MUNICIPAL SOLID WASTE MANAGEMENT AND WASTE-TO-ENERGY IN THE UNITED STATES, CHINA AND JAPAN

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Abstract

In this paper an overview will be given of the current waste management situation in the United States, China and Japan. Every country has its own policies and government incentives where each country has its specific mix of Waste-to-Energy (WtE) technologies. This paper will also discuss briefly a few relevant Waste-to-Energy technologies as well as WtE-economics for these different regions of the world. WtE facilities are capital intensive and depend on various external factors to be viable. There seem to be regional difference in capital costs for constructing WtE plants where Western technologies tend to be more expensive than the Chinese. This said, the variation in capital requirement for plants of the same technology and capacity can be so substantial, that it is difficult to generalise costs of specific technologies.

Introduction

With 387 million tonnes, the United States is the country that generates the biggest amount of Municipal Solid Wastes (MSW) in the world. About 8% of this amount is destined for a WtE facility, mostly a moving grate technology. The majority is still being landfilled. However, large difference between regions can be observed. Most states in the North Eastern part of the U., have a higher level of sustainable waste management than most other regions. Regional differences in land availability and electricity prices seem to play a role.

China is one of the fastest growing countries in the world and has, as a result, a growing waste management problem. Also, due to a lower heating value (LHV) of the MSW, China engaged itself in developing a new technology, more specifically a Circulating Fluidised Bed especially adapted to their waste. With 17% of its MSW being processed in WtE facilities it is clear that China is doing a better job than the US But they still have a long way to go. Also here the majority of waste is still being landfilled.

Japan on the other hand has, of the 3 countries discussed, by far the highest level of sustainable waste management. It generates on a yearly basis about 65 million tonnes of which it treats 40 million tonnes thermally. The rest is being recycled and/or composted and only 2% is landfilled. Moreover, because of strict governmental rules and very limited land availability, newer technologies that do not seem to be economically viable in other regions of the world have been constructed here. Japan can be considered as a leader in developing and implementing traditional and novel thermal treatment technologies.

The United States

The United States accumulate on a yearly basis around 387 million tonnes of MSW (2010). With a population of over 300 million, the waste generation per capita comes down to 1,2 tonnes per year. It is a general fact that the higher the GDP of a certain country, the higher the MSW generation is. However, when comparing the average waste generation per capita with other developed countries, it is clear that people in the US generate more waste. On average, about 8% of the MSW is destined for Waste-to-Energy and around 25% is recycled or composted. The remainder (63%) is landfilled.

Each state in the United States has different characteristics and management systems for Municipal Solid Waste (MSW). Waste management in the United States is not coordinated on a federal level and is very much state dependent. Large variations in waste management and percentages of waste being landfilled can be observed between states (Figure 1). Some states mainly landfill their waste while others have a more advanced level of waste management. The best pupils of the class concerning Waste to Energy (WtE) are mainly situated in the North Eastern region of the United States due to 2 main reasons. New England has higher tipping fees regulations than most other states due to limited land availability.[1] In the much more heavily populated areas of the North East, providing land for landfilling is much more expensive than in other, less densely populated areas. The tipping fee costs in the North East can be up to $100 per tonne of MSW, therefore creating a viable economical basis for WtE facilities.[1] Again, however, large variations can be seen between states where in some states the tipping fees are as low as $10 per tonne of MSW.

Apart from higher tipping fees, electricity prices (also regulated on a state level) are also responsible for the large geographical variation in MSW. The North Eastern States have on an average basis a higher end-user price.[2] The prices for states as

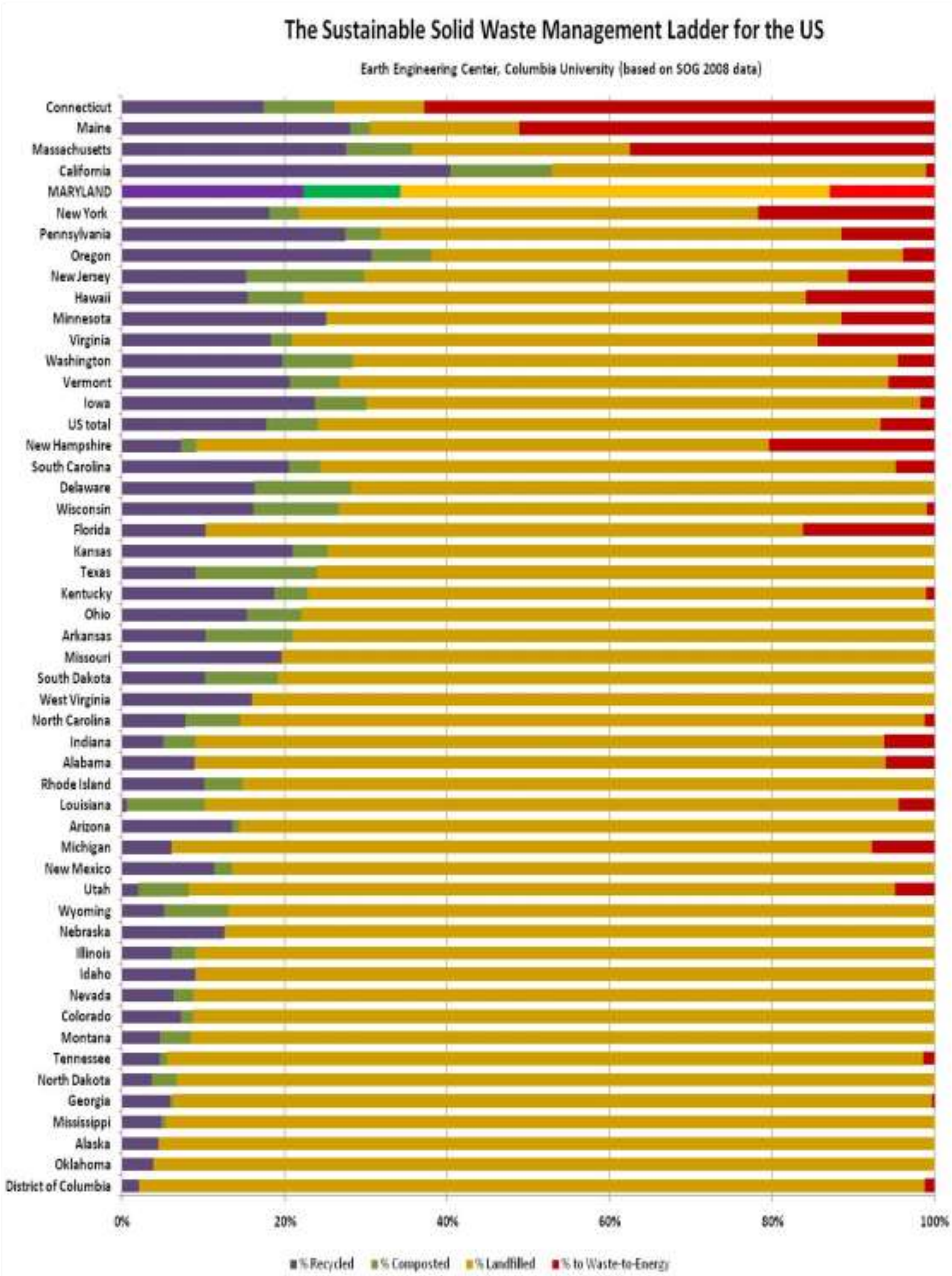

Figure 1: Ladder of Sustainable Waste Management of the United States.[3]

Vermont, Maine, Connecticut have an average end-user price of \$0,16 per kWh while in states such as Utah, Wyoming, Tennessee and North-Dakota, it hovers around \$0,105 per kWh.

Both factors (land availability and higher electricity prices) play a role as to why in certain areas more WtE facilities were constructed than in others. States such as Connecticut and Maine both have over 50% of their waste converted to energy, about 30% composted and/or recycled and only around 10-15% landfilled. On the other hand, states such as Utah and Tennessee pretty much landfill everything (see Figure 1) and are situated at the bottom of the ladder. The average amount of waste converted to energy in the United States is about 10%.

Both private companies and the public sector are active on the municipal waste management market, but the private sector has a bigger market share (about 70%). The largest players on the market are all privately owned and listed on the NY Stock exchange. Major waste management companies in the United States are listed below in order of revenues.

- Waste Management, Inc.: Headquarters: Houston, TX; Revenues: $13,65 billion (2012)
- Simms Metal Management, Inc.: Headquarters: Chicago, IL; Revenues: $9,27 billion (2012);
- Republic Services, Inc.; Headquarters: Phoenix, AZ; Revenues: $8,11 billion (2012);
- Clean Harbors, Inc.; Headquarters: Norwell, MA; Revenues: $2,19 billion (2012);
- Stericycle, Inc.; Headquarters: Lake Forest, IL; Revenues: $1,91 billion (2012);
- Veolia Environmental Services North America Corp.: Headquarters: Lombard, IL; Revenues: $1,9 billion (2011);
- Waste Connections, Inc.; Headquarters: Folsom, CA; Revenues: $1,66 billion (2012);
- Covanta Holding Corp.; Headquarters: Fairfield, NJ; Revenues: $1,64 billion (2012);
- Casella Waste Systems, Inc.; Headquarters: Rutland, VT; Revenues: $0,48 billion (2012);

It must be noted, however, that there have been quite some mergers and acquisitions in the past 5 to 6 years. A study from Harvard University of 2007[4] with the biggest players in the market showed a very different list, with considerably different revenues.

As mentioned, the total amount of waste generated in the United States amounted to 387 million tonnes in 2011.[5] Prior to 2011 the waste generated destined for landfills was slightly higher implying a better waste management nowadays. Recycling plays a bigger role and has become more prominent. Indeed, when looking at figures published by the Environmental Protection Agency,[6] recycling has been increasing steadily over the years with about 25% of all waste generated being reused nowadays. The amount of installed and operating Waste-to-Energy facilities in the United States in 2012 was 86.[7] However, it should be noted that almost all of these facilities were constructed prior to 1996, with only 3 facilities having been constructed later than that. The reason for this is still somewhat unclear, but lack of state incentives and public misperception seem to play a role. Even though only a few facilities have been constructed, it does not seem to hold back the development of new projects and interesting technologies.

For instance, one such a technology for MSW is a new type of gasification process developed by Covanta Corp. and evaluated by the Earth Engineering Center (EEC) of Columbia University. The CLEERGAS (Covanta Lower Emissions Energy Recovery GASification)[8] process was until recently in a testing phase on a plant in Tulsa, Oklahoma. The plant consists of 3 lines, where two of the three lines still have an ordinary moving grate combustion chamber. The third line however, was modified to test the new technology on an industrial scale. CLEERGAS consists of partial combustion and gasification of as-received MSW on a modified moving grate system and full combustion of the generated syngas in an adjoining combustion chamber. The most important attributes of the CLEERGAS gasification process are the fact that it needs a lower amount of excess air for combustion and does not need any pre-processing of the incoming MSW waste. Lower excess air will result in higher thermal efficiency of the process and, more importantly, in lower capital and operating costs per tonne of MSW processed. The two-stage process of gasification followed by syngas combustion also enables better control of NO_x generation by properly designing the air injection to the syngas combustion chamber.

When it comes to landfill mining to recover energy and materials, there are very few such cases in the US, except for cases where it was necessary to remediate and use the old landfill space. Firstly, since there is a lack of tipping fees, the major source of income of WtE facilities, constructing WtE facilities for landfill mining is not economically viable. Secondly, MSW that has been landfilled is bound to have a lower calorific value than new MSW. In recent years there have been rumours of installing WtE capacity coupled with landfill mining, *e.g.* at St. Lucie County, Florida, but so far, non has materialised.

In 2013, the country emerged from a near economic depression, with a slowly improving, but still low growth economy. There are deep divisions in the country regarding regulatory, economic, energy and climate change policy. In such an uncertain environment the exact future of the Waste-to-Energy industry specifically and solid waste disposal policies generally remains cloudy. However, there are some positive markers that may point the way to the growth of Waste-to-Energy. New technologies using gasification have recently been tested which will further reduce air emissions, while responding to the need of customers of all sizes, be they a single military installation, a small or medium size city or a large urbanised county.

In general, it can be said that the United States still has a long way to go in their management of MSW but it is catching up and making more efforts. Improvements in general waste management can be seen and R&D still gets funding to find and implement new types of technologies, such as the above mentioned CLEERGAS. However, when comparing the overall level of sustainable waste management of the country with the Central and Northern European countries (see Figure 2), they still seem to lack far behind in recycling and energy recovery from waste.

One of the lingering questions on many people's mind when it comes to the US energy market is 'What will be the effect of large scale gas-extraction in US on energy prices? Will it possibly jeopardise WtE economics in the long run?'. When looking at the energy market in the US, it is clear that there will be some changes coming to their market due to the vast amounts of shale gas found. About 68% of electricity generated in 2012 was coming from fossil fuels of which 37% was attributed to coal.[9] Of the total amount of natural gas extracted, however, the bulk usage (69%) is used in industrial applications, households and commercial activities.[10] The effective conversion to energy is only 31%. However, where coal, natural gas and nuclear have a large share in power production nowadays, natural gas will most likely play an increasingly bigger role as energy provider, potentially disrupting the energy market.

At the moment, it seems that the market is still quite distributed in its resources. Indeed, when looking at the electricity generated by source, one can see that natural gas is still being used less than coal (30% *vs*. 37%). Nuclear power has a 19% share. This is most likely going to change. What that change will bring for the renewable energy sector, is uncertain, but encouraging signs can already be observed. Recently an article by Bloomberg was published on a record low PPA (Power Purchase Agreement) of a solar plant constructed by Solar Inc. in New Mexico. The 50 MW power plant sells its electricity at $5,79 cents per kWh, cheaper than most coal and nuclear power purchase agreements. Competition in wind turbine manufacturing has also disrupted the wind turbine manufacturing market, driving installation prices down. In the WtE market, some promising competitive technologies are emerging as well, implying less capital intensive requirements. Even though it is quite possible that shale gas is going to dominate the local US market in the long run, it would be unwise to oversee these encouraging signs of competition and should therefore not be neglected.

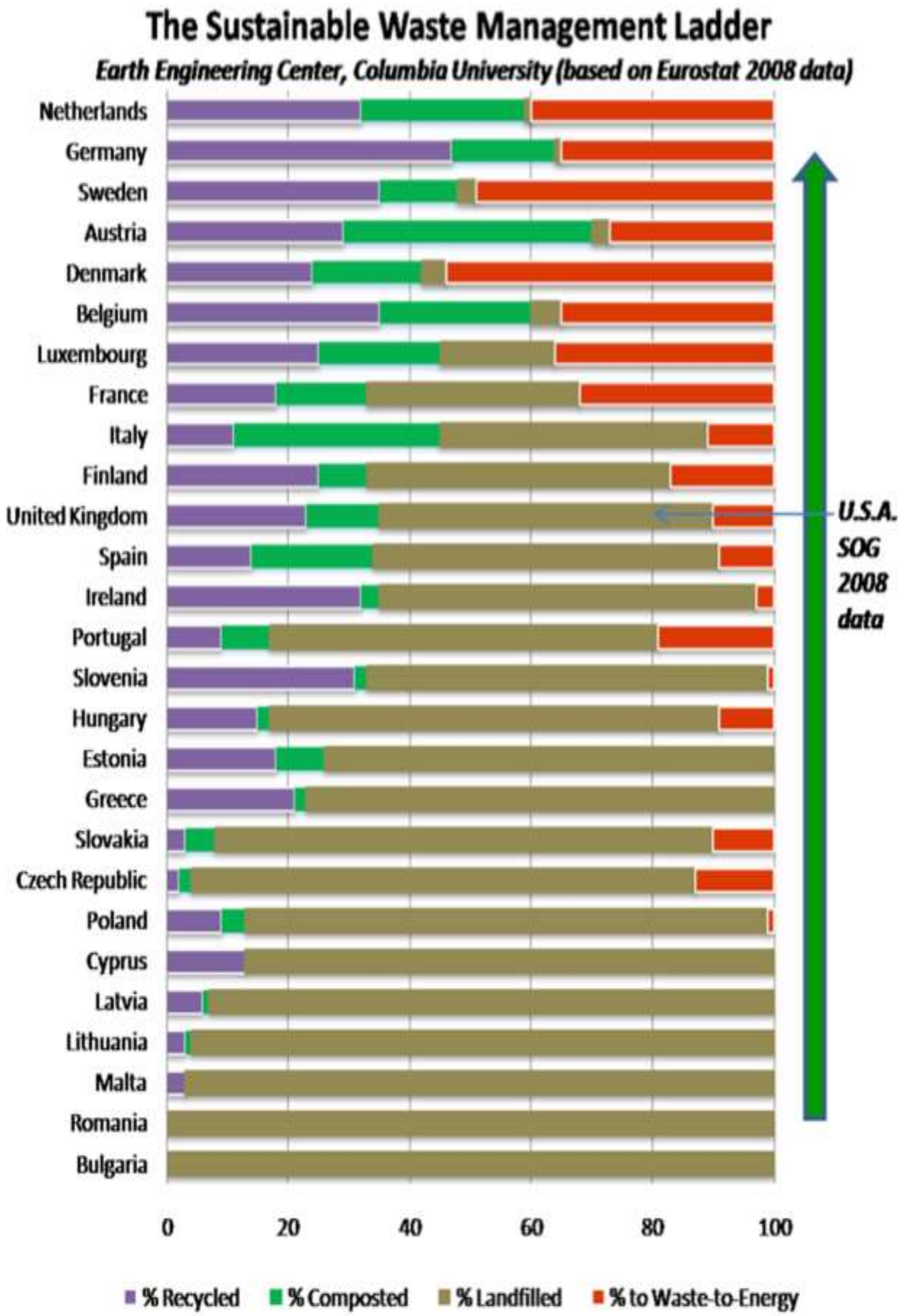

Figure 2: Ladder of Sustainable Waste Management of Europe.[3]

China

China is the country with the largest population (1,33 billion) on Earth and has a nominal GDP of $7,3 trillion. As one of the world's fastest developing countries, China has experienced a high growth rate in economic development and urbanisation. The urban population increased from 58 million in 1949 to 670 million in 2010,[11] indicating a steady rise in material consumption of modern life style and ever growing Municipal Solid Waste (MSW) generation. Waste treatment has become a big problem in many developing countries especially those with large population and limited land resources, like China. A 2012 World Bank report estimated that by 2025, more than 40% of the world's MSW would be generated in East Asia and the Pacific region;[11] in China, more than 180 million tonnes of MSW are collected from urban cities.[12] Similarly to most low to medium income countries, the common practice of MSW disposal in China is by landfilling, either in sanitary landfills or open dumping sites.

Since the mid 1990s however, China has clearly become a major player in the implementation of Waste-to-Energy. Combustion on a moving grate with energy recovery is the most commonly used Waste-to-Energy (WtE) technology for reducing the volume of waste by nearly 90% and the need of land for landfilling. Moreover, incineration plants equipped with boiler and steam turbine recover the hydrocarbon energy as electricity or steam for district heating. Ferrous or non-ferrous material recovery from the incineration of solid wastes is also proved to be feasible. An estimated 15% of the total amount of MSW generated in the country (23 million tonnes of MSW) is processed in over 100 WTE facilities.[13] China is also an exception to the general rule that nations with relatively low GDP per capita have a less pronounced MSW system. Developing countries typically rely exclusively on landfilling, but China clearly seems to have been stepping away from this method and is advancing more sustainable MSW management systems.[13]

A series of favourable policies have been created to encourage the development of WtE in China. The most representative is the "grid electricity pricing", applying specifically to WtE power. A subsidy of US$ 30 per MWh of electricity is provided for plants generating less than 280 kWh/tonne of MSW. The central government launched a campaign (in 2000)[13] for MSW recycling and suggested multi-stage sorting that included some source separation by local residents and neighbourhood authorities, to be followed by secondary sorting at regional waste management centres. The rest of the MSW is disposed in landfills and Waste-to-Energy plants and informal recycling was to be included.

Different cities have modified this model according to their own situation. For instance, Beijing eliminated recycling at the household level and MSW is picked up and sorted at regional MSW centres where Material Recovery Facilities separate the recyclables from what is to be landfilled or incinerated through WtE. In Guangzhou on the other hand, source separation is being encouraged at the household level where no regional MSW centres play a role. Waste management companies are committed to bring the recyclables to the markets and dispose what remains at landfills or WtE facilities.

Two major technologies are mainly being used, namely moving grate combustion of as-received MSW and Circulating Fluidised Bed (CFB). Imported moving grate technology dominates the domestic WtE market. The combination of semi-dry scrubber, activated carbon injection, and baghouse filter is the preferred Air Pollution Control (APC) system. NOx control equipment is used in some facilities. According to the field study in Shanghai and other major cities, the WtE plants have very low emissions of dioxins and mercury, far below the EU 2010 standard. NOx emission is higher than the EU standard but still within the Chinese National Standard. New national standards are coming into effect in 2013 and will bring the limitation for Cd, Pb, *etc*. to the same level as the E.U. standard.

Although, the moving grate combustion technology has been used over one century and more than 1.000 plants are in operation globally, currently most of these plants are built in developed countries or in relatively affluent municipalities because Waste-to-Energy plants are still capital-intensive and costly to operate. Most of these plants are equipped with hydraulic feeders to feed as received MSW to the combustion chamber, a moving grate to burn all combustible materials, a boiler to recovery heat, air pollution control system to clean toxic species in the flue gas, and discharge units for the bottom and fly ash. The air or water-cooled moving grate is the central piece of the process and is made of special alloy to resist the high temperate and to avoid erosion and corrosion. Currently, only a few manufacturers around the world can provide high quality moving grates, the most costly single piece of equipment of the WtE plant.

Apart from the high investment and operating cost, another problem encountered in implementing WtE in developing countries is the high organic and moisture content in the MSW. The "Decision Makers' Guide to Municipal Solid Waste Incineration" provided by World Bank[14] suggests that incineration is applicable only when the lower calorific value (LHV) of the feedstock is on the average over 7 MJ/kg and should never fall below 6 MJ/kg in any season. This prerequisite prevents many developing countries from adopting traditional moving grate WtE systems for treating their MSW. For this reason CFB technology was developed because of the lower heating value of the municipal solid wastes in China. Developing countries have a different type of waste as the developed countries and have generally a lower energy content. Due to the house cooking style, the lack of waste classification and source separation, the Chinese MSW is very high in food waste and moisture, which makes the direct use of moving grate combustion technically difficult.

Table 1 shows that the concentration of food wastes in the MSW of three cities in China are all higher than 60% while other combustible components with high heat calorific value, like paper, plastic and textile are very low because these valuable materials are usually picked out by formal recycling of community or informal recycling by scavengers.

Table 1: MSW components of different cities.[15]

City	Food	Paper	Plastic	Textile	Wood	Glass	Metal	Others
Beijing	64,48	6,71	8,12	1,22	0,05	2,02	0,31	17,09
Shanghai	62,83	8,57	10,83	4,17	0,96	2,17	0,00	10,47
Hangzhou	67,10	7,81	9,61	1,05	3,45	0,97	0,33	9,68
New York	23,00	27,00	17,00	6,00	4,00	3,00	6,00	14,00
Singapore	25,40	26,20	25,40	3,22	3,20	2,01	2,40	12,17
Japan ave,	19,10	36,00	18,30	9,50	4,50	0,30	0,00	12,30

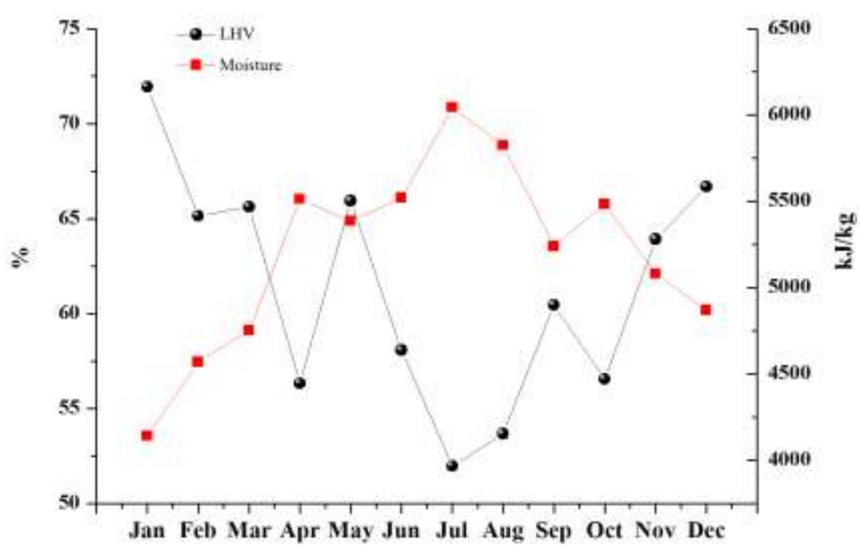

Figure 3: Moisture content and heating value of Shenzhen city at 2011.[15]

A survey of moisture content and heating value (LHV) was carried out in 2011 by the Shenzhen environmental protection department. Figure 3 shows that the moisture concentration increased from 52% at winter to 72% at summer, caused by the high ratio of fruit waste, especially the peel of watermelons.

The first large scale MSW incineration plant of China was built in 1984 in Shenzhen of Guangdong province with a capacity of 300 tonne/day. The plant was equipped with two incinerator lines and the reverse-acting moving grate of Martin Company. In 1996, this plant was expanded to waste treatment capacity of 750 tonnes/day, supplying 22,7 million kWh of electricity to local grid and 49.170 MJ of heat to local industry.[15] After the first two years of operation, a lot of problems emerged and several conclusions were drawn:

- The existing moving grate system was not capable of burning high moisture and low heat value MSW directly and should be modified to improve combustion performance.
- High moisture waste should be stored in the bunker for at least five days for de-watering, before being burned, and the liquid effluent should be treated separately instead of re-injecting into the furnace.
- High quality chemical agents, including active carbon and limestone are essential for reducing dioxin and heavy metal emission.
- In addition to the above technical conclusions, it was also determined that purchasing moving grate equipment from abroad was too expensive and not affordable to developing cities.

On the basis of these findings, the Chinese government realised that the development of domestic incineration technology was essential for solving the MSW treatment problem with relatively limited budgets. Since the 1990s, academic research groups at Zhejiang University, Tsinghua University and the Chinese Academy of Science have thus focused on developing the CFB incineration technology.

Even though China is making considerable efforts and has developed its own in-house technology especially adapted for their MSW, they are still landfilling the majority of the waste. Continuing efforts need to be made in order to stimulate recycling and Waste-to-Energy.

Japan

Japan is the largest user of MSW gasification in the world. The WtE processes called “gasification” are in fact a combination of partial oxidation and volatilisation of the contained organic compounds. Gasification in the first furnace is followed by combustion of the volatile gases and steam generation in a second furnace, or by use of the syngas in a gas engine or turbine. The principal technology used is grate combustion of “as received MSW” but there are over one hundred thermal treatment plants based on relatively novel processes such as direct smelting (JFE, Nippon Steel), the Ebara fluidisation process, and the Thermoselect gasification and melting process. These processes have emissions as low as the conventional WtE combustion process and produce a vitrified ash that can be used beneficially outside landfills.

Transportation of “as collected” MSW from one municipality to another is not allowed in Japan. As a result, the grate combustion facilities are relatively small. Also, the MSW of several communities is processed to a refuse-derived-fuel in local RDF facilities and is then transported to a central WtE that serves several communities. Also, all WtE plants are required to vitrify their ash after combustion, by means of electric furnace, or thermal plasma melting, or other means. These regulations allow for the introduction of thermal treatment processes that would be considered uneconomic in other developed nations.

There are several waste management companies in Japan, most of them are relatively small compared to the sizes of the US management companies. Some of the most important players in the sector are listed below:[4]

- Daiei Kankyo Co., Ltd.; Headquarters/Osaka;
- JFE Kankyo Corporation; Headquarters/Yokohama;
- Ishizaki Sangyo Co., Ltd.; Headquarters/Uozu, Toyama Prefecture;
- Miyama Inc.; Headquarters/Nagano;
- Nakadaya Co., Ltd.; Headquarters/Tokyo;
- Sinsia Inc.; Headquarters/Tokyo.

Japan has been a leader in developing and implementing traditional and novel thermal treatment technologies. This nation generates about 65 million tonnes of MSW, thermally treats 40 million tonnes, and recycles the rest. The table below was prepared for the IDB Guidebook and lists all the types of WtE technologies used in Japan. Despite the abundance of other technologies, 84% of the 37,8 million tonnes of MSW listed are processed in grate combustion plants (see Table 2).

Table 2: Overview of types of WTE technologies used in Japan.[16]

	Number of plants	All plants, tonnes/day	Average tonnes/day per plant	Percentage of WTE capacity of Japan
Martin reverse acting grate (66 plants)*	66	71.500	1083	62%
JFE Volund grate (stoker; 54 plants)*	54	10.100	187	9%
Martin horizontal grate (14 plants)*	14	7.454	532	7%
Nippon Steel Direct melting (28 plants)	28	6.200	221	5%
JFE Hyper Grate (stoker; 17 plants)*	17	4.700	276	4%
Rotary kiln (15 plants)	15	2.500	167	2%
JFE Thermoselect (gasification; 7 plants)	7	1.980	283	2%
All other fluid bed (15 plants)	15	1.800	120	2%
Ebara fluid bed (8 plants)	8	1.700	213	1%
JFE Direct Melting (shaft furnace, 14 plants)	14	1.700	121	1%
Hitachi Zosen fluid bed (8 plants)	8	1.380	173	1%
JFE fluid bed (sludge & MSW; 9 plants)	9	1.300	144	1%
All other Direct Melting (9 plants)	9	900	100	1%
Fisia Babcock (2 forward, 1 roller grate)*	3	710	237	1%
Babcock & Wilcox air cooled grate (43)*	43	690	16	1%
Total	**310**	**114.614**		**100%**
Total tonnes/year (at 330 days-24h/year)		37.822.620		
% of total MSW to grate combustion plants*				84%

* implicates a moving grate technology

A brief overview of these relatively new processes will be given below.

The JFE direct melting process

The JFE Direct Smelting reactor resembles a small iron blast furnace where the feed particles are fed through the top of a vertical shaft (Figure 4). Several Direct Smelting WtE plants have been built by JFE and also, in a similar version, by Nippon Steel. MSW is shredded and converted to RDF, drying the organic fraction in a rotary kiln and then extruding the product under pressure into 20-mm long by 15-mm diameter cylindrical particles. The material produced in several RDF facilities is then transported to a regional Direct Smelting facility, where it is combusted and energy is recovered. For example, the Fukuyama Direct Smelting plant is supplied by seven RDF facilities located at municipalities served by the DS facility.

The RDF is fed by means of a corkscrew feeder on top of the shaft furnace. As the feed descends through the furnace, it is gasified and its inorganic components are smelted to slag and metal, which are tapped at the bottom of the shaft. The gas product is combusted in an adjoining boiler to generate steam that is used to generate electricity in a steam turbine, same as in conventional WtE. Air is introduced into the furnace through primary, secondary and tertiary tuyeres located along the height of the shaft. The primary air, near the bottom of the shaft, is enriched to about 30% oxygen in order to generate the high temperatures required to melt slag and metal at the bottom of the furnace.

The RDF-DS combination can handle up to 65% water in the MSW (the usual allowable range is 40-50%), which in the drying kiln is reduced to 5-6%. The process requires the addition of coke (about 5% of RDF), which is added along with the RDF at the top of the shaft as well as sufficient lime to form a fluid slag at the bottom of the furnace. The JFE process produces slag and metal globules (10% of RDF), that are used beneficially, and fly ash (2% of RDF) that contains volatile metals and is landfilled. The slag and metal overflow from the furnace are quenched in a water tank to form small spherical particles of metal and slag. The copper content of the metal fraction is apparently too high to be used in steelmaking and too low to be suitable for copper smelting; its main use is as a counterweight in cranes and other ballast applications.

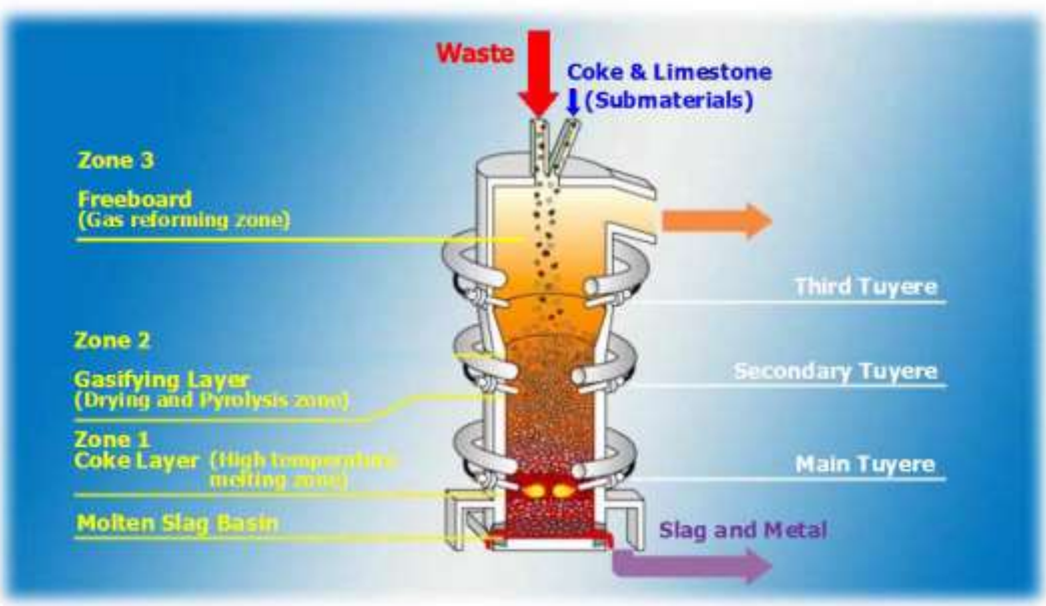

Figure 4: The JFE Direct Smelting process.[17]

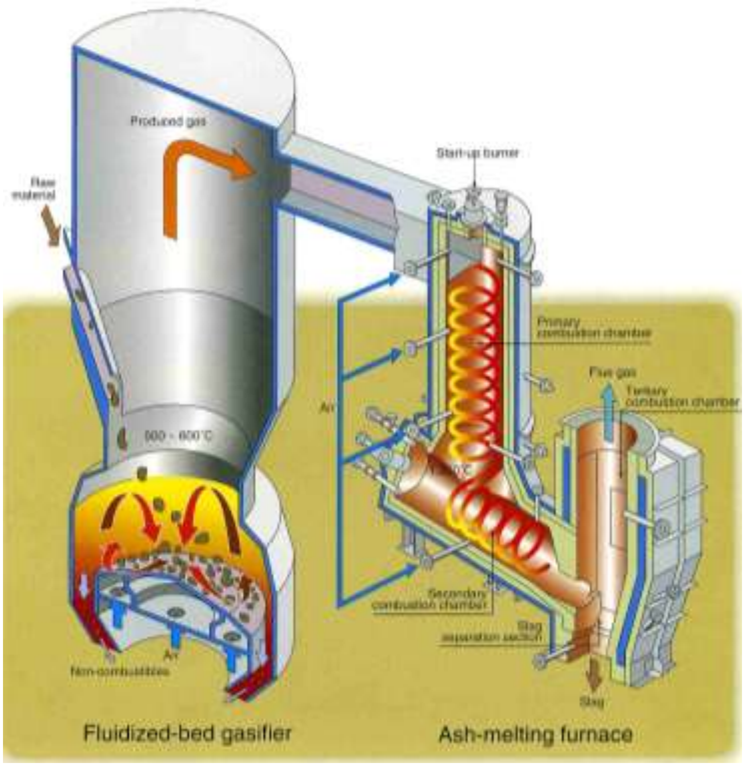

Figure 5: The Ebara fluid bed gasification process.[18]

The Ebara fluidised bed process

The Ebara process (Figure 5) consists of partial combustion of debagged and shredded MSW in a fluidised bed reactor followed by a second furnace where the gas produced in the fluidised bed reactor is combusted to generate temperatures up to 1.350°C such that the ash is vitrified to slag. There is no oxygen enrichment. The largest application of the Ebara process is a three-line 900 tonnes per day plant in Spain. The ash overflow from the fluidised bed is separated from the sand used in the reactor for fluidisation. Separation is by means of an inclined vibrating screen with 3-4 mm openings through which sand particles can pass through, while glass and metal particles cannot. Bottom ash in Japan cannot be used for applications such as road construction and therefore has to be melted into slag, which is the final solid product and can be used in construction. The Spanish plant of the Ebara process produces a net of about 560 kWh per tonne of RDF.

The Thermoselect gasification and melting process

The JFE steel company of Japan operates many plants ranging from grate combustion to the JFE Direct Smelting process described above, and also seven JFE Thermoselect plants of total capacity of 2.000 tonnes per day. The syngas produced in the Thermoselect furnace (Figure 6) is quenched and cleaned before it is used in gas

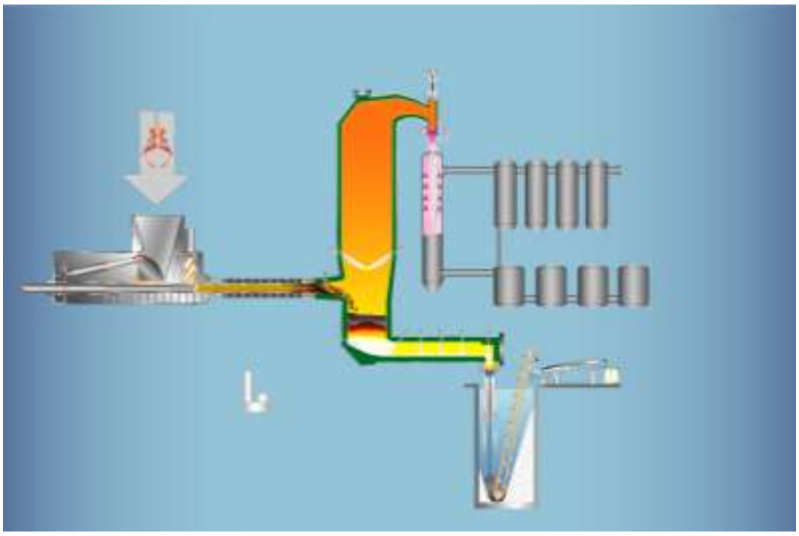

Figure 6: The Thermoselect gasification process.[19]

turbines or engines to generate electricity. The amount of process gas per tonne of MSW is much lower than in conventional grate combustion. However, cleaning a reducing gas is more complex than for combustion process gas. Also, the Thermoselect process uses some of the electricity it generates to produce the industrial oxygen used for partial oxidation and gasification of the MSW. The expectation is that the syngas product can be combusted in a gas turbine to generate electricity at a much higher thermal efficiency than is possible in a conventional WtE plant using a steam turbine.

Economics of WtE Facilities

When it comes to the economics of various WtE technologies, it is well known that it requires quite an intensive capital investment. Gasification technologies are relatively new in their implementation compared to the well-known grate combustion technologies and they are generally more expensive than the grate combustion and CFB.

There are substantial differences to be seen for the same type of technologies and roughly the same annual capacities, due to various challenges in site implementations and land availability. For instance, when comparing a grate combustion WtE plant in the city of Foshan (462.000 tonne/year) with another grate combustion WtE facility in Shanghai (495.000 tonnes/year) a large difference in capital investment can be seen. The Shanghai plant had a specific investment cost of $282 per annual capacity tonne, while the Foshan plant only had a specific investment cost of $120 per annual capacity tonne. Both have installed the facility with Western technologies.[13]

Even with these large variations, it is still possible to see some substantial regional differences from an economics perspective. In China, various plants can be installed at a price roughly half of the capital investment needed in the Western world, especially when talking about their in house developed new technologies such as Circulating Fluidised Bed. As a result, markets of the developing world are more accessible and can adopt the CFB technology largely because they are less capital intensive and have usually similar lower heating values.

Although a lot of studies have been done on the subject, gasification technologies where garbage is used as fuel have only recently gained interest in the US (*e.g.* CLEERGAS), unlike Japan, which has already several gasification plants installed. As mentioned, the capital investment of a gasification plant is usually higher. A recent study from Cornell University showed that for a daily capacity of 750 tonnes, a capital investment of $150 million would be required. Converting this to the specific investment cost brings the figure to almost $550 per annual capacity tonne.[20]

Recurrent incomes in WtE facilities are the electricity generated, material recovery and tipping fees. In terms of revenues, tipping fees constitute about 57%, electricity sales, 38% and recovered material sales 5%. Often operating agreements include a revenue sharing component between the public sector owner and private operator for energy and recovered materials revenues.[21] The prices for the materials recovered in a US plant can be seen in the Table 3.

Table 3: Commodity prices or recyclables: prices vary by type, region and day.[22]

Recycling Revenues	**Value per tonne**	**Presence per tonne**
Glass	$5	2%
Metal	$220	6%
Paper	$75	8%
Plastic	$300	4%

It should be noted that when implementing a material recovery facility, especially in the developing world, a part of recurrent income could be potentially lost if there are no existing markets for scrap metal, paper, glass and plastic recovery. It is difficult however, to generalise the capital investment costs for each technology. Moreover, due to different government incentives, each investment is specific to the region. Even the recurrent incomes (electricity, tipping fees, recyclables, *etc*.) are market and region specific and show price variation even within specific markets.

Conclusion

When comparing the United States, China and Japan, they show a different waste management landscape. The United States and China are still lagging behind in their level of sustainable waste management with respectively only 8% and 15% of their MSW being destined for thermal treatment. The majority of the waste in both countries is still being landfilled. Japan seems to be at the top of their game, with almost no MSW being disposed of in landfills (2%) and the rest being composted, recycled or thermally treated.

However, within a country, regional differences in state-level policies can be seen. As a result, different levels of waste management are observed within the United States and China - both having policies being stimulated on a regional rather than on a federal level. New England, for instance, seems to have the highest level of sustainable waste management, with landfill rates and WtE percentages that are comparable to the better performing countries in Europe. The main reason for these regional differences within a country is due to several reasons. The North Eastern part of the United States, has less land available than other regions in the US and taxes garbage more so that tipping fees are higher. End-user prices for electricity also seem to be higher in New England than in other parts of the country. These factors stimulate a higher level of sustainable waste management and as a result, make WtE facilities more economically feasible.

The technology that has the dominant presence in all three countries is moving grate combustion. Indeed, it is the longest existing and most well-known technology, hence its frequent implementation. However, because of a lower heating value of the garbage in China, the in house developed CFB technology seems to be gaining more and more ground in their domestic thermal treatment of MSW. It also seems to be considerably cheaper than conventional technologies, although one needs to be careful with comparing facilities, as the capital costs can be very much site specific. Japan is considered to be a leader in conventional as well as newly developed technologies (Ebara, Direct Melting, Thermoselect). Because of their geographical challenges, land is scarce. Moreover, stringent rules and heavily taxed waste policies made sure that almost all waste can be disposed of in a more sustainable way than landfilling.

As mentioned in the previous paragraph, it is difficult to compare costs of various technologies, since there are so many factors that play a role in determining the total cost of a facility. Even two facilities installed with the same type of technology and the same type of capacity but implemented in a different region, can have such a substantial difference in costs that it is simply not feasible to come up with a general capital investment cost per technology. This said, it is possible, to see differences of capital costs when comparing Western and Chinese technologies, the latter ones seemingly being less capital intensive. However, since about 64-66% of refuse is of biogenic origins,[23] incentives for renewable energy production should (at least partially) be considered, stimulating the waste management market as well as helping to reach the 2020 renewable energy goal.

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