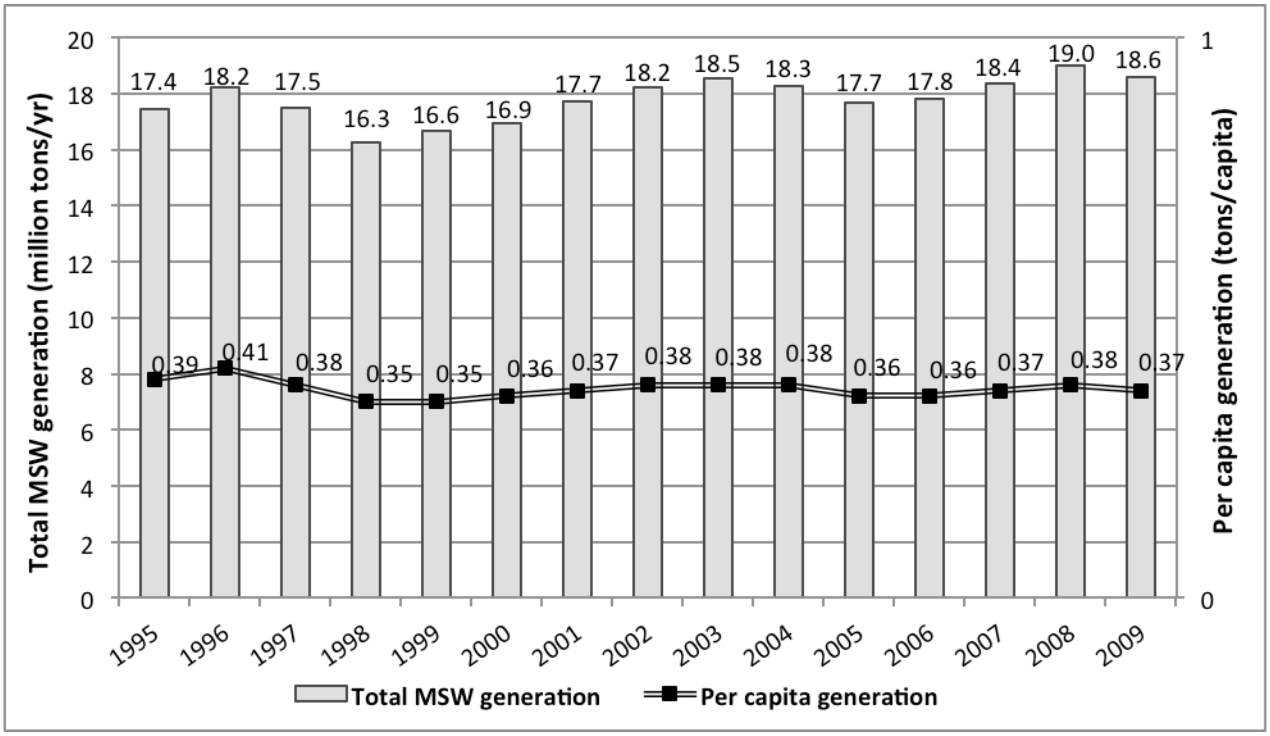


Figure 6: Trends in MSW generation in Korea from 1995 to 2009

2.3.2 Waste Deposit Refund System (1991)

The government-driven Deposit Refund System (DRS) was first introduced with the revision of the “Waste Management Act” in 1991 and later in the “Act on the Promotion of Saving and Recycling of Resources” of 1992. The implementation of the DRS required manufacturers to pay a deposit for a target product and get reimbursed after collecting and treating the waste associated with this product. Both packaging and hazardous wastes were covered by the DRS, as shown in Table 1 [11]. In the case when the items were not recycled, the deposit held by the government was used to support future recycling projects.

Table 1: Target items and prices by Deposit Refund System

Categories	Items	Rates per unit (USD)
Beverage containers	Tetra paks	0.0003 – 0.0005
	Aluminum cans	0.003 – 0.005
	Glass bottles	0.002 – 0.004
	PET bottles	0.004 – 0.009

Batteries	Mercury batteries Oxidized silver batteries	0.125 0.063
Tires	Large size Medium to small size Bicycle tires	0.5 0.125 0.05
Lubricating oil	Lubricating oil	0.025 per liter
Bulky electronics	TV, Washer, Air conditioners, etc.	0.038 per kg

Source: Pricing for Municipal Solid Waste Disposal in Korea [11].

2.3.3 Act on the Promotion of Saving and Recycling of Resources (1992)

In order to reduce and recycle wastes more effectively, the Korean government also implemented in 1992 the "Act on the Promotion of Saving and Recycling of Resources", which by now has been revised over thirty times [12]. Since the introduction of this Act, it became the manufacturers' responsibility to reduce the use of unnecessary packaging materials by designing more environmentally friendly packaging methods. The restriction of the size and number of packaging was initially applied to 23 manufacturers, importers and sellers: It required the packaging sizes to decrease 10% to 35% smaller and to limit the number of packaging to be no more than double [10]. The use of recyclable materials for packaging was recommended and synthetic resin materials such as PVC were either prohibited or strongly discouraged; the government accepted industrial pledges for annual reduction in use [10].

Under the "Act on the Promotion of Saving and Recycling of Resources", business owners were encouraged to replace disposable products with reusable ones and were prohibited from providing plastic bags free of charge [12]. Also, some restaurants, cafeterias, and caterers participated in a system that charges customers a fee for disposable take-out containers and refunds the fee when used goods were brought back for recycling (market-generated deposit refund system) [10]. Most of the fast-food and coffee businesses replaced plastic containers and cups with paper products. Some of these business owners facilitated the use of reusable items by giving customers a discount on beverages when they brought in their own mugs [10].

The Korean government's regulatory policy through the "Act on the Promotion of Saving and Recycling of Resources", along with the "Deposit Refund System", contributed to a gradual reduction in the total MSW generated by cutting the portion of packaging and plastic wastes, and also by stimulating recycling.

2.3.4 The Volume-Based Waste Fee system (1995)

The Korean government concentrated on minimizing waste generation at the source and maximizing waste recycling with the implementation of the Volume-Based Waste Fee (VBWF) system in 1995 based on a revision of the Waste Management Act legislated in 1991 [10]. The VBWF system charged citizens a waste collection fee based on the amount of waste generated, replacing the previous fixed-rate taxation system [12].

In compliance with the VBWF system, households, businesses and institutions are required to separate their MSW into two streams: Designated recyclable materials and all other wastes. They are also obligated to purchase and use VBWF bags as shown in Figure 7 for disposing the non-recyclable wastes. Local municipalities collect the VBWF bags and provide a free collection service for the pre-sorted recyclable wastes, promoting recycling. Thus, the system gives an economic incentive for producing fewer wastes and recycling more [13]. Table 2 shows the various sources and types of MSW in Korea and the way they are managed.

Table 2: Generation and management of various components of MSW in Korea

Source		Type	Use of VBWF bag	Cost at the source	Note
Households and small commercial sector	Urban Area	Household waste	Yes	Yes	Separate collection
		Recyclable waste	No	No	Separate collection
		Food waste	Yes/ No (when collected in designated food waste bins)	Yes	Separate collection
		Bulky waste (Furniture, electric home appliance such as refrigerator, air conditioner, etc.)	No	Yes	Separate collection with a sticker purchased at a local government office
	Rural village (farming/ fishing)	Agricultural waste	No	Yes	Use of village's communal VBWF bag
Large commercial sector/small business		MSW type	No	Yes	Wastes volume larger than 0.3 ton/day are not subject to the VBWF system

Note: * Large quantity generators (more than 0.3 tons per day) were originally excluded from the VBWF system; instead, they used private waste collectors for waste collection and treatment. Recently, it has been recommended to them that they sort their own wastes and use VBWF bags for the waste types similarly to the rest of MSW.

Source: Performance of Waste Management Policy in Korea [13]

Figure 7: Volume-Based Waste Fee bags

For easy accessibility to the residents, different sizes of VBWF bags ranging from 3 liters to 100 liters are available at local grocery stores, convenience stores and supermarkets. The price of the VBWF bags varies depending on the bag size and also from one municipality to another; for example, in 2009, the VBWF bag for 20 liters in Seocho-gu, a borough of Seoul, was 30 cents, while the same size bag in Jin-gu, a borough of Busan was priced at 90 cents [13, 15]. Average prices for VBWF bags throughout the country are listed in Table 3.

Table 3: Average prices for VBWF bags in years 2006 thru 2010 (USD/bag)

Size (liter)	2006	2007	2008	2009	2010
3L	0.07	0.06	0.06	0.07	0.06
5L	0.09	0.11	0.11	0.11	0.11
10L	0.18	0.21	0.21	0.21	0.21
20L	0.36	0.41	0.42	0.42	0.42
30L	0.60	0.58	0.57	0.58	0.58
50L	0.89	1.02	1.04	1.04	1.04
75L	1.57	1.51	1.44	1.53	1.52
100L	1.84	2.04	2.09	2.10	2.10

Note: US dollar (USD) was calculated based on currency exchange rate of 1,100 won to 1 USD.

Source: Current status of VBWF system [17]

2.3.5 Extended Producer Responsibility initiatives (2003)

The Extended Producer Responsibility (EPR) initiative is based upon the principle that the producers are responsible for the entire life-cycle of their products from the selection of materials and product design to the treatment and disposal of the products [16]. In response to the international trend of OECD countries, the Korean government in 2003 initiated the EPR to revise and expand on the previous DRS. In this new system, although the manufacturers play the main role in the recycling of the products and packaging materials after use through payments into a special account for environmental improvement, the responsibility of the government and the consumers have been extended. While the government carries out collecting recyclable wastes and putting them into the recycling process, it is up to the consumer to separate and recycle their wastes [10, 12].

Under the EPR, the new items subject to the mandatory producer recycling program were added on top of the existing ones from the DRS as stated in Table 4. Furthermore, specific design requirements for restrictions on excessive packaging and disposable goods were applied to all goods. Free distribution of disposable vinyl bags in markets was completely banned as were other disposables such as plastic utensils, containers and toothpastes at specific business locations [13].

Table 4: Existing and Newly added items subject to mandatory producer recycling

Existing items for deposit (DRS)	Products	Electric home appliances (TVs, washers, air conditioners, refrigerators, tires, lubricants, fluorescent lights, batteries, etc.)
	Packaging materials	Tetra paks, aluminum cans, glass bottles, PET bottles (from food and beverage products, liquors, cosmetics, detergents, some medical and pharmaceutical products)
Newly adopted items (EPR)	Products	Mobile phones, audio equipments, computers
	Packaging materials	Plastic packaging materials (from Food and beverage products, medical and pharmaceutical products, liquors, detergents, cosmetics, etc.) Foamy synthetic resin buffers (from electric & electronic equipments)

Source: Performance of Waste Management Policy in Korea [13]

2.3.6 Mandatory Food Waste Separation (2006)

The Korean government has focused on reducing food wastes with various activities such as TV and radio campaigns since the late 1990s. Landfilling of food wastes without pre-treatment was completely banned in 2005 and residents were required to separate food wastes from other non-recyclable wastes that go into the VBWF bags. Municipalities started providing free containers for food waste disposal and made VBWF bags solely for food wastes. By providing a free collection service for separated food wastes starting in 2006, the Korean government has facilitated food waste recycling for fertilizers and animal feeds [14].

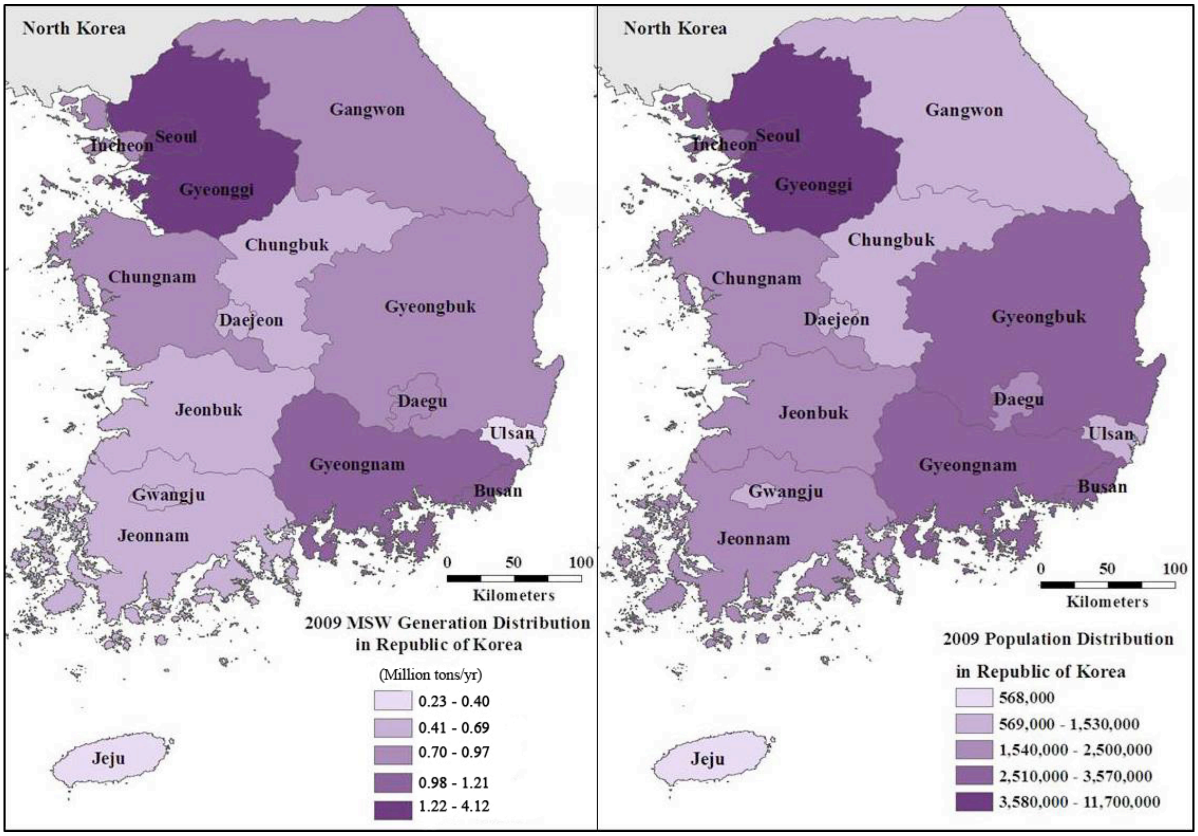
2.3.7 Region-by-Region MSW Generation in Korea

Table 5 lists the MSW generation, population, and per capita MSW generation on a region-by-region basis for the year 2009. Seven metropolitan cities (Seoul, Incheon, Busan, Gwangju, Daegu, Daejeon, and Ulsan) had as great a population, and generated as much waste, as the neighboring provinces. Seoul, the capital city of Korea, had the largest MSW generation, with 4.1 million tons, followed by Gyeonggi-do, adjacent to Seoul, with 3.7 million tons. Busan, the second largest city in the ROK, and Gyeongsangnam-do, the neighboring province with Busan, tied for third for MSW generation after Seoul and Gyeonggi-do. Among the seven metropolitan cities and nine provinces, the capital region, which includes Seoul, Incheon and Gyeonggi-do, generated 8.7 million tons of MSW, together making up 47% of the total MSW generation in the country. The capital region is the most concentrated in the nation, with over 24.5 million people or about half the total population of Korea. The spatial distribution of MSW generation and the population in Korea for the year 2009 are shown in Figure 8.

Table 5: MSW generation by metropolitan cities and provinces in 2009

Metropolitan cities/Provinces (do)	Total MSW Generation (Mton/yr)	Population	Per Capita MSW Generation (tons/cap/yr)
Seoul	4.1	10,059,793	0.41
Gyeonggi-do (Gyeonggi)	3.7	11,726,613	0.32
Busan	1.2	3,574,340	0.34
Gyeongsangnam-do (Gyeongnam)	1.2	3,227,963	0.37
Chungcheongnam-do (Chungnam)	1.0	2,034,689	0.47
Gyeongsangbuk-do (Gyeongbuk)	1.0	2,628,286	0.36
Gangwon-do (Gangwon)	0.9	1,512,295	0.58
Daegu	0.9	2,499,365	0.37
Incheon	0.9	2,756,694	0.30
Chungcheongbuk-do (Chungbuk)	0.7	1,534,073	0.43
Jeollanam-do (Jeonnam)	0.7	1,899,016	0.36
Daejeon	0.6	1,486,184	0.37
Jeollabuk-do (Jeonbuk)	0.6	1,869,963	0.32
Gwangju	0.5	1,449,621	0.36
Ulsan	0.4	1,125,728	0.36
Jeju-do (Jeju)	0.2	567,751	0.40

Source: 2009 Waste generation and treatment, Ministry of Environment [9]



(a) (b)

Figure 8: Spatial distribution of (a) MSW generation and (b) population in Korea in 2009

The per capita MSW generation differed by region, ranging from 0.30 to 0.58 tons per capita in 2009 [9]. Figure 9 shows the spatial distribution of per capita MSW generation in Korea in 2009. However, it is difficult to state that the amount of waste per person correlates with urbanization in Korea because urban and rural communities are widely interspersed throughout the country. One way to analyze it would be to compare the average per capita MSW generation between metropolitan cities and provinces. The average per capita MSW generation in the seven metropolitan cities was 0.36 tons per person, whereas in the nine provinces, the average per capita MSW generation was 0.40 tons per person. It may be suggested that citizens in mega-cities generated less MSW because they had greater access to recycling programs and better education on reusing and recycling materials.

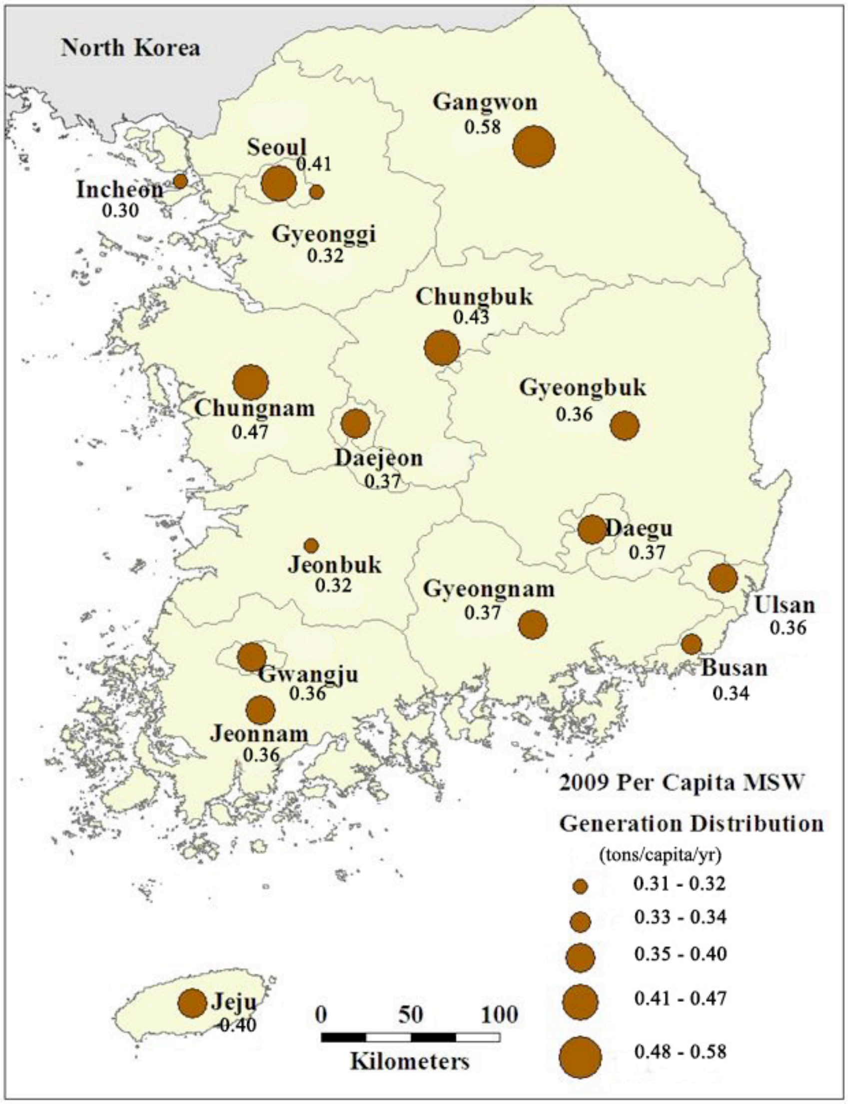


Figure 9: Spatial distribution of per capita MSW generation in the ROK in 2009

2.4 MSW Collection in Korea

As previously stated, in Korea, it is the local governments' responsibility to collect MSW while all citizens are obligated to separate their wastes into recyclables, non-recyclables, and food wastes before disposing of their wastes. The MSW collecting system in Korea is based on a door-to-door collecting system as shown in Figure 10, with some exceptions such as in multi-family buildings and in communities that have communal stations for waste disposal [17].

(a) (b)

Figure 10: Dumper for garbage collection in (a) Seoul and (b) Ulsan

2.4.1 MSW collection in Multi-Family Residential Buildings in Korea

According to the 2010’ Population and Housing Census , 57.2% of the Korean population lives in multi-family residential buildings, including apartment buildings [18]. Figure 11 shows the spatial distribution of the people who inhabit apartment buildings throughout the country.

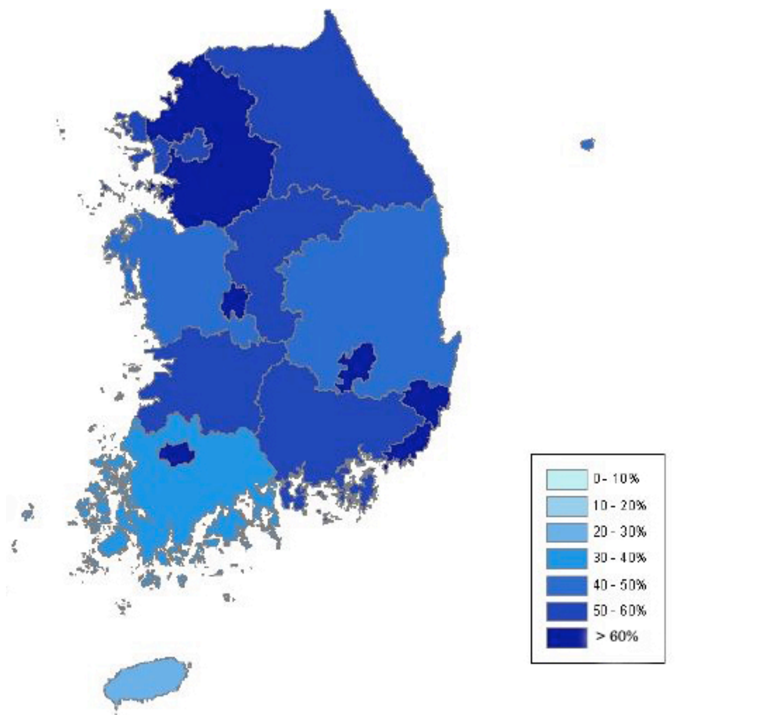


Figure 11: Spatial distribution of apartment inhabitants in 2010

Source: Population and Housing Census [18]

MSW is collected communally whereby apartment residents bring their garbage to such collection points as the stationary waste containers and bins that are located in front of, or close to, their buildings. An example of such community containers is shown in Figure 12a. In this system, everyone is responsible for following the rules and buying and using VBWF bags for non-recyclable wastes, and discarding the wastes appropriately. The tenants or owners of each unit must purchase their own VBWF bags, which vary in size and price as illustrated in Table 6. Municipalities must work with apartment management to prevent or minimize violations to the VBWF bag rules. Food wastes are exempt and are collected separately and put into communal food waste containers (see Figure 12d). Recyclables are sorted and placed into different recycling bins, which appear on different days of the week.

Figure 12a: MSW collection in Misung apartment in Songpah-gu, Seoul

Figure 12b: Communal container waste for garbage collection

Figure 12c: Clothing collection bin for donation or resale

Figure 12d: Communal food collection containers

Figure 12: MSW collection in Multi-Family Residential Buildings in Korea

Table 6: Average prices of VBWF bags in years 2006 thru 2010 (USD/bag)

Size (liter)	2006	2007	2008	2009	2010
3L	0.07	0.06	0.06	0.07	0.06
5L	0.09	0.11	0.11	0.11	0.11
10L	0.18	0.21	0.21	0.21	0.21
20L	0.36	0.41	0.42	0.42	0.42
30L	0.60	0.58	0.57	0.58	0.58
50L	0.89	1.02	1.04	1.04	1.04
75L	1.57	1.51	1.44	1.53	1.52
100L	1.84	2.04	2.09	2.10	2.10

Note: US dollar (USD) was calculated based on currency exchange rate of 1,100 won to 1 USD.

2.4.2 MSW collection in single-family houses in Korea

Koreans living in single-family houses, accounted for 39.6% of total population in 2010 [18], follow the similar rules for waste disposal as people from the multi-family buildings and put out their wastes at the door. Non-recyclable wastes are put in VBWF bags while recyclable wastes are sorted in ways local governments indicate. For separated food wastes, rather than sharing communal food waste containers as in multi-family buildings, people from single-family houses use a different type of VBWF bag used only for food wastes shown in Figure 13a.

Figure 13a: Food waste VBWF bags (3, 5, 10 liters) used in Pochun

Figure 13b: Food waste segregation methods in Korea: single-family house vs. multi-family residential building

Figure 13: Food waste collection in Korea

2.5 Overall MSW composition

According to the MOE, MSW disposed of in Korea for the year 2009 is composed of the following:

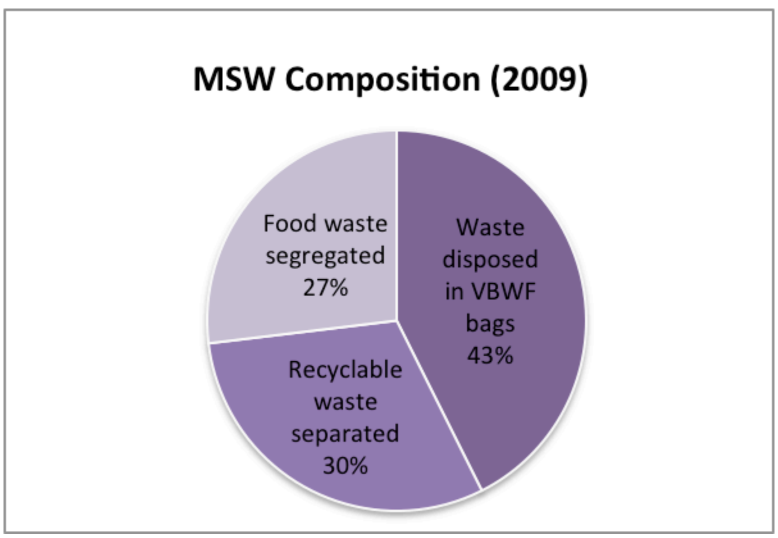


Figure 14: Reported disposition of MSW in the ROK in 2009

43% of the total MSW was disposed of in VBWF bags, while 27% was segregated as food waste, and 30% was sorted as recyclable waste for the year 2009 . Compared to the data in 1997, the waste set out for disposal in VBWF bags had decreased by 39% (Figure 15). The major cut down in that category was due to the mandatory separate collection of food waste starting in 2006. The fraction of food waste, which has had its own category since 2006, had stabilized in the last three years leading up to 2009, while the amount of waste disposed of in VBWF bags had slightly decreased. On the other hand, the quantity of recyclable waste had continually increased from 4.6 million tons in 1997 to 5.7 million tons in 2009 as illustrated in Figure 15. More detailed MSW composition in each category will be discussed in the following sections.

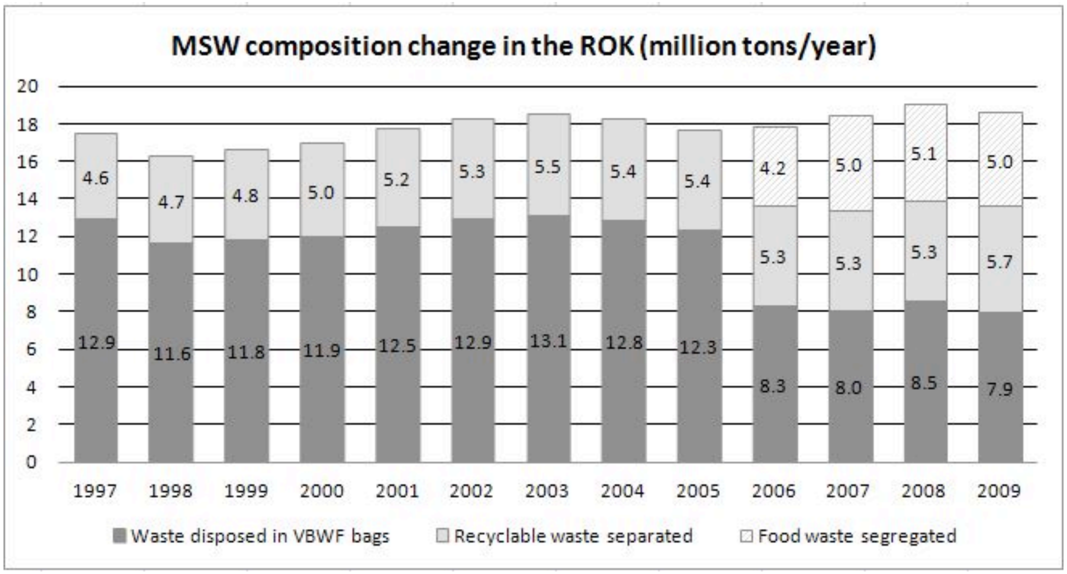


Figure 15: Changes in the MSW composition in Korea, 1997 to 2009 (million tons/year)

2.5.1 General Characteristics of MSW disposed in VBWF bags

Figure 16 reflects the composition percentages of the ten MSW components categories: *food, paper, plastic, wood, rubber/leather, miscellaneous combustibles, metal, briquette ash (glass), sand/soil, and miscellaneous incombustibles*. As shown in the pie chart, *miscellaneous combustibles* accounted for 29% of the 7,916,850 tons of MSW disposed in VBWF bags, while *paper* made up approximately 23% of the total tonnage for the year 2009. In addition, *plastic, wood, and miscellaneous incombustibles* were the next largest components that accounted for 13%, 11%, and 9% of the MSW, respectively. *Food, metal, and glass* were the smallest components of the MSW disposed of in VBWF bags in 2009, making up only 2% each of the total amount.

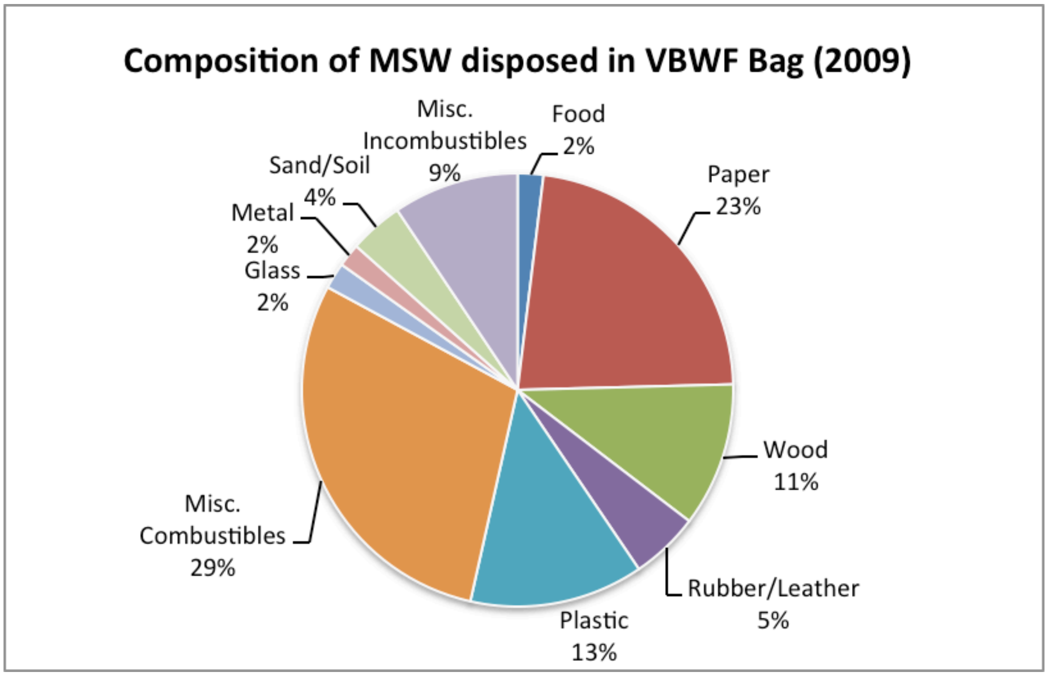


Figure 16: Composition of MSW disposed of in VBWF bags in Korea in 2009 (about 7.9 million tons total)

Figure 17 illustrates the composition of waste disposed of in VBWF bags between 1998 and 2009 for the ten categories of MSW. The fraction of *food*, which had previously made up the greatest component of MSW disposed of in VBWF bags, showed a significant change beginning in 2006. *Food,* previously accounting for more than 30% of the MSW disposed of in VBWF bags between 1998 and 2005, was slashed when the separate collection of food started in 2006. By 2009, food had become one of the smallest components in the VBWF bags.

Miscellaneous combustibles are combustible materials including leaves, grass, carpet, wax, bar soap, cigarette butts, disposable diapers, feminine hygiene products, and other organic materials not classified elsewhere. The portion for this category had gradually increased over the years 1998 to 2009. Compared to the 12% of MSW that this category made up in 1998 (the third largest after *food* and *paper* in that year), in 2009 it made up 29%, or the largest category. *Paper* and *plastic*, despite the separate collection of these recyclable wastes, had noticeable increases in fractions, opening up further potential to reduce in the consumption of these disposable goods and increase in the recycling. The portion of *wood* has also increased slightly, whereas that of *metal* has had subtle decreases over this period of time. Inert materials such as *briquette ash, sand/soil*, and *miscellaneous incombustibles*, or other non-combustible materials not classified elsewhere, comprised a consistently low portion (less than 20%) of the MSW when summed together. The comparison between combustible and incombustible waste disposed of in VBWF bags is better presented in Figure 16.

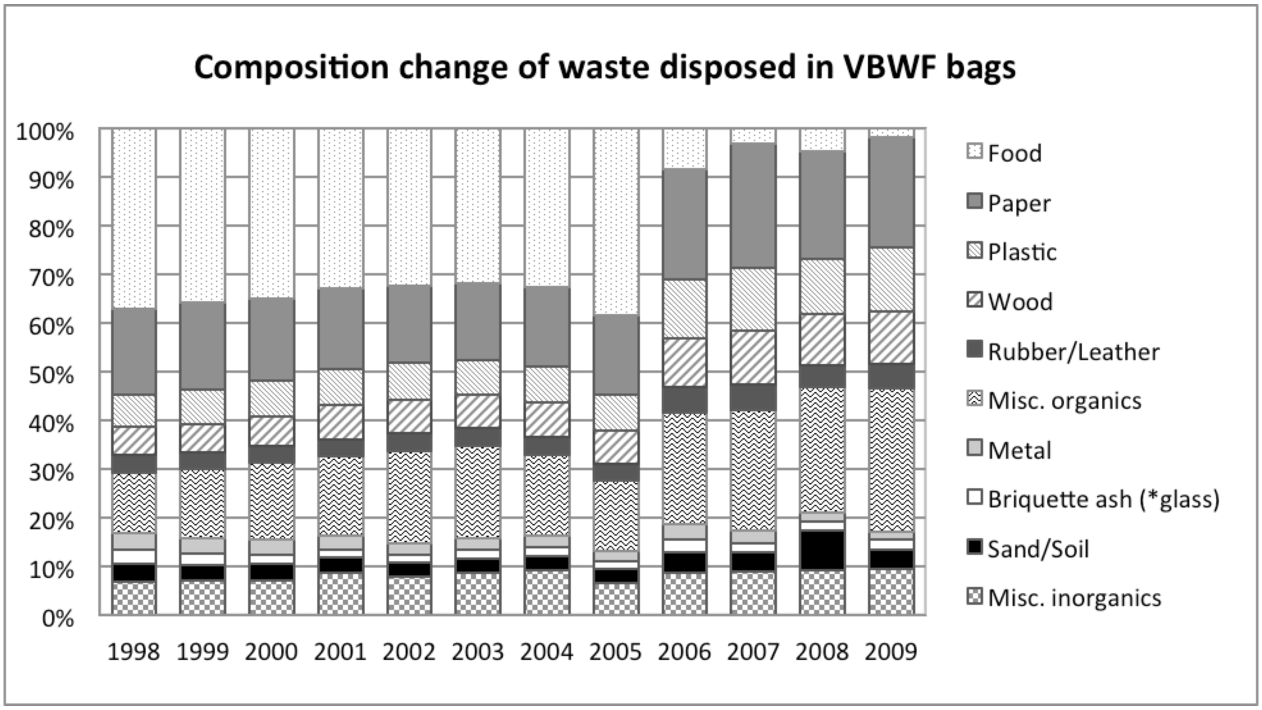


Figure 17: Percent breakdown of waste disposed of in VBWF bags in Korea, 1998-2009. (Note: * The category for 'briquette ash' has been replaced with 'glass' starting in 2007.)

As shown in Figure 18, the amount of combustible waste in VBWF bags had slightly increased before a sudden drop in 2006 when citizens were mandated to separately dispose of their food waste. The food waste segregation rule changed the total quantity of waste in VBWF bags, but not much of the fractions of waste components in terms of combustibility. The total waste disposed of in VBWF bags in 1997 was 12.9 million tons, while it was only 8 million tons in 2009. However, the ratio of combustible-to-incombustible waste in VBWF bags for the year 1997 was 81.4:18.6, and that for the year 2009 was 82.5:17.5. Decreased incombustible waste by weight along with the decrease in combustible materials in VBWF bags brought about the consistency in the percentages of the two categories.

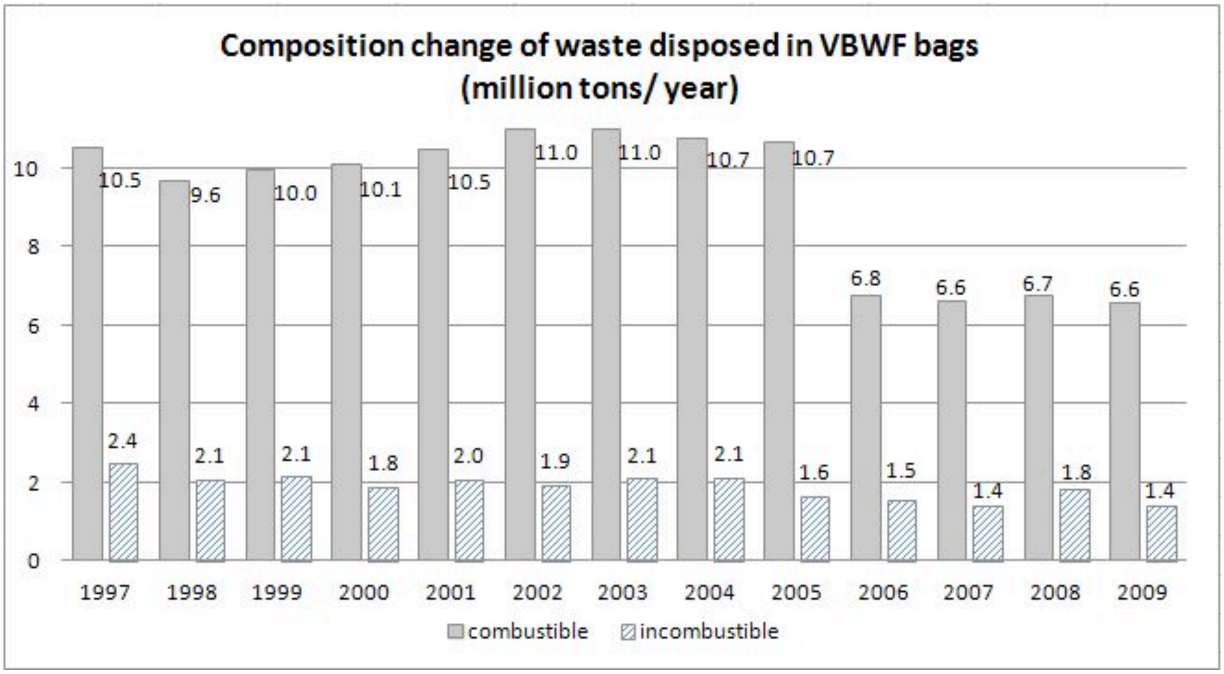


Figure 18: Composition change of waste disposed of in VBWF bags (combustible VS. incombustible) in Korea, 1997-2009

2.5.2 Chemical Characteristics of MSW disposed of in VBWF bags

For evaluating various types of waste treatment options, accurate information on the chemical composition of the waste is important. The moisture content and the higher and lower heating values of the MSW need to be considered for WTE recovery. If the organic materials from MSW are to be composted, properties such as carbon/nitrogen ratio, dissolved oxygen, pH, and moisture content are used. Furthermore, the hazardous components of MSW are directly related to the landfill leachate composition and GHG emission. Table 7 lists some values for some chemical characterizations for the year 2007 in Korea.

Table 7: Elemental properties and lower heating value (LHV) of MSW disposed of in VBWF bags

Component of Waste Stream	% in ROK	% by Weight (wet basis)								LHV (MJ/kg)
		Moisture	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	Chlorine	Ash	
Paper	35.10	17.72	32.28	4.70	28.44	0.38	0.01	0.30	16.17	12.06
Misc. Combustibles	25.10	60.00	14.57	2.10	11.01	0.17	0.01	0.15	12.00	4.24
Plastics	21.40	5.94	70.08	9.38	5.15	0.71	0.14	1.22	7.37	32.62
Food	8.10	65.08	14.43	2.00	11.10	0.80	0.02	0.36	6.21	4.08
Incombustibles	7.00	30.00	0.00	0.00	0.00	0.00	0.00	0.00	70.00	-2.21
Fabric/Rubber/leather	1.70	8.07	47.56	5.98	20.03	1.48	0.09	4.31	12.47	19.79
Wood	1.60	14.11	39.53	5.18	30.86	0.59	0.02	0.24	9.47	15.02
Average		30.29	32.60	4.53	15.58	0.43	0.04	0.51	16.03	12.99

Source: Potential of Municipal Solid Waste for Renewable Energy Production and Reduction of Greenhouse Gas Emission in South Korea [19].

Using dataset from the national waste statistic survey, the organic fractions of MSW disposed of in VBWF bags were calculated. The ultimate analysis of the MSW generated in Korea in 2007 derived the hypothetical compound, $C_6H_{9.9}O_{2.3}$, as shown in Table 8. The hypothetical compound, $C_6H_{9.9}O_{2.3}$ is a less oxidized compound than the hydrocarbon formula of typical MSW, $C_6H_{10}O_4$, and also less than the chemical formula of New York City wastes, $C_6H_{9.3}O_{3.5}$, calculated by Themelis and Kim (2002).

The chemical reactions for complete combustion of $C_6H_{10}O_4$ and $C_6H_{10}O_3$ are:

$C_6H_{10}O_4 + 6.5O_2 = 6CO_2 + 5H_2O$ + **27,000 kJ per kg** of MSW

$C_6H_{10}O_3 + 7O_2 = 6CO_2 + 5H_2O$ + **23,000 kJ per kg** of MSW

Thus, it is assumed that the potential of heat generated by Korea's MSW combustibles is relatively lower than of the two exemplified compounds above.

Table 8: Ultimate Analysis of Source-Segregated MSW before Materials Recovery

Component of MSW	% in ROK*	Weight of Comp.* (g/day/person)	% by Weight (dry basis)* *Carbon*	*Hydrogen*	*Oxygen*	*Nitrogen*	*Sulfur*	*Chlorine*
Paper	35.1	73	43.67	6.36	38.48	0.51	0.02	0.40
Plastics	21.4	45	75.87	10.15	5.77	0.77	0.15	1.32
Food	8.1	17	45.89	6.36	35.30	2.55	0.06	1.13
Wood	1.6	3	47.38	6.21	37.00	0.71	0.02	0.29
Rubber	0.9	2	61.54	8.66	12.07	1.12	0.27	5.42
Leather	0.4	1	52.48	5.91	24.11	1.96	0.02	8.95
Fabric	0.4	1	50.80	6.17	33.58	2.05	0.01	0.58
		142	77.5	10.8	38.7	1.2	0.1	1.3
Atomic Weight (kg/kmol)			12.01	1.01	16.00	14.01	32.07	35.45
# of moles			6.45	10.67	2.42	0.09	0.00	0.04
Molar Ratio C=6			6.0	9.9	2.3	0.1	~0.0	~0.0
Approximate Chemical Formula					$C_6H_{9.9}O_{2.3}$			

Source*: The Third (2006-2007) National Waste Statistics Survey [20]

2.5.3 Composition of recyclable waste

As stated earlier, 30% of all MSW generated in Korea in 2009 was separated out at the source as recyclable wastes. Figure 19 illustrates the breakdown of recyclable waste as of 2009.

In 2009, the largest component of the recyclable wastes was *paper* at 33%, followed by *glass/bottle* and *scrap iron/metal* (15% each), *plastic* (9%), *others* (7%), *synthetic resin* (6%), *aluminum can* (5%), *agricultural waste* and *furniture* (3% each), *clothing*, *lubricant*, *tire*, and *electronics* (1% each), *battery* (0.002%), and *fluorescent lamp* (0.0003%). The categories *synthetic resin*, *electronics*, *battery*, *tire*, *lubricant*, *fluorescent lamp*, *clothing*, *agricultural waste*, and *furniture* were added in 2007.

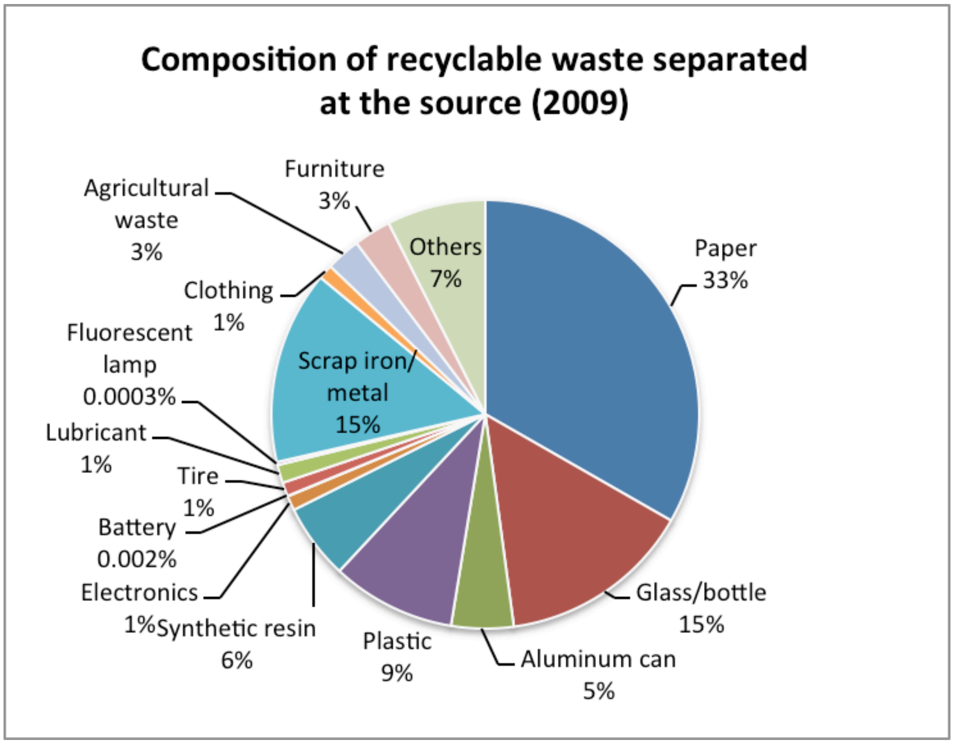


Figure 19: Composition of recyclable waste separated at the source in Korea in 2009 (5,662,975 tons total)

Figure 20 shows the trend in the shares of the different categories of recyclable waste. In 1998, *paper* made up almost half of all recyclable wastes, but by 2009, the share had dropped to 33%. *Glass/bottle* and *plastic* saw a slight increase, while *scrap iron/metal* saw a decrease. *Aluminum can*, *synthetic resin*, *agricultural waste*, and *clothing* all remained flat, while *electronics* and *battery* saw a significant drop. The recycling of *furniture* was instituted in 2009 [7,8,9].

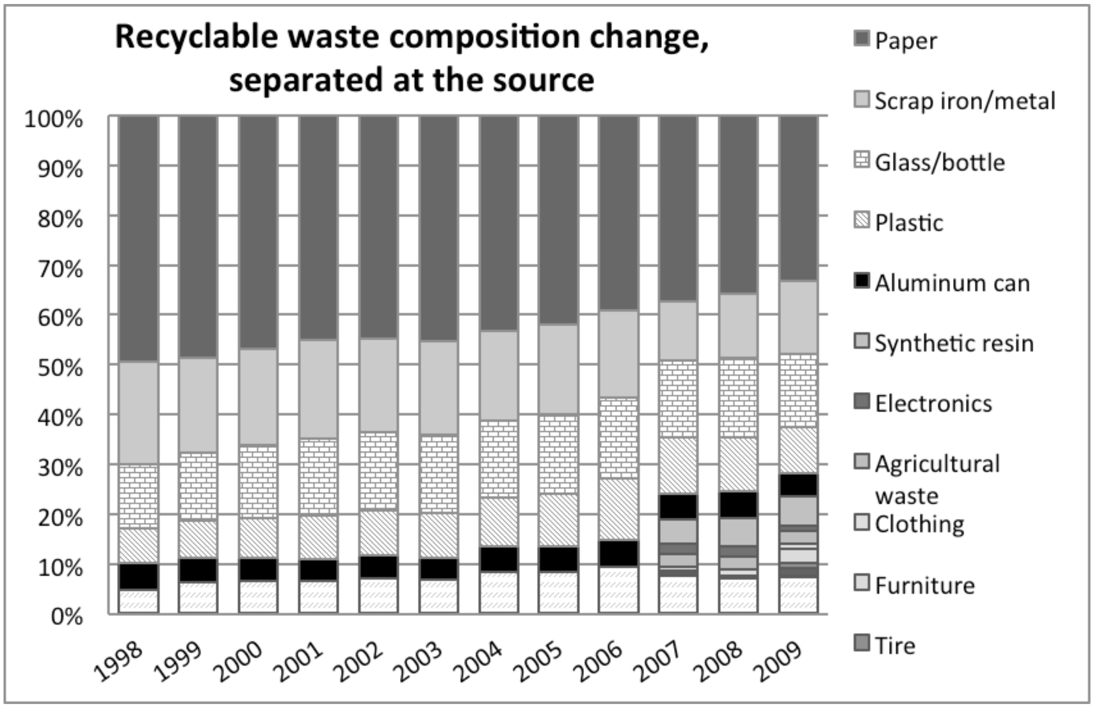


Figure 20: Percent composition change of recyclable waste separated at the source in Korea, 1998-2009

2.6 MSW treatment in Korea

In year 2009, out of a total of 18.7 million tons of MSW that was generated, 11.4 million tons (61% of the total) were recycled or composted, while 3.8 million tons were incinerated, and 3.5 million tons were landfilled (20% and 19%, respectively). Figure 21 illustrates the trend in the treatment of MSW between 1995 and 2009. It can be seen in this illustration that MSW recycling and composting had reached the level that it did in 2009 from merely 4.1 million tons (24%) in 1995. Waste incineration or WTE had also gone up, from 0.7 million tons (4%) in 1995 to 3.8 million tons (20%) in 2009. As a result, landfilling had been drastically reduced from 12.6 million tons (72%) in 1995 to 3.5 million tons (19%) in 2009 [6,7,8,9]. Chapter 3 will discuss about incineration with energy recovery (Waste-to-Energy) in Korea.

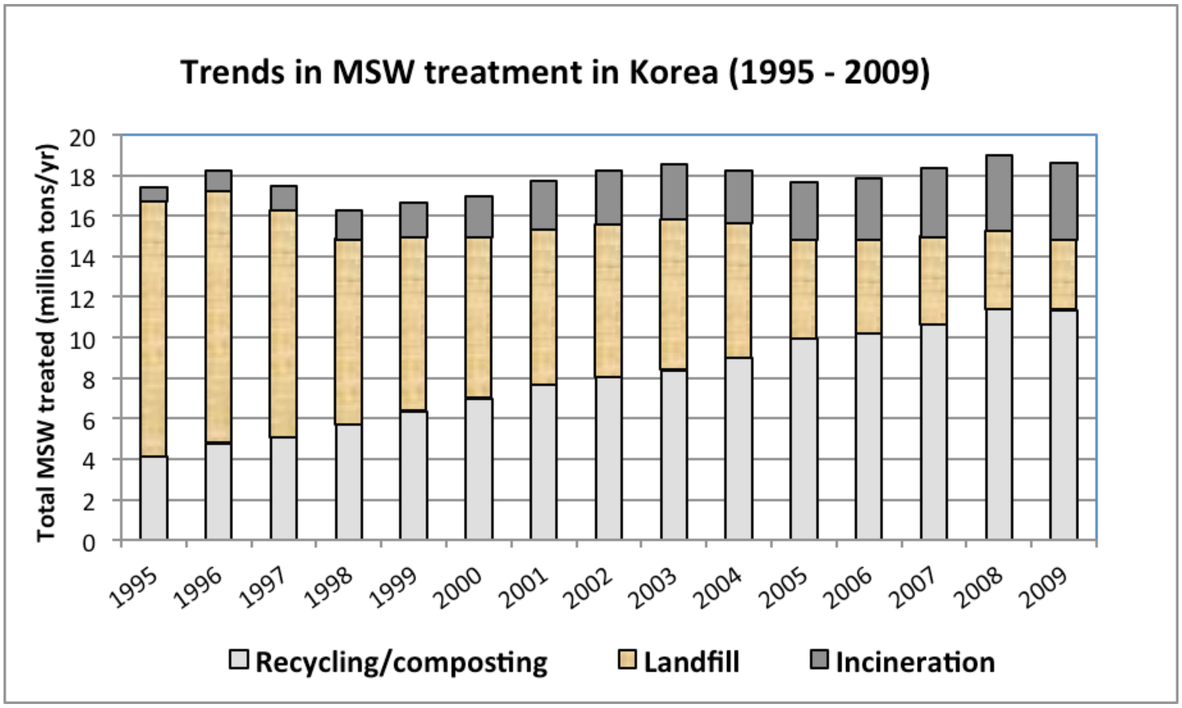


Figure 21: Trends in MSW management in Korea from 1995 to 2009

2.7 Final disposition

For the year 2009, it was estimated that 3.5 million tons (19% of the total) of the MSW generated in Korea was disposed of in landfills. According to the Korean government's annual report [9], there are 226 sanitary landfills that are owned and monitored by the municipalities and MSW made up 38% of the 9.2 million tons received into these landfills in 2009 (Table 9). The rest of the waste received into municipal landfills is construction waste and is not of interest in this study.

Table 9: Total amount of waste received in the 226 landfills and waste disposal capacity (existing and remaining) as of 2009

Facility	Number of landfills	Waste landfilled in 2009 (million tons)	Total area (million m^2)	Existing landfill capacity (million m^3)	Remaining capacity (million m^3)
Municipal Landfills	226	9.2	30.8	196.9	200

2.7.1. Sudokwon Landfill Site

The Sudokwon Landfill is one of the largest sanitary landfill sites worldwide with a size of 20 million square meters (19,790,000 m^2). It handles 37% of the waste generated in Korea [54]. The Sudokwon Landfill, situated in Incheon, 35km west of Seoul, has been serving the 58 cities of Seoul, Incheon and the surrounding metropolitan areas since its first operation in 1992. In 2009, out of the 4.4 million tons of waste received into the Sudokwon Landfill, 2.9 million tons were MSW (65.6% of the total) (Table 10). This sanitary landfill is equipped with modern technologies such as a synthetic liner, a leachate and landfill gas collecting system and a 50MW steam cycle power plant that converts landfill gas into electricity [28]. According to the Ministry of Environment, the power plant started operating in December 2006 and generates 30 million USDs worth of electricity that is fed into the local power grid.

Table 10: Distribution of the waste received in Sudokwon landfill in 2009

Waste	Million tons/y	Percent (%)
Municipal Solid Waste (MSW)	2.9	65.6
Construction Waste	1.5	34.4
Total	4.4	100

The Sudokwon landfill consists of four sectors: the landfill site 1 filled with 71.5 million tons of waste from 1992 to 2000, the landfill site 2 that is currently receiving waste, and the landfill sites 3 and 4 that are planned to be opened after the closing of the landfill site 2 [29]. The area map of the Sudokwon landfill from Figure 22 clearly shows how the site is divided into 4 sections. Figures 23 and 24 show a bird's eye view of the landfill site and the inside of the landfill. A further study on landfill gas collection and its use through energy recovery in the Sudokwon Landfill and other landfills in Korea is needed.

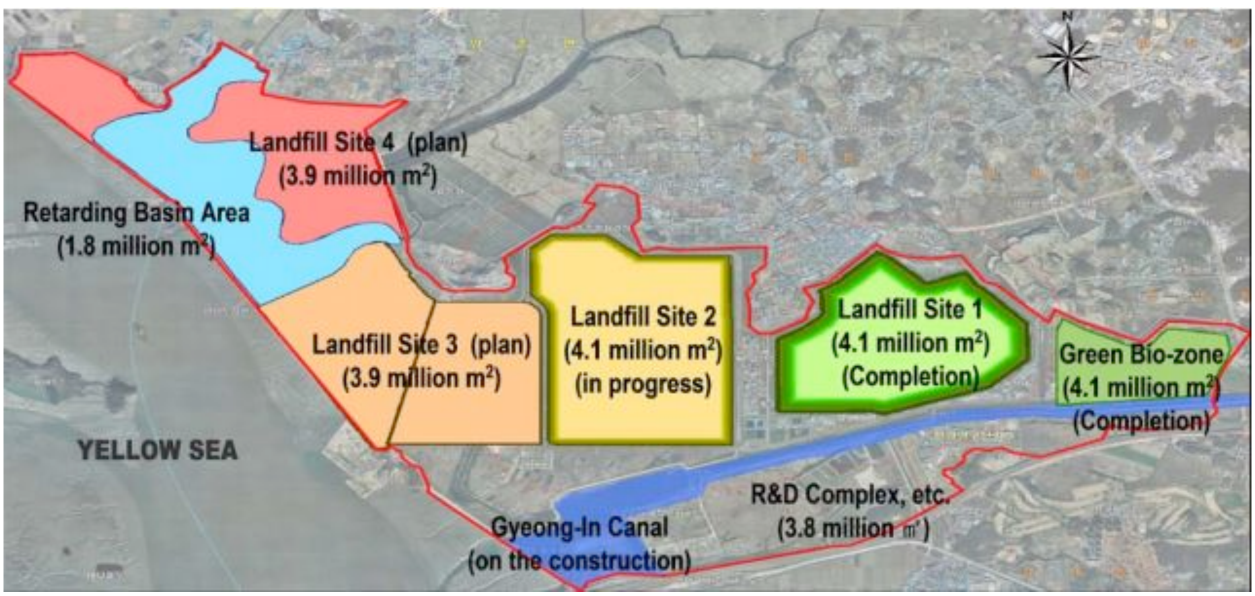


Figure 22: The area map of the Sudokwon Landfill

Figure 23: A satellite view of the Sudokwon landfill site 2

Source: Ministry of Environment, Republic of Korea

Figure 24: Waste dumping in the Sudokwon Landfill [30]

CHAPTER 3: CURRENT WASTE-TO-ENERGY STATUS IN KOREA

3.1 Background

The priority in waste management is waste reduction followed by the recovery of recyclable materials through recycling and composting. Since not all wastes can be recycled, energy recovery from non-recyclable materials takes place in the next best waste management option: waste-to-energy (WTE) incineration [21]. Incineration using non-recyclable, combustible MSW as fuel is the most common WTE implementation. Since the volume of waste is reduced by 95-96% through combustion [19], WTE is highly desirable over land filling in countries such as Korea where land is scarcer. The incineration WTE option is also important in Korea because it reduces the need for the importing of fossil fuels by generating heat, steam and/or electricity in place of fossil fuels. The reality is that Korea ranked tenth in total energy consumption amongst all the nations of the world in 2009 [23], but the nation's energy dependence is at 96.4% as of 2009 [22]. Because MSW can play a role as an important energy resource, the Korean government has focused on building WTE plants and developing WTE technologies in recent years.

3.2 WTE facilities in Korea

Although the Korean government has had in place plans to build and operate waste incineration plants since 1984 [24], the nation has not made great strides in the development of these WTE facilities. As shown in Figure 25, out of a total of 177 incinerators, only 35 large incineration plants concentrated in metropolitan areas are currently involved in energy recovery in a form of heat and/or electricity production as of 2010. The rest are incinerators with small capacities that only burn local MSW.

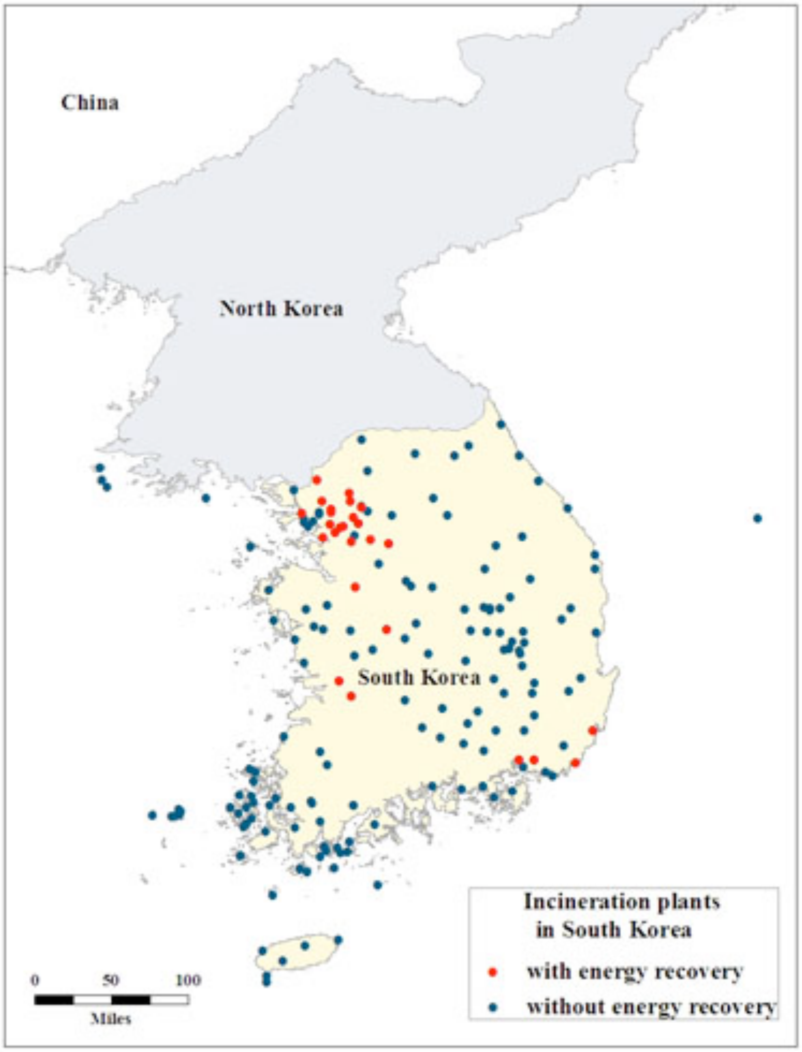


Figure 25: Incineration plants in Korea; 35 facilities out of 177 are currently generating and supplying heat and/or electricity in 2010; made using GIS application, Arcmap 10; based on data from [9]

Figure 26 shows the locations of the 35 WTE plants in Korea as of 2010 in greater detail. As stated above, the facilities are concentrated in the capital city, Seoul, and in the metropolitan areas.

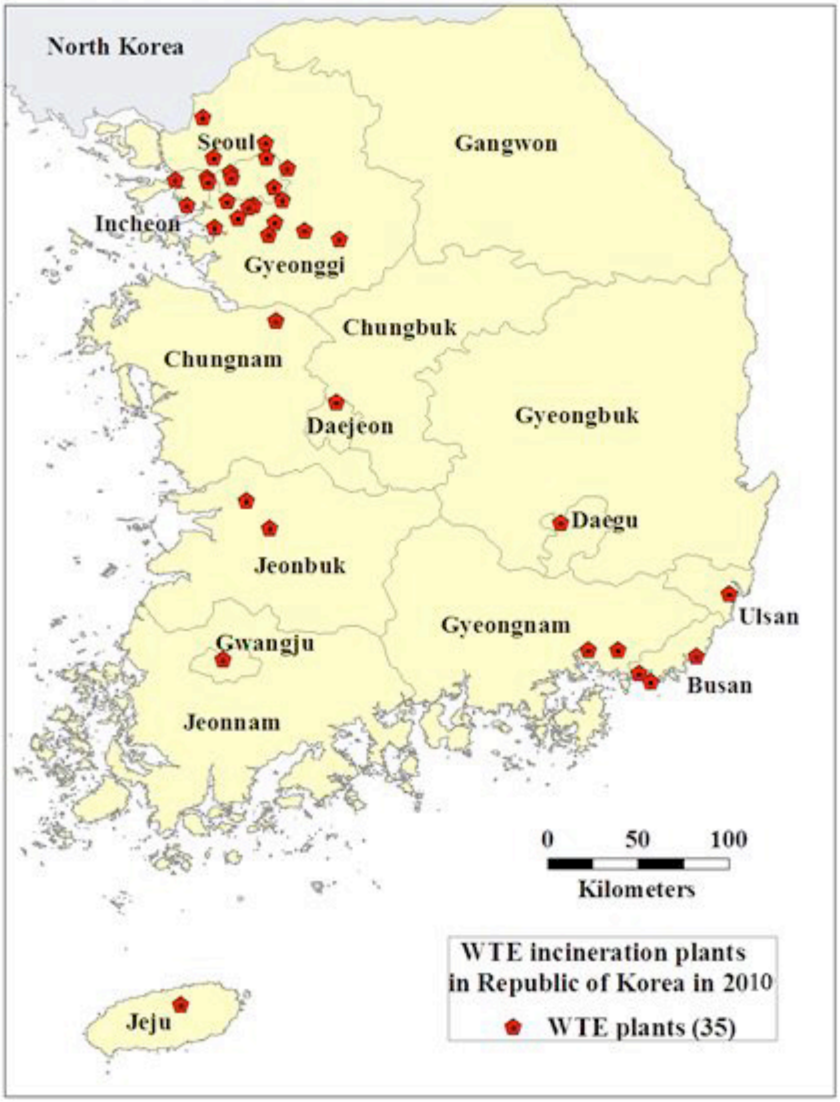


Figure 26: Locations of incineration plants with energy recovery (WTE) in Korea in 2010; made using GIS application, Arcmap 10; based on data from [25]

3.3 Capacities and energy recovery of WTE plants in Korea

The annual capacity of these 35 WTE facilities in 2010 was 3.1 million tons [25], accounting for about 90% of the total amount of incineration in Korea (3.44 million tons per year from the 2009 data [9]). Based on the 2009 waste treatment data, the proportion of waste that ends up at WTE facilities in Korea is calculated to be approximately 18%. From the comparison with the E.U. countries (Figure 27), the status of recycling and composting (61% participation rate together) in Korea resembles Belgium's, where the proportion of WTE waste is about 27%, while being at the same stage with Finland's for the

WTE waste volume. Koreas' primary energy consumption in 2009 was 10.2 billion GJ, in which the proportion of renewable energy was only 2.2% [22].

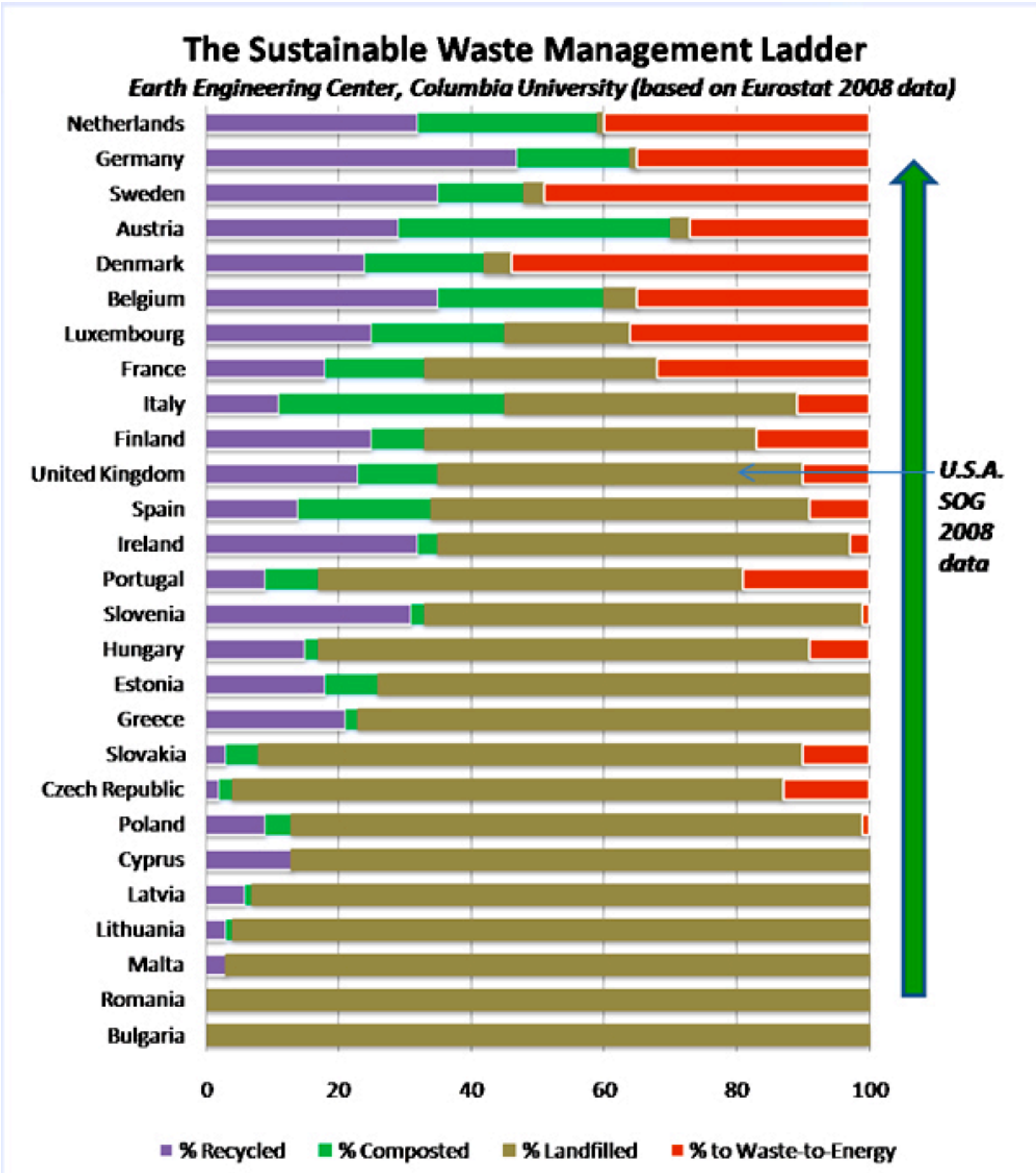


Figure 27: The E.U. "Ladder" of Sustainable Waste Management [21]

Table 11 presents the status of energy generation and use of heat and/or electricity in the 35 large WTE plants in 2010. In 2010, total thermal energy input from burning MSW in these facilities was 8.3 million MWh from 3.1 million tons of waste received, whereas the amount of energy contributed for energy supply (the yield) was only 4.5 million MWh (combining the quantities for district heating and electricity sold to grid).

Table 11: Energy generation and use in 35 WTE plants in 2010; based on data from [25]

WTE plants	Waste Received (ton/y)	Thermal Energy Input (MWh)	In-plant electricity and heat use/loss (MWh)	District heating (MWh)	Electricity to grid (MWh)
Kangnam	264,035	771,667	179,722	591,944	0
Mapo	202,134	617,222	159,722	448,611	1,007
Nowon	161,915	316,111	48,611	267,500	0
Suwon	159,172	389,167	105,833	283,333	0
Songdo	137,152	391,389	173,611	217,778	0
Seongnam	132,385	401,944	138,056	264,167	0
Seongseo	127,819	283,333	76,389	164,167	109
Cheongna	123,887	311,944	96,111	49,444	1,193
Yangcheon	109,972	322,222	95,556	213,889	1,479
Ulsan	107,231	266,111	51,111	100,556	776
Haeoondae	104,282	209,722	71,111	120,833	1,425
Myungji	103,931	298,056	124,167	170,000	121
Daejeon	103,181	280,833	89,722	191,111	0
Changwon	98,362	310,833	131,111	76,944	514
Jeonju	87,161	275,556	41,111	8,611	12,518
Icheon	85,827	244,444	156,944	51,667	23,307
Sangmu	84,723	190,000	26,944	46,389	1,256
Gwangmyeong	80,162	179,722	20,000	159,722	0
Daejang	71,664	225,000	66,111	157,778	0
Yongin	68,733	163,333	31,944	18,889	1,946
Goyang	67,073	189,722	62,778	126,944	890
Iksan	62,673	207,222	47,500	18,056	6,468
Cheonan	57,832	147,500	26,389	121,111	0
Ansan	54,768	175,278	90,556	84,722	0
Anyang	51,695	136,667	20,556	116,389	0
Sanbuk	48,329	118,611	48,889	556	0

Uijeongbu	47,889	125,278	46,944	2,778	365
Gimhae	46,579	147,500	55,833	82,500	2,252
Guri	45,556	110,556	35,278	13,333	0
Dadae	45,537	111,944	63,611	40,833	46
Paju	41,296	146,667	56,944	74,167	1,459
Gunpo	31,568	103,056	36,944	66,111	0
Gwacheon	24,107	48,889	13,611	36,667	0
Suji	22,491	40,000	3,889	36,111	0
Samjung	11,036	35,833	13,056	22,778	0
Total of 35 plants	3,072,157	8,293,333	2,506,667	4,446,389	57,131

3.3.1 Calorific values of the 35 WTE plants

The calorific value or heating value is the amount of heat produced by the complete combustion of a specified amount of material [47]. It is a very important factor to the operation of WTE plants because the thermal energy is generated during combustion of waste when the lower heat value (LHV) is higher than 5MJ/kg [48]. As the calorific value of MSW increases, MSW becomes a more efficient fuel for producing electricity and/or heat. In the year 2010, the average value for the 35 WTE plants in Korea was 9.7 MJ/kg (Figure 28). This number is slightly lower than the average value of 10.2 or 10.3 MJ/kg for the MSW from the 97 E.U. WTE facilities (Figure 29). Considering that the value of 10 MJ/kg corresponds to about 2.8 MWh (megawatt-hours) of thermal energy per ton, Korean MSW has less energy potential than the MSW of European countries.

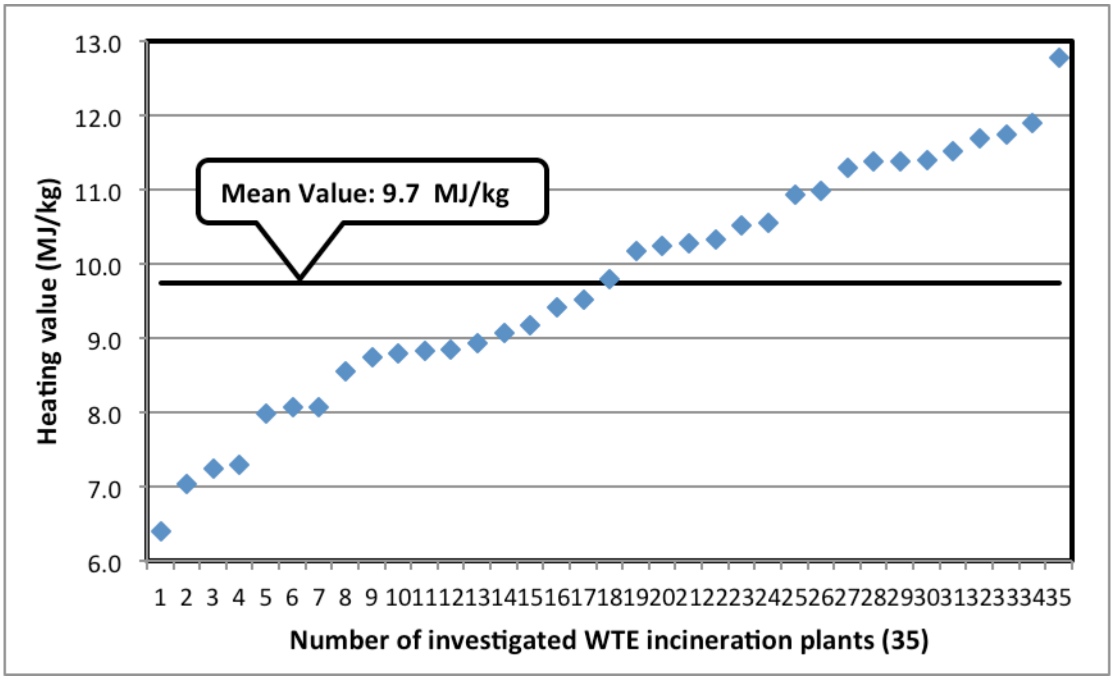


Figure 28: Heating values of MSW of 35 Korean WTE plants

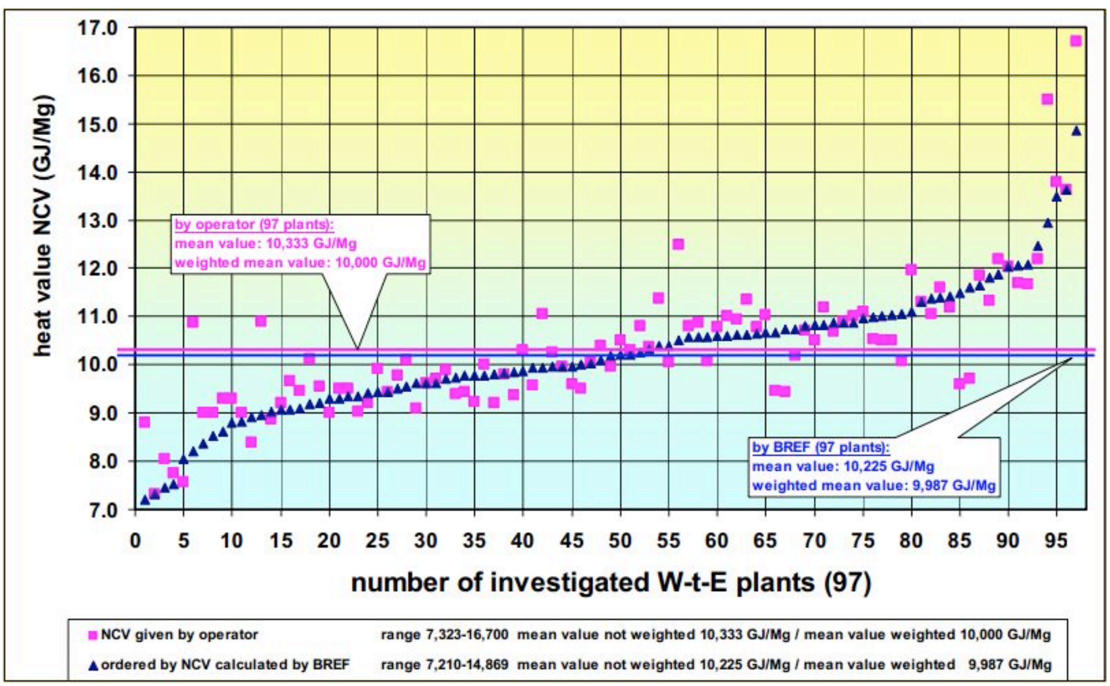


Figure 29: Calorific values of MSW of 97 E.U. WTE facilities (Reimann, D.O., "CEWEP Energy Report (Status 2001-2004)", www.cewep.org

3.3.2 In-plant energy consumption in the 35 WTE plants

In order to investigate the Korean WTE in-plant energy loss and/or use per ton of MSW, the slope of the line was derived based on the data from table 9. The average energy consumption in the 35 WTE plants in 2010 was 0.67 MWh of thermal energy per ton of MSW as shown in Figure 30.

Because a portion of energy or heat is initially lost from a furnace by the ash, designing a furnace is very important to reduce energy and heat losses. However, this applies to a future plan on building a new WTE facility. For the existing plants, the facilities can minimize the in-plant use and/or loss of the primary energy generated from the plants by installing new equipments and also by improving on their operation. For example, less combustion air during start up and shut down may lower the loss of energy.

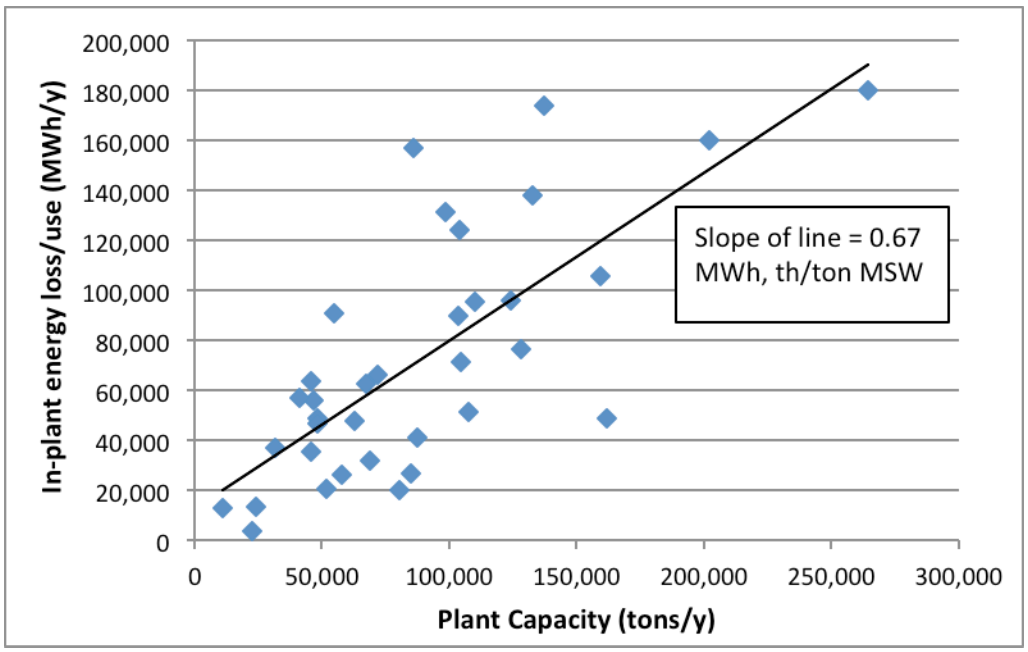


Figure 30: In-plant energy loss/use vs. plant capacity of the 35 WTE plants

3.3.3 Energy efficiency in terms of "the R1 formula"

The energy efficiency of the Korean WTE plants can be calculated using the R1 formula as specified in the European legislation. According to the Waste Framework Directive of the E.U., a WTE plant is considered to be on energy recovery status if the energy efficiency factor, R1, is equal to or above 0.60 for plants permitted before January 2009, and 0.65, for plants permitted in 2010 or later. When the auxiliary fossil fuel use in WTE plants is negligible, the R1 factor can be calculated using a simplified formula as follows [49]:

R1 (energy efficiency factor) = $(2.6kWh_{el} + 1.1\ Wh_{h})/0.97kWh_{chem.}$

Where

el: net electrical energy produced by the WTE plants

h: Heat energy produced by the WTE plants

chem: chemical energy stored in the MSW.

Table 12 lists the calculated values for the chemical heat in the MSW received into the facilities, the electrical energy and heat energy produced by the plants, and the R1 factor for each of the plants. The average R1 factor of 35 Korean WTE plants in 2010 was 0.59. Figure 31 shows that 22 WTE plants in Korea are on an energy recovery status (R1 status) according to the E.U. standard. Most of the large plants processing more than 100,000 tons of MSW have an R1 factor equal to or greater than 0.60. Among the large plants, only Cheongna and Ulsan plants have a low R1 value of 0.19 and 0.44, respectively. From the table 12, it can be seen that the heat energy produced by both plants are significantly smaller than the other large plants.

Table 12: Calculated chemical heat in MSW, electrical energy, heat energy and R1 factor in 35 WTE plants in 2010

WTE plants	Tons of MSW processed (tons/y)	Chemical heat in MSW (kWh/ton)	Electrical energy (kWh/ton)	Heat energy (kWh/ton)	Calculated R1 factor
Kangnam	264,035	2,923	0	2,242	**0.87**
Mapo	202,134	3,054	5	2,219	**0.83**
Nowon	161,915	1,952	0	1,652	**0.96**
Suwon	159,172	2,445	0	1,780	**0.83**
Songdo	137,152	2,854	0	1,588	**0.63**
Seongnam	132,385	3,036	0	1,995	**0.75**
Seongseo	127,819	2,217	1	1,284	**0.66**
Cheongna	123,887	2,518	10	399	0.19
Yangcheon	109,972	2,930	13	1,945	**0.77**
Ulsan	107,231	2,482	7	938	0.44
Haeoondae	104,282	2,011	14	1,159	**0.67**
Myungji	103,931	2,868	1	1,636	**0.65**
Daejeon	103,181	2,722	0	1,852	**0.77**
Changwon	98,362	3,160	5	782	0.29
Jeonju	87,161	3,161	144	99	0.16
Icheon	85,827	2,848	272	602	0.50

Sangmu	84,723	2,243	15	548	0.29
Gwangmyeong	80,162	2,242	0	1,992	**1.01**
Daejang	71,664	3,140	0	2,202	**0.80**
Yongin	68,733	2,376	28	275	0.16
Goyang	67,073	2,829	13	1,893	**0.77**
Iksan	62,673	3,306	103	288	0.18
Cheonan	57,832	2,550	0	2,094	**0.93**
Ansan	54,768	3,200	0	1,547	0.55
Anyang	51,695	2,644	0	2,251	**0.97**
Sanbuk	48,329	2,454	0	11	0.01
Uijeongbu	47,889	2,616	8	58	0.03
Gimhae	46,579	3,167	48	1,771	**0.68**
Guri	45,556	2,427	0	293	0.14
Dadae	45,537	2,458	1	897	0.41
Paju	41,296	3,552	35	1,796	**0.60**
Gunpo	31,568	3,265	0	2,094	**0.73**
Gwacheon	24,107	2,028	0	1,521	**0.85**
Suji	22,491	1,778	0	1,606	**1.02**
Samjung	11,036	3,247	0	2,064	**0.72**
Total/Average of 35 plants	Total tons 3,072,157	Average 2,700	Average 19	Average 1,447	Average R1 : 0.59

Note: The R1 factors equal to or greater than 0.60 were bolded.

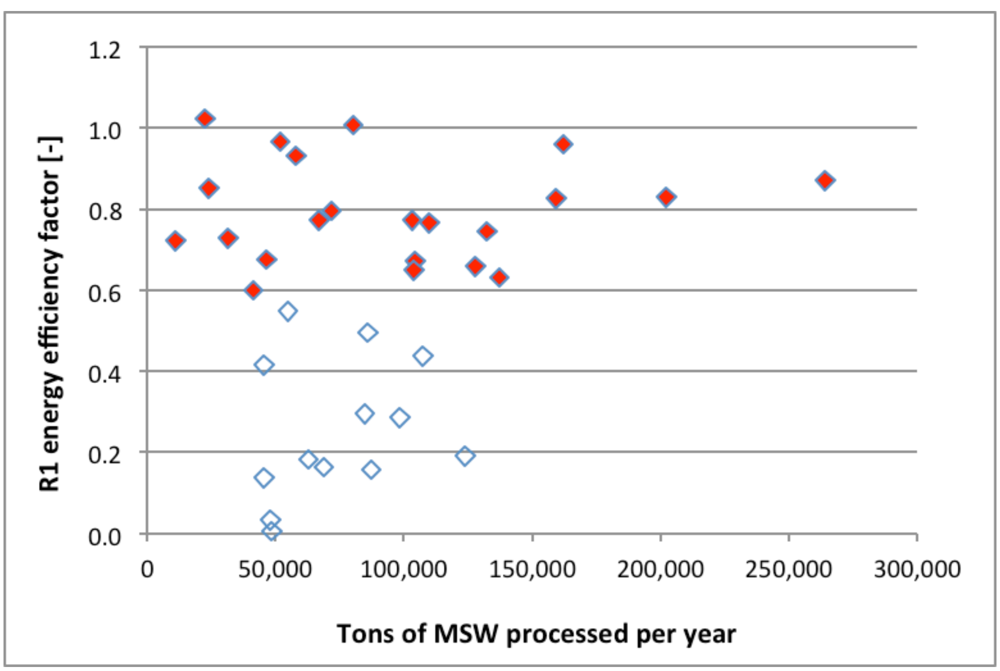


Figure 31: R1 factor for 35 Korean WTE plants in 2010

As shown in Figure 32, the average R1 factor of 314 WTE plants in the E.U countries is 0.69. From the CEWEP Energy Report No. 3, Dr. Reimann reported that 206 plants out of the total of 314 had reached the R1 status between 2007 and 2010. 71 plants in Northern Europe were the best performers in terms of energy recovery, achieving a very high value for the averaged R1 factors of 0.97. The average R1 factor for 188 plants in the central Europe was 0.62 while the 55 plants in South-Western Europe had a relatively low averaged R1 factor of 0.58. The Korean WTE plants' status in terms of energy efficiency can be said to be similar to that of the WTE plants in South-Western Europe.

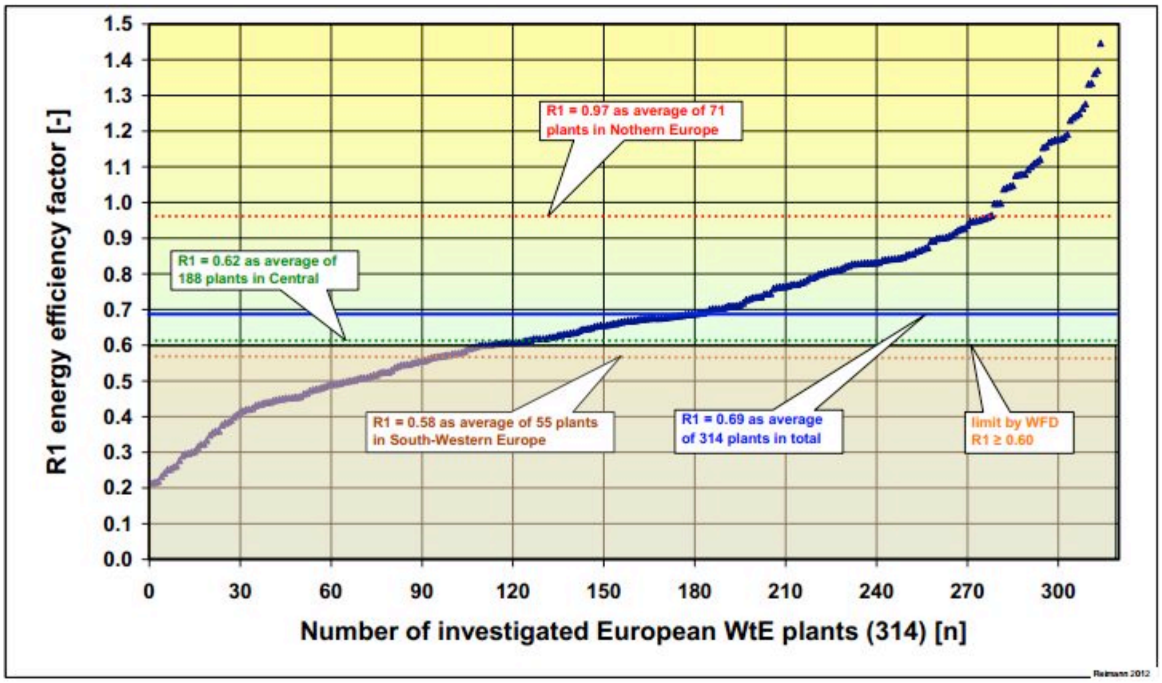


Figure 32: R1 factor for 314 European WTE plants: 71 from Northern Europe, 188 from Central Europe and 55 from South-Western Europe from 2007 to 2010 [55]

3.3.4 Comparison of the current Korean WTE status to that of Denmark

Denmark's 29 WTE plants are known to have a very high energy recovery rate, supplying 38 million GJ of energy to the public from 3.7 million tons of waste in 2007 [26]. The locations of the WTE facilities throughout this world-leading country are shown in Figure 33.

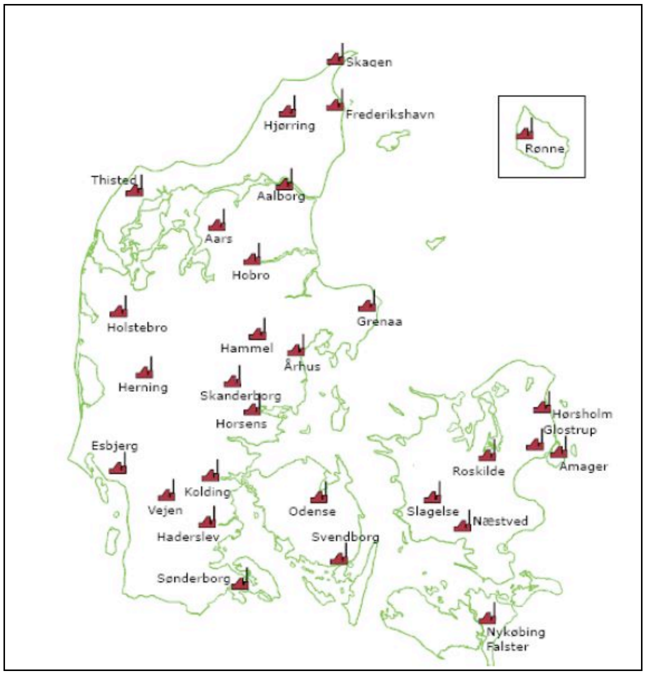


Figure 33: Denmark's 29 WTE facilities as of 2007 [26]

Calculating with data for 2009 from the Yearbook of Energy Statistics, it is discovered that in Korea, the energy production from MSW accounts for only 0.24% (0.55% for the total waste including MSW) of the total primary energy supply. This percentage is extremely low by Danish standards as in Denmark, 20% of the total district heating production generated, and 4.5% of the electricity produced, was from waste in 2007 [26]. The percentage of energy that is used or lost from operations in the 35 large WTE plants in Korea was calculated and entered in table 9. The high in-plant energy use and loss explains the low energy supply in Korea from the 35 large plants (16.2 million GJ in 2010), being at about half of Denmark's (38 million GJ in 2007).

3.4 Grate Technologies in the Korean WTE plants

For modern WTE plants, there are various types of grate technologies available depending on how the "fuel" wastes are fed onto the combustion grate. They include the horizontal grate, the forward moving grate, the reverse-acting grate and the roller grate. The grate used by a WTE plant should be able to accommodate fluctuations in the waste composition and calorific value. Currently, in Korean WTE plants, a moving grate (stoker) is dominantly used with 2 or 3 units to combust MSWs. Table 13 lists the number of furnace lines, commissioning years, grate technology used and grate system manufacturer for each plant. Figure 34(a) and 34(b) show a forward moving grate by Von Roll and a horizontal grate by Marin GmbH.

Table 13: Korean WTE plants: Quantities of waste received in 2010, daily plant capacity, number of furnace lines, commissioning years, grate technology used and grate system manufacturer

WTE plants	Waste received in 2010 (TPY)	Capacity (TPD)	No. Lines	Start-up Year	Grate Technology	Grate system manufacturer
Kangnam	264,035	900	3	2002	Horizontal grate	Martin GmbH
Mapo	202,134	750	3	2005	Aircooled VS grate	Babcock & Wilcox
Nowon	161,915	800	2	1997	Roller grate	Fisia Babcock
Suwon	159,172	600	2	1999	Reverse-acting grate	Martin GmbH
Songdo	137,152	500	2	2006	Horizontal grate	Hitachi Zosen
Seongnam	132,385	600	2	1998	Roller grate	Fisia Babcock
Seongseo	127,819	480	3	1993, 1998	NA	Hitachi Zosen
Cheongna	123,887	500	2	2002	Reverse-acting grate	Martin GmbH
Yangcheon	109,972	400	2	1996	Stocker (ladder)	Keppel Seghers
Ulsan	107,231	400	2	2000	Aircooled VS grate	Babcock & Wilcox
Haeoondae	104,282	400	2	1996, 1997	SITY 2000	Martin GmbH
Myungji	103,931	400	2	2003	Opposed motion grate	Fisia Babcock
Daejeon	103,181	400	2	1998, 2005	NA	NA
Changwon	98,362	400	2	1995, 2000	Aircooled VS grate	Babcock & Wilcox
Jeonju	87,161	400	2	2006	SITY 2000	Martin GmbH
Icheon	85,827	300	2	2008	Forward moving grate	Fisia Babcock
Sangmu	84,723	400	2	2001	Reverse-acting grate	Keppel Seghers
Gwangmyeong	80,162	300	2	1999	Forward moving grate	Fisia Babcock
Daejang	71,664	300	1	2000	NA	Hitachi Zosen
Yongin	68,733	300	3	1999, 2005	NA	NA
Goyang	67,073	300	2	2010	Reverse-acting grate	Martin GmbH
Iksan	62,673	200	2	2009	NA	Hitachi Zosen
Cheonan	57,832	200	1	2001	Aircooled Dynagrate	Babcock & Wilcox
Ansan	54,768	200	1	2001	Forward moving grate	Fisia Babcock
Anyang	51,695	200	1	1994	Forward moving grate	L&C Steinmuller
Sanbuk	48,329	200	2	2003	NA	Babcock-Hitachi Zosen
Uijeongbu	47,889	200	2	2000	Aircooled grate	Keppel Seghers
Gimhae	46,579	200	1	2001	Horizontal grate	Martin GmbH
Guri	45,556	200	2	2001	Reverse-acting grate	Martin GmbH
Dadae	45,537	200	1	1995	Aircooled VS grate	Babcock & Wilcox

Paju	41,296	200	2	2002	NA	NA
Gunpo	31,568	200	1	2001	NA	NA
Gwacheon	24,107	80	1	1999	Horizontal grate	Martin GmbH
Suji	22,491	70	2	2000	NA	NA
Samjung	11,036	200	1	1995	forward acting grate	Von roll
TOTAL	**3,107,784**	**12,380**	**65**	**NA**	**NA**	**NA**

*NA: Not available

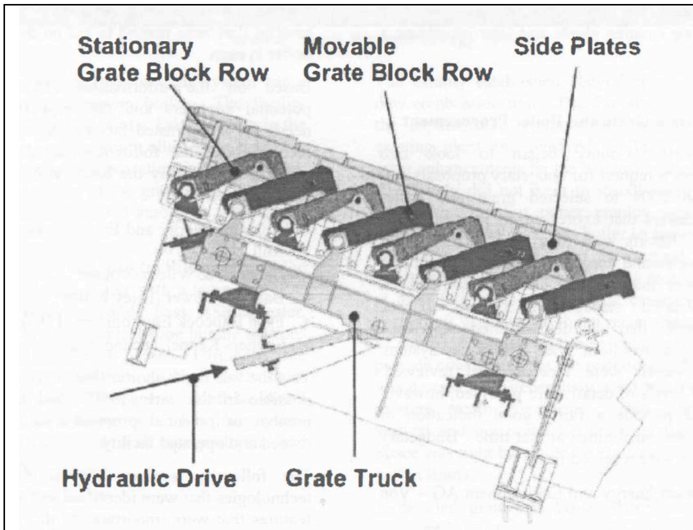


Figure 34a: Von Roll Forward Reciprocating Grate System [50]

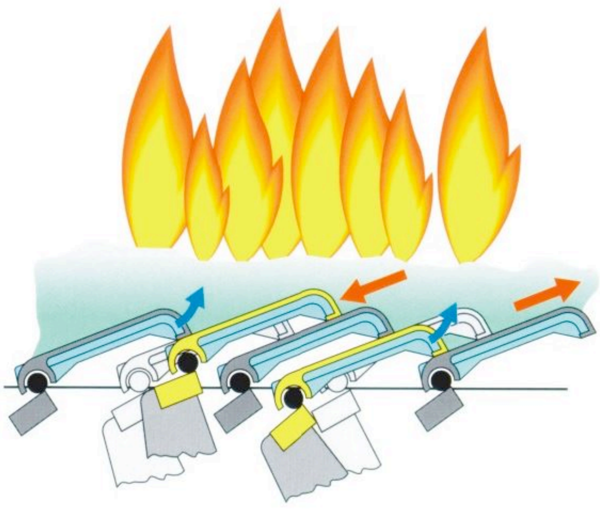


Figure 34b: Martin Horizontal Grate System [51]

Figure 34: Forward Moving Grate System VS Horizontal Grate System

3.5 Air emissions in the 35 WTE plants

The Korean government discloses data for stack emissions from WTE plants each year. Emissions data are for the six flue gas pollutants: sulfur oxides (SO_X), nitrogen oxides (NO_X), hydrogen chloride (HCl), carbon monoxide (CO), particulate matter (PM) covering the full range of sizes, and finally dioxins that are ultrafine, organic compounds. Since air emissions are among the major public concerns, they are strictly monitored and regulated by government agencies.

Table 14 lists the air emissions in the 35 WTE plants in 2010. The air emissions levels for air pollutants all meet the Korean standards, which are better shown in Figure 35(a) through Figure 35(f). As summarized in the bottom of the Table 14, all plants meet Korean air emission standards for the six air pollutants. Out of the six pollutants, dioxin levels were of more importance because of their extremely high toxic potency even at trace quantities. The average dioxin emission in 2010 was 0.005ngTEQ/Nm3 while the Korean standard was 0.1ngTEQ/Nm3. The total dioxin emission of all Korean WTE plants in 2010 was 0.08gTEQ.

Table 14: 2010 WTE plants' air emissions and emissions standard in Korea

WTE plants	No. of furnaces	Capacity (TPY in 2010)	Capacity (TPD)	Dioxin (ngTEQ/Nm3)	SOx (ppm)	NOx (ppm)	HCl (ppm)	CO (ppm)	PM (mg/Sm3)
1 (Kangnam)	1	89,858	300	0.002	0.18	24.32	3.19	8.88	1.09
	2	89,339	300	0.001	0.26	19.20	2.23	19.11	0.85
	3	89,225	300	0.002	0.36	23.30	2.26	11.83	1.22
2 (Mapo)	1	67,039	250	0.001	1.48	20.42	4.18	15.32	0.11
	2	67,524	250	0.001	1.38	20.01	4.19	7.05	1.28
	3	67,721	250	0.000	0.77	18.27	3.56	9.13	0.80
3 (Nowon)	1	81,777	400	0.000	2.12	23.43	0.75	9.06	1.69
	2	78,413	400	0.002	2.19	23.45	0.64	8.95	2.20
4 (Suwon)	1	82,842	300	0.000	1.59	41.12	5.70	16.10	1.35
	2	76,972	300	0.017	1.35	44.33	4.37	14.26	1.72
5 (Songdo)	1	69,672	250	0.001	1.40	25.48	1.33	6.32	0.42
	2	67,775	250	0.009	0.99	20.32	2.47	7.07	0.21
6 (Seongnam)	1	67,037	300	0.007	1.88	19.63	0.18	4.71	1.53
	2	67,030	300	0.007	0.71	18.38	0.18	3.37	1.94
7 (Seongseo)	1	35,638	200	0.001	0.50	20.07	0.30	4.58	2.24
	2	44,847	200	0.024	0.48	13.53	0.19	11.27	1.30
	3	46,326	80	0.000	0.47	14.96	0.40	9.39	2.18
8 (Cheongna)	1	61,373	250	0.002	0.74	35.15	0.45	5.45	2.13
	2	61,334	250	0.001	0.43	39.80	1.28	9.87	1.45

9 (Yangcheon)	1	54,734	200	0.002	1.45	25.08	3.96	13.91	1.59
	2	55,412	200	0.000	1.68	25.17	1.97	13.49	1.11
10 (Ulsan)	1	54,814	200	0.000	1.15	11.66	1.40	6.66	2.16
	2	53,244	200	0.001	0.99	9.64	0.91	2.80	2.82
11 (Haeoondae)	1	50,719	200	0.006	1.75	35.58	0.31	6.70	3.90
	2	53,525	200	0.001	1.13	37.78	0.43	7.05	3.09
12 (Myungji)	1	51,306	200	0.000	0.02	45.30	0.50	4.06	4.30
	2	51,159	200	0.000	0.87	47.73	0.58	4.01	3.92
13 (Daejeon)	1	50,091	200	0.015	4.49	31.76	3.39	4.95	2.66
	2	52,496	200	0.010	9.56	33.33	6.64	4.81	2.20
14 (Changwon)	1	51,221	200	0.013	7.54	38.68	4.42	2.54	3.32
	2	45,518	200	0.007	7.25	31.67	3.67	5.30	2.57
15 (Jeonju)	1	41,482	200	0.001	0.93	43.08	1.49	8.73	0.26
	2	46,145	200	0.005	0.70	41.32	1.25	9.63	0.03
16 (Icheon)	1	43,814	150	0.001	0.79	36.15	5.55	2.26	2.09
	2	41,885	150	0.002	0.47	33.52	4.67	1.95	1.79
17 (Sangmu)	1	43,030	200	0.006	0.47	36.45	6.80	1.44	1.76
	2	42,650	200	0.006	0.54	33.03	7.16	3.50	1.76
18 (Gwangmyeong)	1	38,530	150	0.006	1.37	31.13	0.99	4.72	1.61
	2	41,310	150	0.001	1.12	33.55	2.94	3.69	0.96
19 (Daejang)	1	72,903	300	0.000	1.12	27.74	3.99	4.05	2.20
20 (Yongin)	1	19,072	100	0.004	1.72	26.37	4.12	1.41	1.18
	2	22,647	100	0.007	4.04	28.75	3.69	5.43	1.58
	3	26,930	100	0.006	1.10	35.24	1.81	5.29	0.29
21 (Goyang)	1	35,337	150	0.012	0.98	28.31	3.51	11.81	1.93
	2	35,806	150	0.019	1.02	24.29	3.86	10.93	1.40
22 (Iksan)	1	32,213	100	0.006	3.68	30.13	0.39	5.09	1.67
	2	30,818	100	0.004	2.63	29.29	0.46	6.00	1.87
23 (Cheonan)	1	58,080	200	0.003	0.37	28.16	7.35	1.37	3.82
24 (Ansan)	1	54,815	200	0.000	0.66	43.15	5.94	6.93	1.36
25 (Anyang)	1	51,609	200	0.007	1.61	44.08	1.47	6.49	2.07
26 (Sanbuk)	1	23,052	100	0.009	2.55	31.49	4.27	22.29	4.42
	2	24,532	100	0.010	2.58	25.66	3.96	21.02	4.20
27 (Uijeongbu)	1	23,449	100	0.001	1.09	27.37	2.25	7.39	1.72
	2	24,620	100	0.000	0.88	23.35	3.67	7.59	2.13
28 (Gimhae)	1	46,779	200	0.010	3.30	46.48	4.34	3.66	3.35
29 (Guri)	1	23,251	100	0.006	2.03	34.68	5.04	7.35	1.80
	2	22,483	100	0.002	2.32	36.08	4.34	5.98	1.95
30 (Dadae)	1	45,554	200	0.000	0.41	39.53	1.08	3.90	2.04
31 (Paju)	1	19,947	100	0.001	1.74	23.58	6.18	3.65	1.01
	2	22,061	100	0.000	2.13	23.52	4.77	2.12	0.99

32 (Gunpo)	1	31,686	200	0.035	0.93	7.61	1.38	1.24	1.85
33 (Gwacheon)	1	23,869	80	0.009	1.98	32.66	2.82	6.04	1.96
34 (Suji)	1	11,449	35	0.000	1.94	38.20	1.07	13.06	1.61
	2	11,430	35	0.008	2.01	39.56	0.94	19.58	1.79
35 (Samjung)	1	12,258	200	0.001	1.73	27.20	0.05	5.64	3.74
Average emissions of all 35 WTE plants:				0.005	1.69	29.68	2.76	7.53	1.90
Korean air emissions regulation for MSWI:				0.1	30	70	20	50	20

Number of plants listed: 35
Total WTE capacity: 12,380 tons/day
Total waste incinerated in 2010: 3,081,477 tons

Korean standard for dioxin emission as of 2010: 0.1ngTEQ/Nm3
Average dioxin emission of all WTE: 0.005 ngTEQ/Nm3
2010 Dioxin emissions of all Korean WTE plants, grams TEQ: 0.08gTEQ

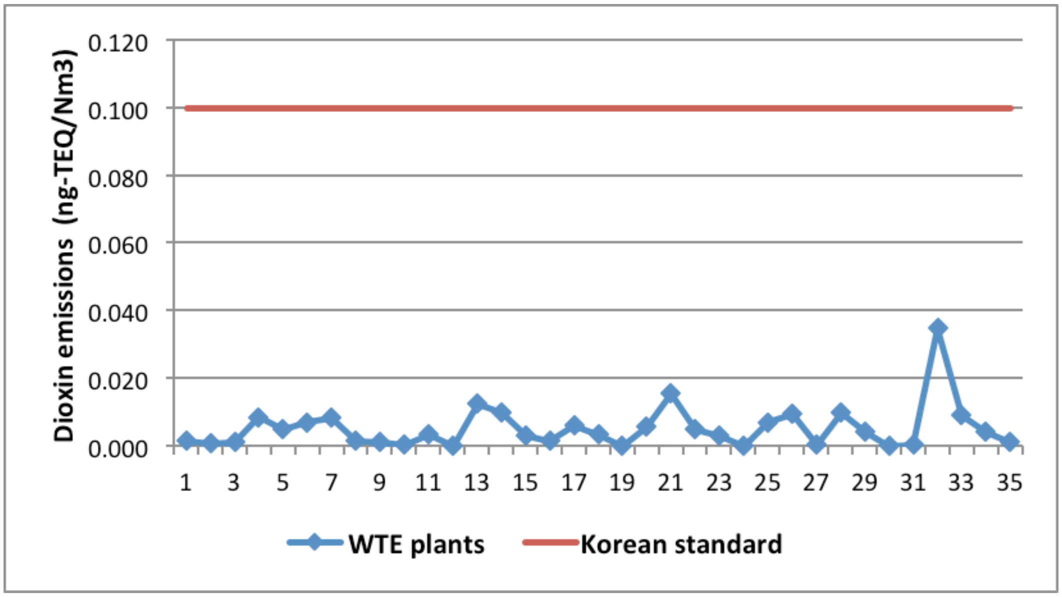


Figure 35a: 2010 Dioxin emissions in 35 WTE plants

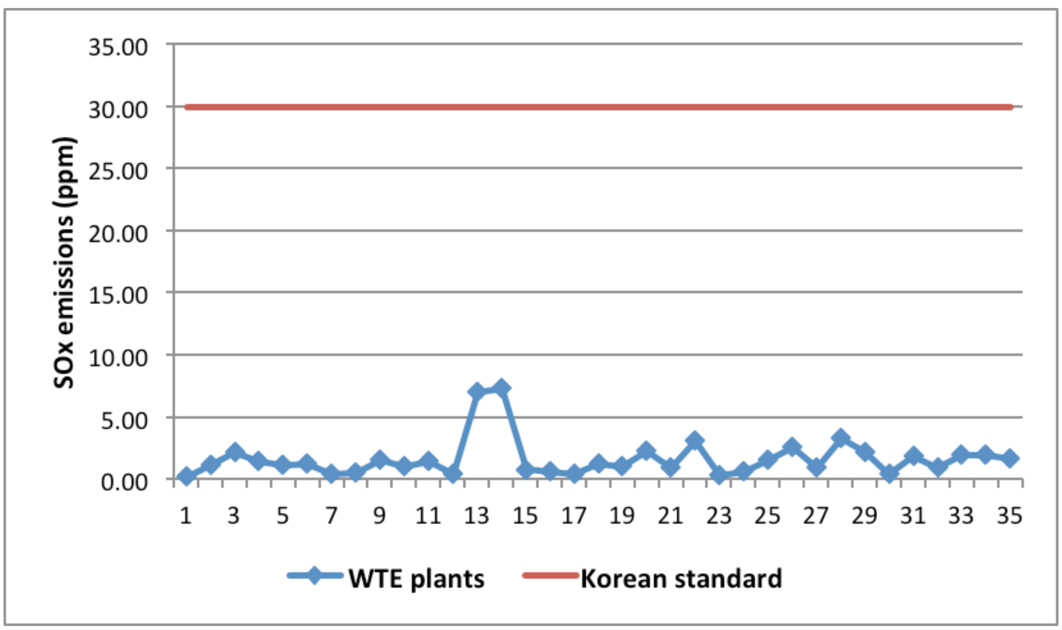


Figure 35b: 2010 SOx emissions in 35 WTE plants

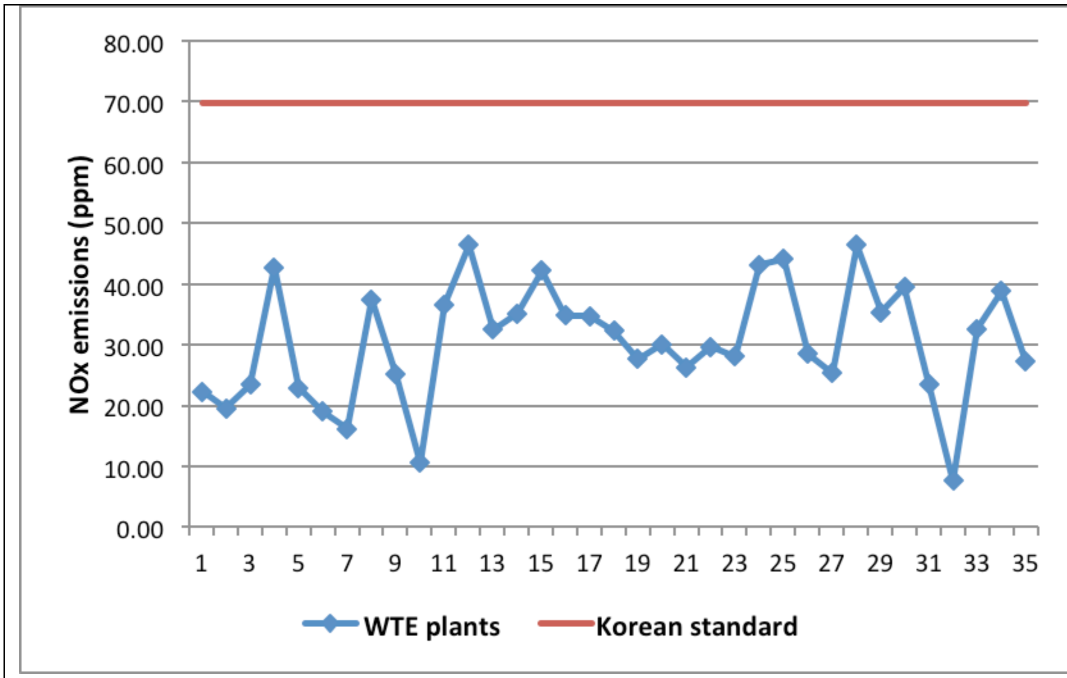


Figure 35c: 2010 NOx emissions in 35 WTE plants

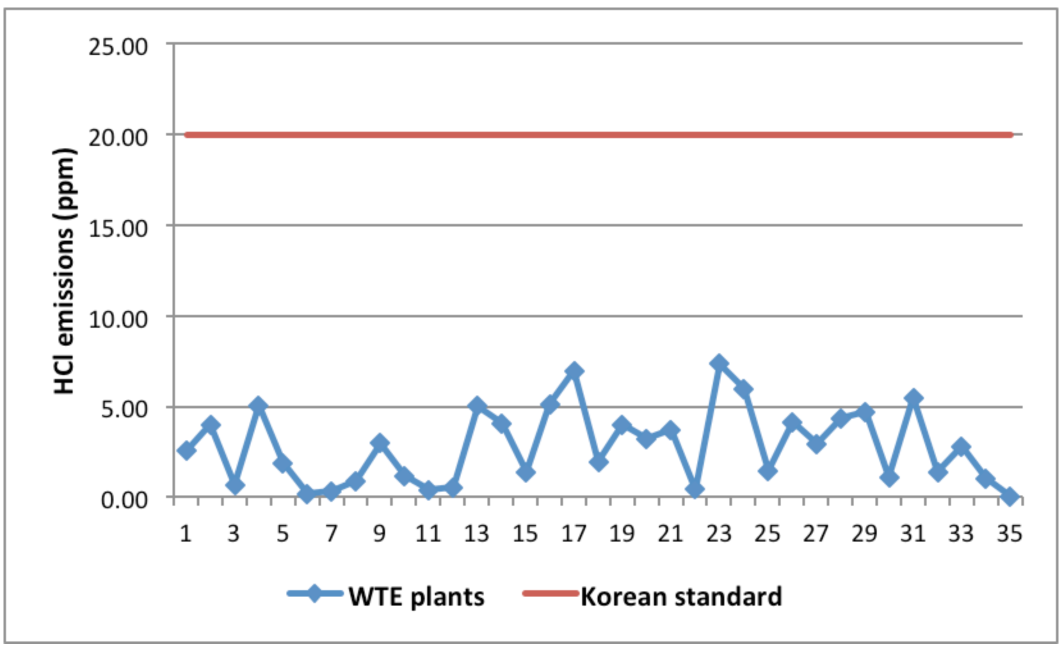


Figure 35d: 2010 HCl emissions in 35 WTE plants

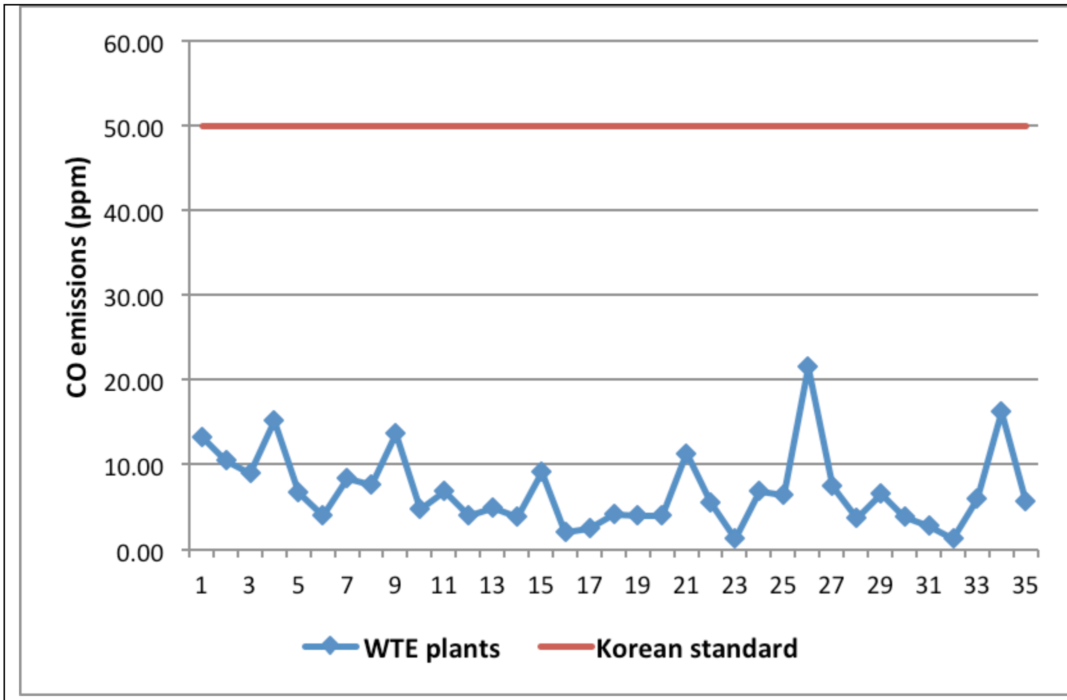


Figure 35e: 2010 CO emissions in 35 WTE plants

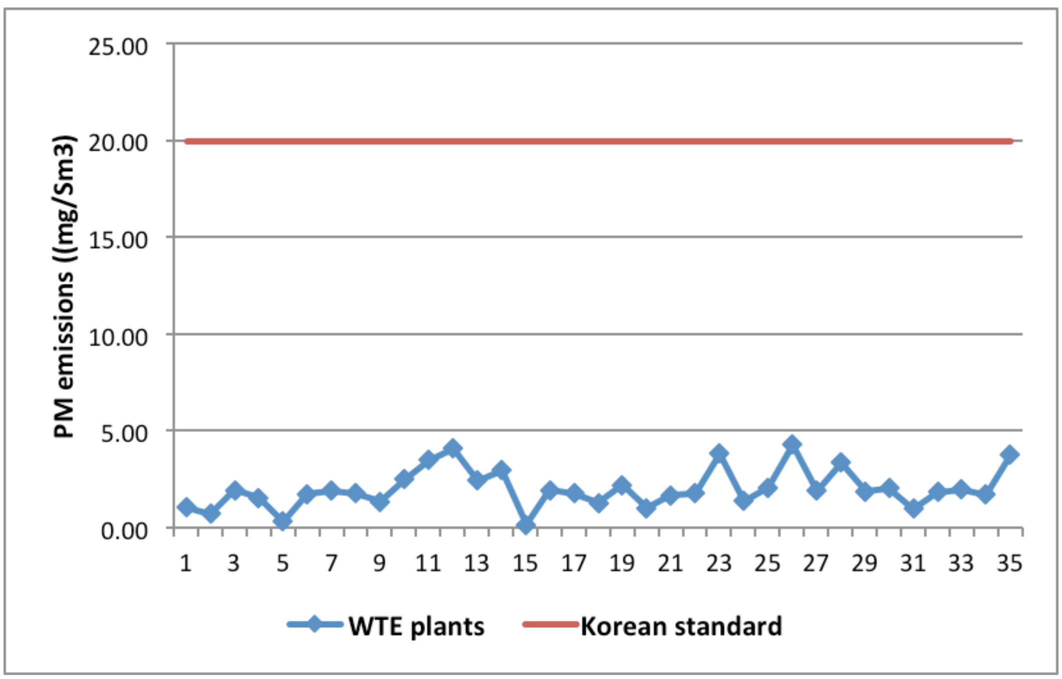


Figure 35f: 2010 PM emissions in 35 WTE plants

Figure 35: 2010 Air emissions and Korean standard for six air pollutants

Korean WTE plants limit their air emission levels by several processes using different pollution control equipments. For example, the Kangnam plant treats flue gas generated from MSW combustion using selective non-catalytic reduction (SNCR), scrubber, semi-dry removal (SDR) type dry flue gas desulfurization, bag filter, and selective catalytic reduction (SCR) while the Mapo plant uses SNCR, SDR, bag filter, and SCR [27]. Table 15 shows gas cleaning systems and the respective typical range of reduction for each type of air pollutant.

Table 15: Gas cleaning process steps and typical range of specific air pollutant reduction [52]

Air pollutant	Process Steps	Reduction (%)
SOx	Wet scrubber or dry multicyclone	50 - 90
HCl	Wet scrubber or semi-dry	75 - 95
NOx	Selective catalytic reduction (SCR)	10 - 60
Heavy metals	Dry scrubber + electrostatic precipitator	70 - 95
Fly ash*	Electrostatic precipitator + fabric hose filter	95 - 99.9
Dioxins & Furans	Activated carbon + fabric hose filter	50 - 99.9

Note*: Fly ash surface very often adsorbs other pollutants such as dioxins and heavy metals.

Scrubber systems are commonly used to remove particulates, acid gases, and heavy metals from a gas stream through three steps: the gas cooling system, the reagent injection and the filtration system. The wet scrubbers can simply use water, or specific solutions to wash out targeted pollutants; however, in dry or semi-dry scrubbing, alkaline ingredients such as lime and/or sodium bicarbonate are used to remove acidic gases by absorption and adsorption. Dry scrubbers are often used in conjunction with electrostatic precipitators (ESP) and fabric hose filters to collect particulates. NOx can be reduced by catalytic reduction with ammonia (SCR) and/or by a high-temperature reaction with ammonia (SNCR). Semi-dry removal (SDR) type dry flue gas desulfurization systems remove SOx, HCl, Mercury, and other toxic components from flue gases. Activated carbon or slaked lime is sprayed in front of a bag filter to eliminate toxic substances such as SOx, HCl, mercury or dioxin. The chemical reacting with and absorbing the toxic gas along with the fly ash is collected by the bag filter as shown in Figure 36.

The very low levels of dioxin emissions from Korea's WTE plants can be attributable to the activated carbon used during the gas cleaning process. According to an expert from the National Institute of Environmental Research in Korea, the Paju plant, with a capacity of 200 tons of MSW per day, treats its flue gas through SDR, bag filter and SCR and with 0.156 kg of activated carbon per ton. Korean government is currently investigating how their WTE plants have achieved such low emission levels on each pollutant.

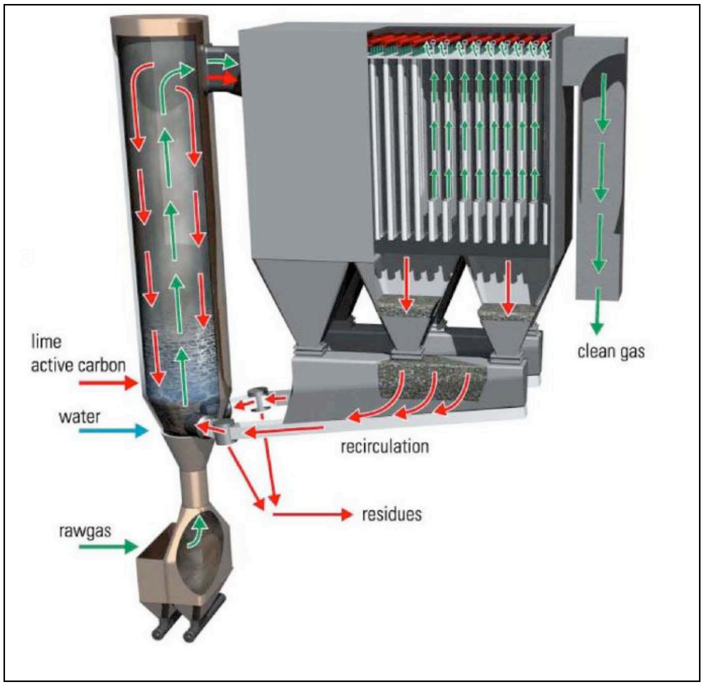


Figure 36: Dry flu gas cleaning [53]

CONCLUSIONS AND RECOMMENDATIONS

This report presented an overview of the management of MSW in Korea and analyzed the current WTE status throughout the 35 Korean WTE plants. Since the implementation of several waste management policies in Korea, including the Volume Based Waste Fee system in 1995, Korea has shown great progress in its management of MSW. As evidenced by the author's examination, the once increasing per capita waste generation rate in Korea has decreased from 0.39 tons in 1995 to 0.37 tons in 2009, despite the population growth and economic development and as a result of the new policies. Korean government's efforts to improve waste management also resulted in a drastic reduction in the landfilling rate, and increases in the recycling and incineration rates. Of the 18.7 million tons of MSW generated in 2009, only 3.5 million tons (19% of total) were landfilled, 11.4 million tons (61% of total) were recycled and 3.8 tons (20% of total) were incinerated.

Korea has been making progress in its recovery of energy from MSW as well. However, the analysis of the current status of WTE in Korea has shown that its rate of energy recovery from MSW is not as high as some of the leading countries in Europe. The Korean MSW has a calorific value of 9.7 MJ/kg that is slightly lower than that of northern European plants' (10.2-10.3 MJ/kg). However, the in-plant energy consumption of Korean WTE plants was relatively high at 0.67 MWh of thermal energy per ton of MSW. Utilizing the R1 factor as specified in the European legislation, this report determined that only 22 of the 35 Korean WTE plants have R1 factors to qualify as energy recovery plants (R1>0.61), rather than as waste disposal plants. By increasing their R1 efficiency factor, WTE plants can contribute to the national energy supply and CO2 emission reduction. From an emissions standpoint, all Korean WTE plants are excellent performers, with very low air emissions levels for the six most objectionable air pollutants as examined. The Republic of Korea can serve as a model to other developing countries for the effective use of air pollution control systems in the WTE facilities as part of a sustainable and integrated waste management approach. It is recommended that the Korean government also adds heavy metals, such as mercury and lead, to its annual report for air emissions from the WTE plants.

Throughout this report, it has been shown that, in many ways, Korea is near the top of the sustainable waste management nations, despite the relatively lower GDP of that country. This exemplifies what can be achieved through the good will and intelligent action of a nation's planners.

Currently, the sister Waste-to-Energy Research and Technology Council (WTERT)/Korea organization is under establishment and can be found on its website: http://wtert.kr (Figure 37) headed by Prof. Yong-Chil Seo of Yonsei University and President of the Korea Society of Waste Management (KSWM).

The mission of the global WTERT Council is to "identify the best available technologies for the treatment of various waste materials, conduct additional academic research as required, and disseminate this information by means of publications, presentations, and the various WTERT web pages.

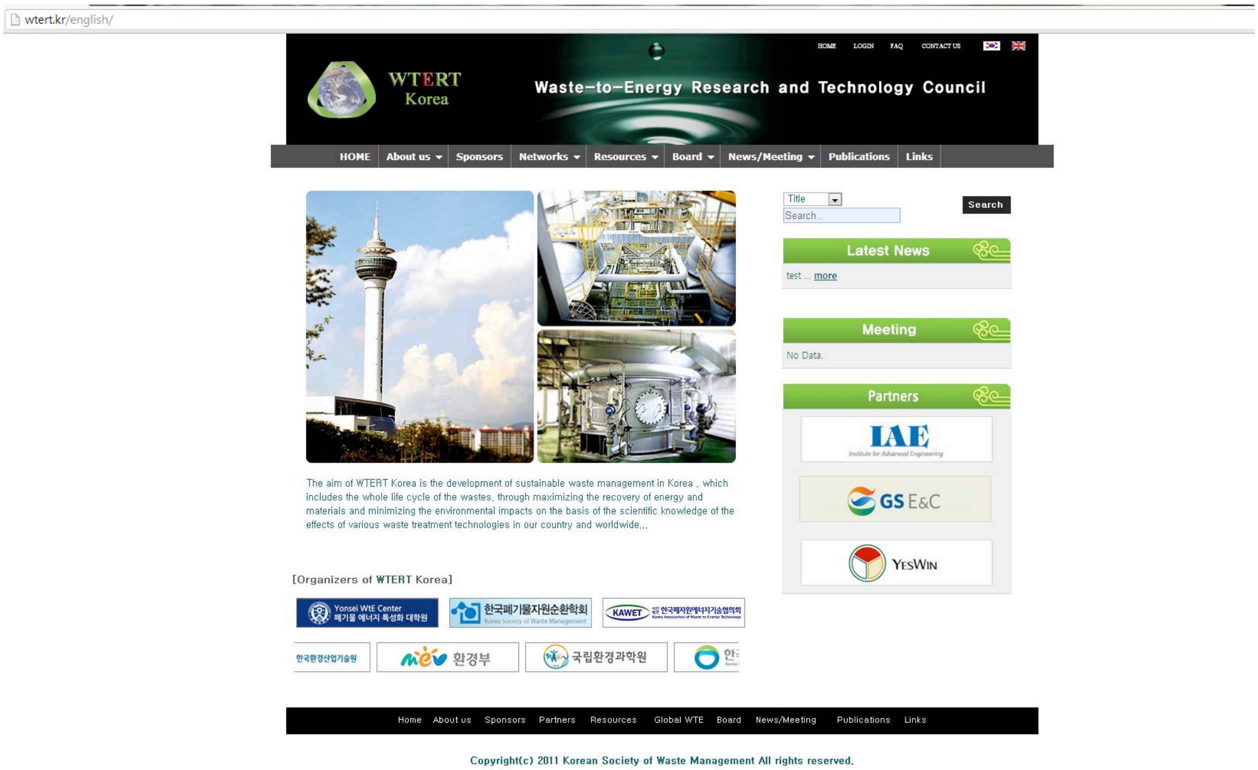


Figure 37: The WTERT-Korea website

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Yoonjung Seo, New York City, 2013

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