Pre-feasibility study of using the Circulating Fluid Bed (CFB) waste-to-energy technology in Mexico City

Andres Estrada Wiechers

Advisor: Prof. Nickolas J. Themelis

Department of Earth and Environmental Engineering
Fu Foundation School of Engineering
Columbia University
January 2015

Submitted in partial fulfillment of the requirements for M.S. in Earth Resources Engineering

Research supported by CONACYT and Fulbright-Garcia Robles scholarships

Research sponsored by

COLUMBIA UNIVERSITY
EARTH ENGINEERING CENTER

Pre-feasibility study of using the Circulating Fluid Bed (CFB) waste-to-energy technology in Mexico City

EXECUTIVE SUMMARY

Waste generation in Mexico is growing at 3.3% per year, as the economy is expanding and population is increasing. Mexico City, the country's capital, is one of the largest megalopolis in the world with a population of over 20 million. The City's waste management has started to move away from landfilling and the objective of this thesis was to determine whether the Circulating Fluid Bed (CFB) Waste-to-Energy (WTE) technology could play a role in the management of the municipal solid waste (MSW) of the City and the country in the near future.

The City has decreased landfilling from 93% in 2007 to 44% in 2012, while increasing composting and informal recycling. Composting now treats nearly half of the organic fraction of the waste and 17% of the total MSW. The sale and use of the larger production of compost are still problems to be solved. However, the compost produced is proven to be a high quality product meeting the required standards.

With regard to the technologies used for WTE, combustion on a moving grate (MG) is the most widely used technology across the world. An earlier Columbia thesis examined the implementation of moving grate (MG) technology in Toluca, Mexico. The present study concentrated on the CFB technology developed by Zhejiang University (Hangzhou, China) and examined the main differences between CFB and MG furnaces.

The CFB technology has worked well in China and now almost half of the Chinese WTE capacity uses this type of reactors. The technology is inherently less capital intensive than MG as a smaller reactor and Air Pollution Control (APC) system are needed for the same capacity. The Zhejiang University CFB design has key improvements: the use of low-speed high-torque (LSHT) shredders and their location in the refuse pit has allowed for pre-shredding the MSW at a relatively low capital investment. Air preheating allows better temperature control in the reactor. Additionally, energy efficiency of the plant is 20%, and the APC system used in several CFB plants allows emissions to meet EU standards.

The project evaluated for Mexico City is a three-line, 700,800 ton/year WTE plant, which would reduce landfilling by 30%, still allowing improvements in recycling and composting in the future.

To plan for the project, the Earth Engineering Center Guidebook for WTE in Latin America was used as a guide for the pre-feasibility analysis, using as a reference three previous case studies. The capital cost of this plant was estimated, using information provided by Zhejiang University, at US$185 million installed in Mexico City. The projected gate fee of US$20 was estimated after reviewing the current costs

of the City in transporting and landfilling MSW in a survey conducted by the City government. The electricity price of US$90/MWh was estimated based on current cost of production of electricity plants in Mexico and the price paid by the final users. Also, a sensitivity analysis was carried out to evaluate the financial impact changes in these assumptions would cause.

The WTE plant studied yields an internal rate of return (IRR) of 13.5% and a positive net present value (NPV) with a 5%-10% discount rate. Financing options have to be detailed in the feasibility stage of the project.

In recent years, Mexico has implemented important reforms regarding energy. The country now allows for private parties to sell electricity and connect into the grid, which will make the construction of new electricity generation plants easier. Also, Clean Energy Certificates will be issued to help new renewable energy producers get more income for cleaner electricity production.

Overall, the lower capital cost of the CFB WTE technology, with adequate pricing for gate fees and electricity makes this a profitable project and the energy scenario in Mexico is also favorable. The construction of this WTE plant would reduce landfilling Mexico City, generate renewable energy and lead the WTE introduction to the rest of the country.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Prof. Nickolas Themelis for his guidance and support. His continued encouragement and vast knowledge made this work easier and more meaningful. Also, a special appreciation goes to Liliana Themelis for kindness and her help on keeping track of the work.

I would like to specially thank my wife Andrea. Her help, encouragement, reviews, talks, love and support helped me work through my studies and kept the final goal in sight. To my family, who has encouraged and believed in me for many years and has inspired my interest in engineering and taking care of the environment. Thanks to my friends at Columbia, with whom these days have been much more fun and interesting; their comments helped improve the final version of the project. To Fernanda Gómez for her help and recommendations on the Infomex process which led to important results.

It is of great importance to thank CONACYT for their financial support, which allowed me to study my Masters degree at Columbia University, one of the best universities in the world. Also, a great thank you goes to the Fulbright Commission and COMEXUS for trusting in me and giving me the opportunity and funding to participate in the Fulbright - García Robles student program. Thanks also to the help from COMECYT to cover my relocation expenses. Mexico gave me a great opportunity to continue my studies in the US and it is my sincere hope that this work contributes to a better future in my country.

To the scientists and communicators devoted to the environment and climate change for their encouragement and motivation to this global cause.

Table of Contents

List of Figures

List of Tables

1. Mexico

1.1. Population, economic level and major cities of Mexico

Mexico is a developing country with a population of 123 million. Its 2013 GDP was US$1.26 trillion, placing Mexico in 15th place among nations, on this basis. The GDP per capita (PPP adjusted) is US $16,463 (The World Bank, 2014a) which makes Mexico an upper middle-income country, but half of its population is still living below the poverty line, making the income inequality an important issue. Environmentally, the greenhouse gas emissions per capita were 3.8 tons of CO_2eq, below the 4.9 tons of CO_2eq world average. (The World Bank, 2014b)

Mexico is currently experiencing a changing scenario within several infrastructure areas, especially in the energy sector where a deep legislative reform now allows private parties to generate and sell electricity to the national grid. Regarding waste management, Mexico City is in a dynamic change as new waste management strategies are being explored to turn away from landfilling, which has become more expensive after the city's largest landfill closed in 2011. At this time, there are no WTE combustion facilities in Mexico, however, there are several landfill gas-to-energy projects in operation.

In this dynamic scenario, a pre-feasibility analysis for a WTE facility may shed light on this waste management technology and encourage further exploration on the subject.

According to data from 2000 to 2010 (Consejo Nacional de Población, 2013), Mexico's population is increasing at a yearly mean rate of 1.4%. There is a higher population growth in urban metropolitan areas, of 1.6%. Similarly, data from the World Bank mentions that as of 2013, 79% of the population of the country was urban, increasing from 76% in 2005 (World Bank, 2014). In Figure 1 the largest cities in Mexico are shown, including the population in their metropolitan areas.

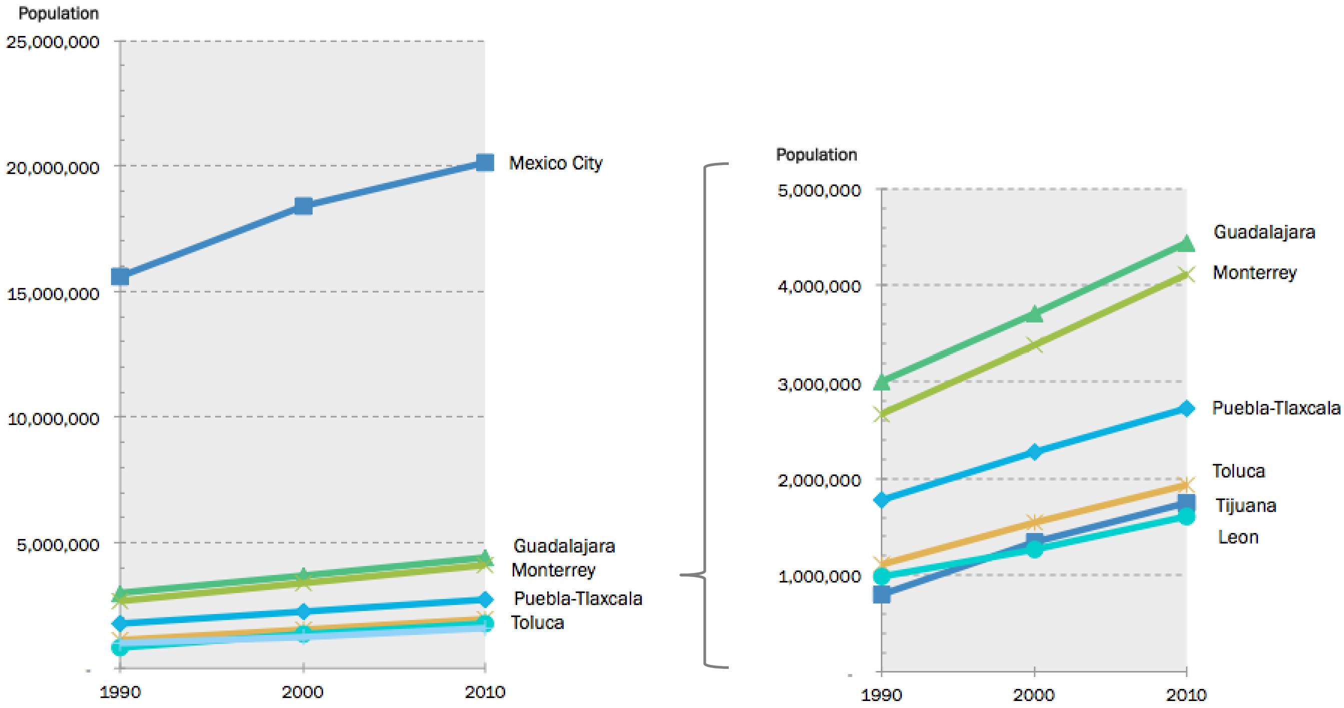

Figure 1 - Largest metropolitan areas by population (Source: Consejo Nacional de Población, 2013)

The largest city by far is Mexico City, whose metropolitan area exceeded 20 million residents in 2010. The Federal District (F.D.), the capital of Mexico, sets the boundaries for Mexico City within the metropolitan area and had a population of 8.85 million people in 2012. The second largest Mexican city is Guadalajara with 4.4 million habitants, followed by Monterrey with 4.1 million. These cities are growing at a fast pace, so their waste management strategies will have to be planned accordingly. Several smaller metropolitan areas, such as the Puebla and Tlaxcala, which hosts a large automotive industry, are also developing quickly; Toluca, Tijuana and León are also growing at a similar pace. Further studies of these cities may be important, as innovative waste management strategies may prove useful as urban planning takes place.

The waste generation per capita is calculated using the NMX-AA-61-1985 norm (Secretaría de Desarrollo Urbano y Ecología & Departamento del Distrito Federal, 1992). For residential waste, a random statistical sample is taken in pre-determined socioeconomic clusters. Throughout a one-week period, the wastes generated during the previous day are recovered, weighted in situ and analyzed.

In Figure 2, the MSW generation per capita data is shown for four regions of the country, the Mexico City Federal District, and the country average. This data is updated yearly by SEMARNAT and shows an increasing trend in the whole country. In 2002, the country daily average was 0.88 kg/capita, which has increased 12% to 0.99 kg/capita/day in 2012. Also, it is notable to see that the highest producer of

MSW per capita is the Federal District, which generates 1.52 kg/day/capita, 50% more than the country's average.

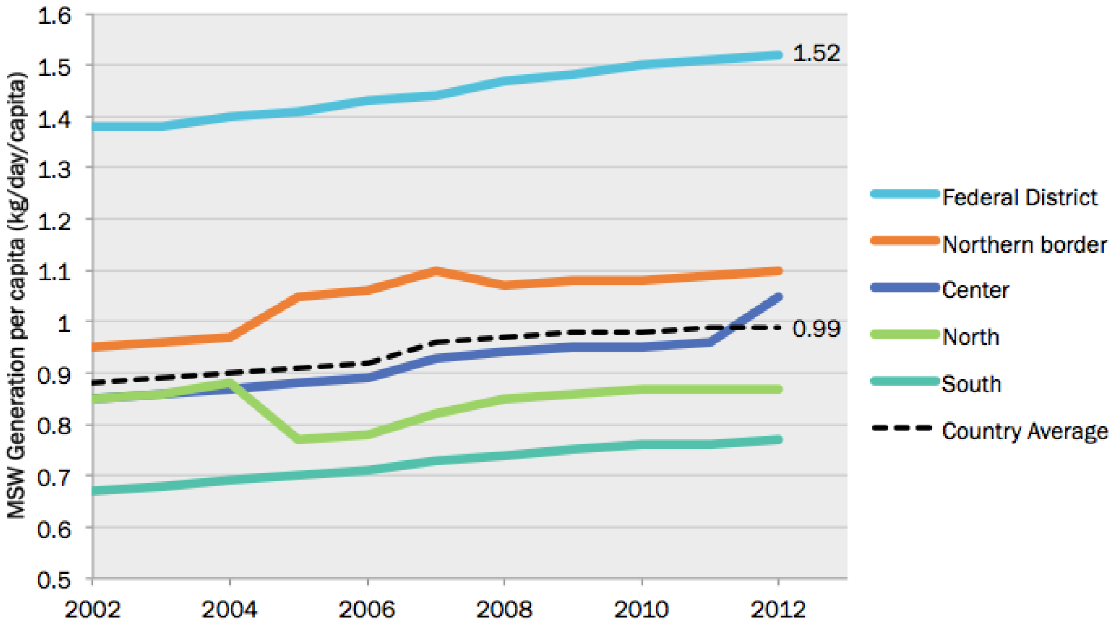

Figure 2 - MSW generation per capita per region (SEMARNAT, 2014a)

The 8.5 million people living in Mexico City and the highest generation of MSW per capita in the country leads to a challenging waste management scenario.

MSW generation is closely linked to the economy and consumption of the population. As the economy of the country grows, the population can access more products and the MSW generation increases. Figure 3 shows a similar trend between the generation of MSW and GDP PPP. MSW generation has increased in average 3.3% per year, while GDP PPP has increased 6.2%, almost twice the MSW rate (Own calculation, data from SEMARNAT, 2014a; The World Bank, 2014a). As the country's economy continues to grow, the generation of MSW is expected to continue to increase, though at a lower rate than GDP growth.

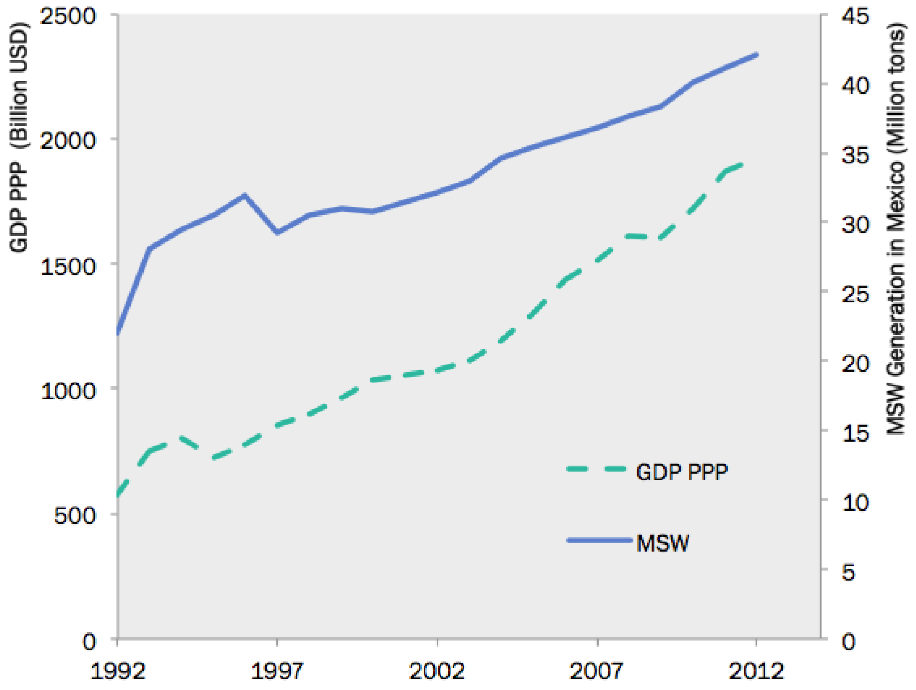

Figure 3 - GDP PPP and MSW generation trends in Mexico (SEMARNAT, 2014a; The World Bank, 2014a)

Traditional waste management practices have environmental and social impacts that will escalate with this growth. To mitigate this impact, the country will need to use more diligently their resources and plan to move to more advanced technologies and strategies for managing waste.

1.2. MSW generation and composition

The amount and composition of the Municipal Solid Waste (MSW) in Mexico has changed significantly since 1992. As shown in Figure 4, the total amount of MSW generated in Mexico in 1992 was 22 million tons. It has increased at an average 4.6% per year, reaching 40 million tons in 2010. Regarding the waste composition, the organic fraction has remained at 52%, unchanged in the last 20 years. Plastics on the other side have increased from only 4.4% to 10.9% in 2010 due to more applications of these materials such as packaging.

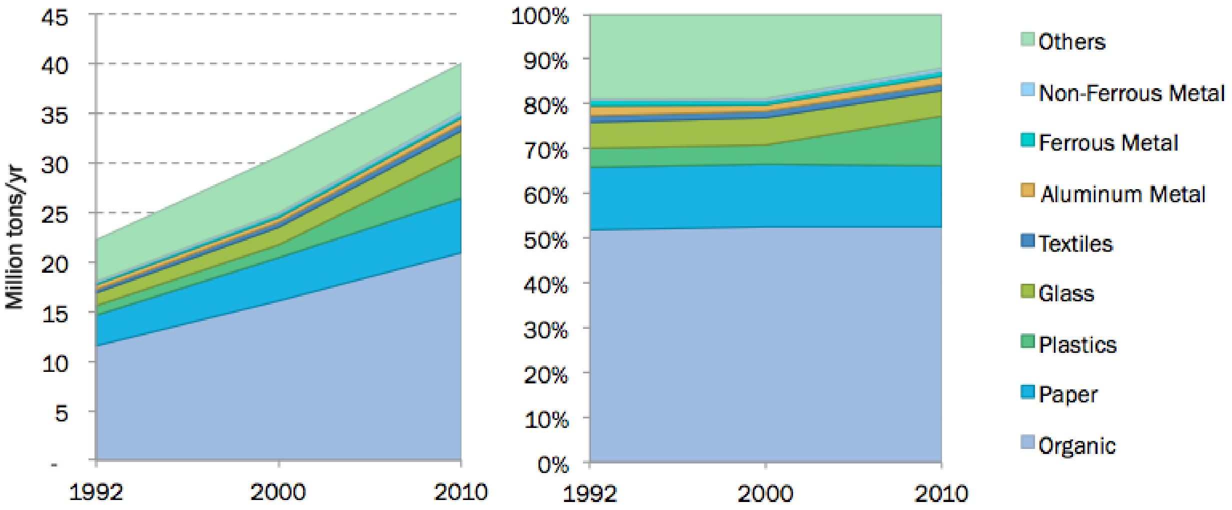

Figure 4 – Waste amount and composition in Mexico, nationwide 1992–2010(SEMARNAT, 2014a)

Table 1 - Waste amount and composition in Mexico, nationwide 1992-2010(SEMARNAT, 2014a)

	1992		2000		2010	
Materials	Thousand tons	%	Thousand tons	%	Thousand tons	%
Paper	3,090	13.9%	4,324	14.1%	5,540	13.8%
Textiles	327	1.5%	458	1.5%	573	1.4%
Plastics	962	4.3%	1,346	4.4%	4,362	10.9%
Glass	1,296	5.8%	1,813	5.9%	2,355	5.9%
Aluminum Metal	488	2.2%	492	1.6%	693	1.7%
Ferrous Metal	246	1.1%	247	0.8%	434	1.1%
Non-Ferrous Metal	151	0.7%	152	0.5%	251	0.6%
Organic	11,512	51.8%	16,104	52.4%	20,999	52.4%
Others	4,143	18.6%	5,796	18.9%	4,851	12.1%
Total	22,215		30,733		40,059	

1.3. Waste Management Hierarchy

The most widely used guideline used to compare the strategies for waste management is the waste management hierarchy, shown in Figure 5, where waste management strategies are ordered from the most desirable to the least from top to bottom, starting with waste reduction and ending in unsanitary landfills. For composting as well as recycling, the waste requires a separation. This is best achieved by a source separation.

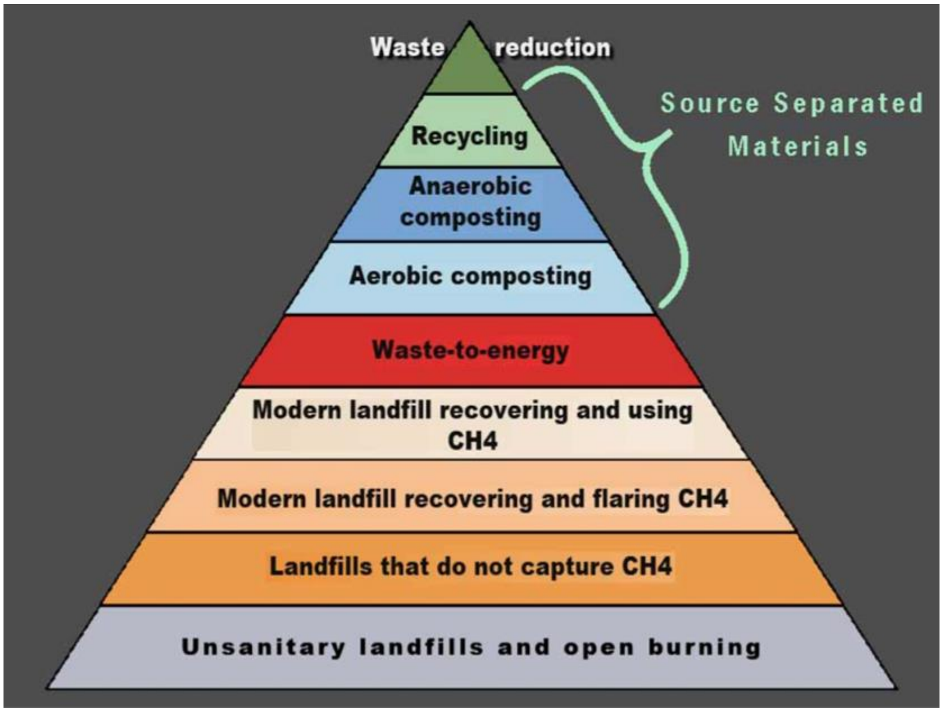

Figure 5 – The Hierarchy of Waste Management

As seen in Figure 5, unsanitary landfills are the least desirable disposal method, as it has the largest impacts on the environment and no energy and material is recovered. Using sanitary landfills improves the waste management process, as the waste is appropriately contained and less pollution is dispersed into the surrounding environment; however, the CH_4 generated is vented to the atmosphere with a large global warming impact. The next step in the ladder is the recovery of CH_4 which decreases this global warming impact. Using the CH_4 to generate energy is more desirable as some energy from the waste is recovered and used. Waste to energy is higher in the hierarchy as it recovers more materials and energy, which will be described thoroughly in Chapter 2. Composting, which can be used to treat food and garden wastes to produce compost, which in the case of developing countries can be 50% or more of their waste. Recycling is the best process for material recovery, which saves energy as well. And at the top, waste reduction is the most important step.

1.4. Disposition of MSW in Mexico

The disposition of MSW in the last three decades has changed considerably, according to official sources (SEMARNAT, 2014a). Figure 6 shows that the use of sanitary landfills increased from only 20% in 1995 to 66% in 2012. However, there is still an important amount of waste disposed in non-controlled waste dumps. These non-sanitary sites are more prevalent in midsize cities and rural or semi-urban areas, as shown in Figure 7. Small, disperse towns where a sanitary landfill construction is not economically feasible, or transportation of wastes is financially burdensome seem to be the reasons for the remaining non-sanitary waste disposal. These waste dumps pose challenges to the management strategy of Mexico and setting feasible targets for waste management performance indicators throughout the nation.

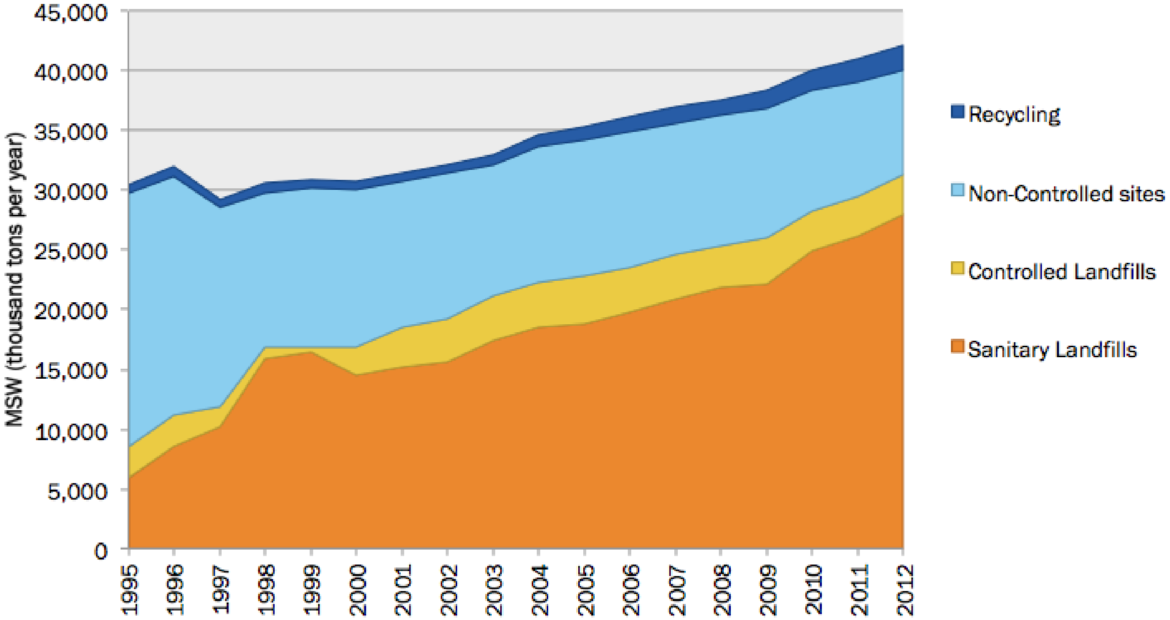

Figure 6 - Final Disposition of MSW in Mexico – Nationwide (SEMARNAT, 2014a)

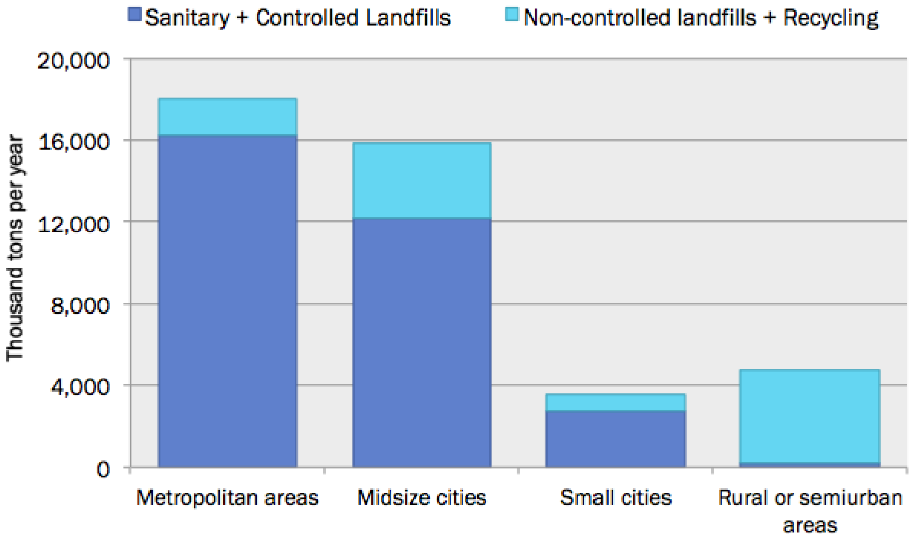

Figure 7 - Final disposition by type of populated area in 2012 (SEMARNAT, 2014a)

1.5. Recycling

The formal recycling sector is expanding in Mexico. It doubled from 2.4% in 1995 to 5% in 2012 (SEMARNAT, 2014a) as seen in Figure 8.

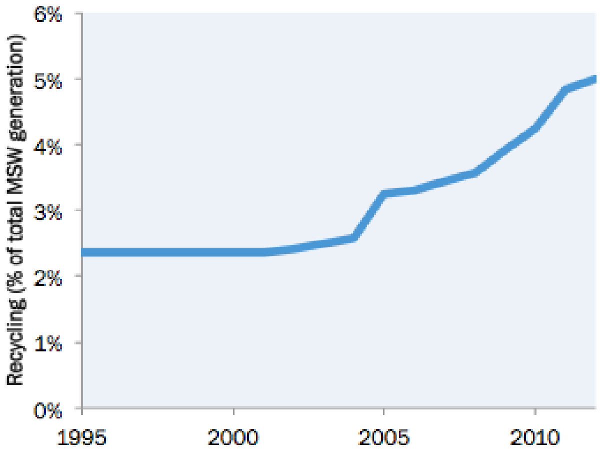

Figure 8 – Formal recycling in Mexico. (SEMARNAT, 2014a)

To complement the recycling effort, the informal sector is very active. Scavengers, called "pepenadores", are an important part of the waste management system, as they are the main collectors of recyclable materials. However, they work in non-sanitary conditions with many health risks, as they are exposed to the wastes without personal protection equipment. Usually, they are informal workers that make arrangements with the waste collectors to ride together with them in the garbage collector trucks, where they separate the wastes as the truck collects them. (Gaviota, Pérez, & Themelis, 2011)

1.5.1. PET recycling

The market for PET plastic in Mexico is large, as the country is one of the world's largest soda consumers. Following Coca-Cola Company's sustainability targets to achieve 50% recollection of packaging by 2015 and source 25% of PET plastic from recyclable or renewable material, in July 2014 the world's largest PET bottle-to-bottle recycling plant was started up in Toluca. PetStar, has a total capacity of 65,000 tons per year. According to information from ECOCE (ECOCE, 2014), a non-profit organization that intends to inform about ecological value of recycling of packaging and bottles, 60% of the total PET plastic bottles in Mexico are recovered. Since 2002 until 2014, ECOCE has recovered 2 million tons of post-consumer PET packaging. In 2013 alone 428,000 tons were recovered, an improvement of 3.3% vs. 2012. Of that amount, 38% is recycled in Mexico and the rest is shipped overseas.

1.5.2. Paper and carton

Recycling across the country of paper and carton products is estimated to be approximately of 49% in 2010. As shown in Table 2, most of the recovered materials are corrugated carton boxes, with an 81% recovered of 3 million tons generated. Newspapers and printed paper have also a high material recovery with 52% and 42%.

Table 2 – Generation and recovery of paper and carton in Mexico, 2010 (Gutierrez Avedoy, Ramirez Hernandez, Encarnación Aguilar, & Medina Arévalo, 2012)

Type of Paper	Estimated consumption Thousand tons	Share of total %	Recovered paper Thousand tons	Recovery per type %
Newspaper	390	6%	201	52%
Printing and writing	1,250	18%	541	43%
Bags and wrappings	254	4%	76	30%
Corrugated carton box	3,001	43%	2,444	81%
Cartons	526	8%	81	15%
Carton for liquids packing	166	2%	27	16%
Special	405	6%	15	4%
Facial and sanitary	985	14%	15	2%
Total	**6,977**	**100%**	**3,400**	**49%**

1.6. Energy sources and use in Mexico

As will be discussed in Section 4.3, the use of MSW as a fuel is of the ways that the need for landfilling can be decreased. Using MSW as part of the fuel is already being used in Mexico in cement production plants. However, the possibility of using MSW to generate electricity is large and currently untapped. According to Arvizu (Arvizu Fernandez, 2010), the potential from capturing the landfill gas and producing electricity is estimated to be 165 MW. More importantly, the energy potential from solid waste incineration was estimated at 2,415 MW.

Related to the costs of waste management is the energy environment in Mexico, as one of the sources of income of a WTE plant is the sale of electricity and/or heat to the market. Countries with great success in the waste incineration and energy recovery sector have used both of these vectors: heat and power; their locations are usually in colder climates at high latitudes. In Mexico, unless there is a heat demanding industry or process next to the plant, such as a partnership between both sites to sell and purchase heat, there is no requirement for district heating due to the mild weather the country experiences year wide. The most probable scenario will be the sole sale of electricity. In this section, we will explore the dynamic environment that Mexico is experiencing regarding energy production and where WTE could play a role.

Mexico is the world's 9th largest oil producer as of 2013(EIA, 2014), being a net exporter of oil but increasingly an importer of natural gas. The country also uses mostly oil and natural gas for its energy consumption.

Most of the total energy used by the country was from the Oil & Gas Sector: Oil (65.2%), Gas (22.3%) and Condensed gases (1%), summing 88.5% of the total primary Energy. Renewables follow with 6.9% of the energy generated, mostly from biomass, followed by Geothermal/Solar/Wind with 1.7% and Hydro with 1.3%. Coal plays a small role with 3.6% of the generation, followed by 1% of nuclear energy generated by Laguna Verde, the only nuclear power plant in Mexico.

Electrical energy follows a similar pattern with high dependence on fossil fuels, as shown in Figure 9; natural gas is the largest source of electricity with 50%, followed by fuel oil with a 18% of the energy share. Hydro is next with 12%, coal 13%, nuclear 3% and geothermal 2%. Wind and solar power represent less than 1% of the total electricity generation. Natural gas has increased its share for electricity generation substituting the more costly and polluting oil. This trend is expected to continue.

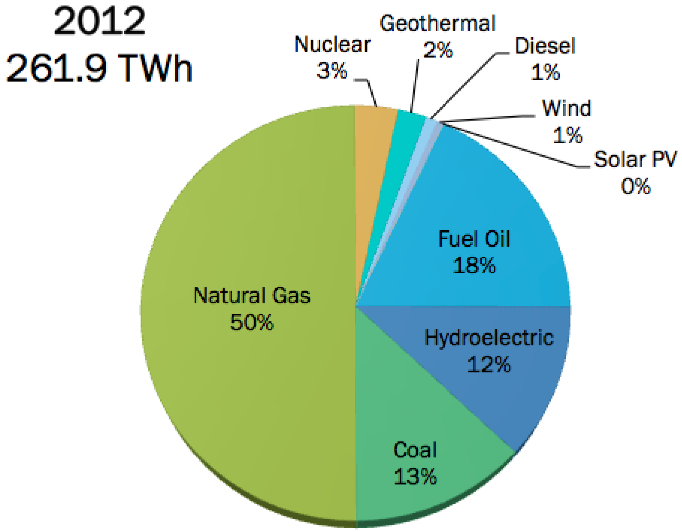

Figure 9 - Energy sources for electricity generation (data from Secretaría de Energía, 2013)

1.7. Legislation on climate change and energy transition

The energy environment in Mexico has recently changed. After76 years of a constitutional state monopoly on energy extraction and production, a profound set of energy reforms, instituted in 2013 changed the market and have allowed the private sector to invest and extract oil & gas, as well as generate electricity. On the oil & gas sector, this reform was necessary as *Petróleos Mexicanos* (PEMEX), the State's oil monopoly, has had a declining production of oil since peaking in 2003-2004. After this peak, despite higher investment, oil production had been in decline, thus jeopardizing energy security and income from the oil and gas sector of the country. It should be noted that the country's GDP from oil & gas has been only 6% of the total. However, the oil & gas rent funds 30% of the government's budget. This makes this reform critical.

In the electricity sector, this energy reform has resulted in significant changes. The previous electricity monopoly run by the state enterprise CFE (Federal Electricity Commission) will stop being the sole generator of electricity allowing for new generation capacity from private parties, such as wind farms, solar and waste to energy plants, to be connected to the energy network and sell their electricity in a wholesale market. This electricity market will be created and regulated by the Electricity Regulatory Commission (CRE), an independent entity.

The “National Energy Strategy for 2026” establishes the goals and strategies for the next 15 years and is based on three pillars: energy security, economic and productive efficiency, and environmental sustainability. Though several measures are targeted towards the oil and gas sector, there are two key strategies for stimulating renewable energy sources: a) Diversify the energy sources, giving priority to increasing the participation of non-fossil technologies; and b) Reduce the environmental impact of the energy sector.(Secretaría de Energía, 2012)

In 2012, only 18% of the electricity was generated from renewable and clean sources, including hydroelectric and nuclear power. The LAERFTE (use of renewable energy and energy transition financing law or *Ley de Aprovechamiento de Energías Renovables y Financiamiento a la Transición Energética*) states that by the year 2026, 35% of the electricity must be produced by non-fossil sources; by 2035 the goal is 40%, and by 2050, 50%. These goals have also to include the projected growth of electricity consumption, which is estimated to increase by 3.6% per annum.

Additionally, the Climate Change General Law requires reducing by 30% the greenhouse gas emissions in 2020 and by 50% in 2050. Additionally, market incentives will be set to promote renewable energy, in the form of Clean Energy Certificates (CEC) that will be issued for clean energy generators. Utilities will have the opportunity to purchase these Certificates from renewable energy generators to meet their renewable energy targets. This strategy is intended to help finance new renewable energy capacity, providing a second source of income from these certificates as well as from electricity sales.

An important goal, stated on the Climate Change General Law, is related to waste disposal areas: Cities larger than 50,000 people will need to develop and build infrastructure to avoid the emissions of methane gas, and if viable, implement technology for electricity generation.

In summary, the country’s energy sector is currently highly dependent on fossil fuels, with an increasing participation of imported natural gas. However, there is an increased focus from the government to diversify the production of energy and increase the share of renewable resources in the production portfolio. The energy reform now allows the sale of energy from private companies to the grid, enabling easier connections of new electricity producers. This is important progress, as a WTE plant that generates electricity could now be connected to the grid with more ease.

1.8. Greenhouse gas emissions inventory

Climate change poses an important risk to Mexico. Several of the coastal areas will be more prone to flooding and the dry areas in the country are susceptible to droughts. Tropical storms and hurricanes that are commonly a threat to both the southern part of the country and the northern pacific coasts will become more extreme. Understanding these risks, Mexico has been a leader in climate change policy. The country has set emission reduction targets and has started efforts on lowering emissions.

According to the National Inventory of GHG Emissions (Secretaría de Medio Ambiente y Recursos Naturales, 2013), in 2010 the total GHG emissions were 748 Million tons of CO_2eq. Compared to the 1990 baseline, this was a 33.4% increase. Despite the increase, the GHG emissions growth rate has been lower than the economy's: in average, the economy grew 2.5% per year while emissions grew 1.5% per year. This means the economy is becoming less carbon intensive, as more efficient processes are implemented. This decarbonization will have to become more significant as emissions reductions take place to achieve the climate change targets.

The emission sources are shown in Figure 10. The largest emitter is the energy sector with 67.3% of the total. The waste sector is a small emitter with 5.9% of the total or 44.1 Mton CO_2eq per year. This figure includes the solid wastes treatment and disposal (49.4%) as well as the wastewater treatment activities in the municipal (38.6%) and industrial (12.0%) sectors.

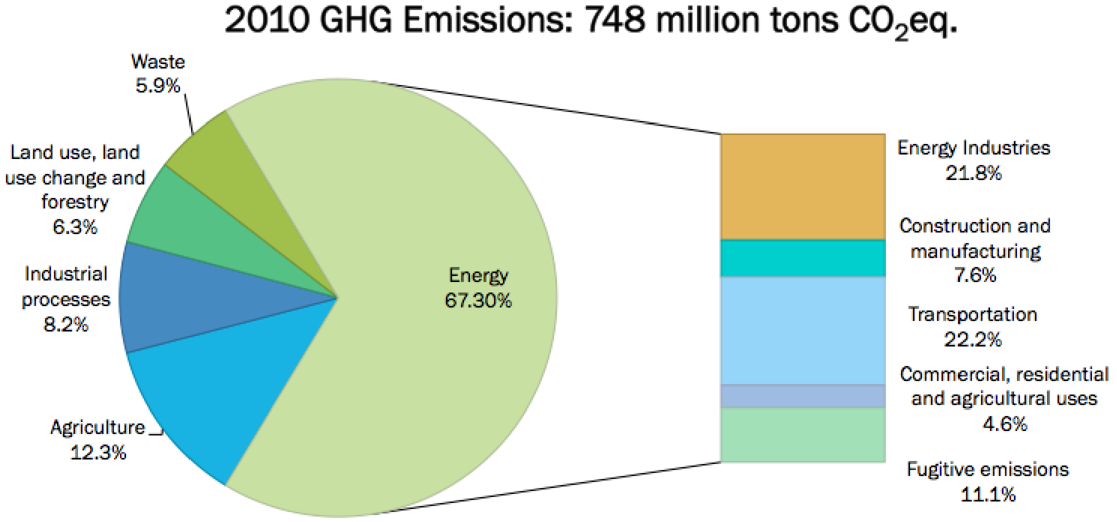

Figure 10 – Mexico GHG emissions by source. (Secretaría de Medio Ambiente y Recursos Naturales, 2013)

Even though the waste sector was a small GHG contributor, the emissions of the waste sector are growing at a fast pace. They grew 167% from 1990 to 2010, much faster than any other category. Even though the MSW generation doubled from 1990 to 2010, the emissions growth was three times larger. This may be explained by the fact that wastes that accumulated in landfills and waste dumps continue to emit biogas for several years after they were disposed of, so the effect is cumulative. The details are shown in Figure 11:

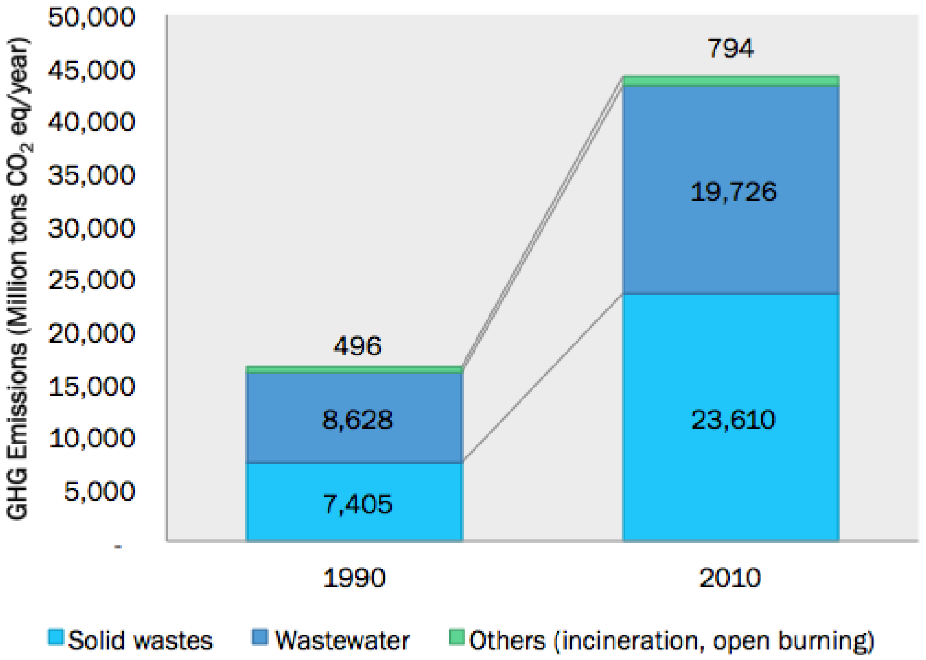

Figure 11 - Solid waste and wastewater GHG emissions. (Source: Secretaría de Medio Ambiente y Recursos Naturales, 2013)

The gas that has the highest contribution to the greenhouse effect in the waste sector is methane. CH_4 contributed 93.6% of the total CO_2eq impact of the sector, N_2O and CO_2 trailed afterwards with 5.1% and 1.3% respectively.

As the MSW generation continues to grow, emissions will tend to increase. This is why the State set the objective to avoid the emissions of methane gas in waste management sites of communities of more than 50,000 people (Diario Oficial de la Federación, 2012). Additionally, methane, that constitutes 50% of the landfill biogas, can be used as a fuel. The methane gas can be captured from landfills and wastewater treatment facilities and used to generate electricity, or simply flared to decrease its GWP. Also, wastes can be incinerated to generate electricity. These strategies can contribute two-fold to GHG emissions reduction: first by reducing the methane emissions in the waste sector, and second by generating electricity or heat which would displace some of the use of fossil fuels in the energy sector.

The Emissions to the Atmosphere and Climate Change section in Chapter 3 describes with more detail the differences between venting, flaring and using the biogas in a life cycle assessment.

2. Mexico City's Waste Management

Being the largest city in Mexico, and one of the most populous in the world, Mexico City poses serious challenges and opportunities in its waste management. The City is located in the southern central area of the country, within a valley at an altitude of 2,240 m above the sea level. The city's center is located in the Federal District but as the city has expanded, the metropolitan area now includes part of the surrounding states: the State of Mexico (59 of its 125 municipalities), and part of the State of Hidalgo (29 of its 84 municipalities). Consequently, this adds complexity to the waste management of this area, since the governments of the Federal District, the State of Mexico, and the State of Hidalgo, each take care of their own wastes.

There has been collaboration among the three governments on subjects such as the Water and Water Sanitation, Transportation, Security, Environment, and Human Settlements. The Commission that regulates these subjects *(Comisión Ejecutiva de Coordinación Metropolitana)* is formed by representatives from the three federal entities to plan and implement actions for the city.

According to the Federal District's "Municipal Waste Inventory of 2012", the estimated generation for the area is 12,740 ton/day, or 1.4 kg/day/capita. This is significantly higher than the rest of the country (average waste generation of 0.98 kg/day per capita). In 2007, the City landfilled 93% of its MSW. The remaining fraction was composted or recycled informally. However, this situation improved, deviating waste from landfills. In 2012, only an estimated 48% of the MSW was disposed in landfills, the rest being composted, recycled or sent for co-combustion at cement plants.(Secretaría del Medio Ambiente del Distrito Federal, 2012) This leaves the F.D. in a better status compared to the rest of the country which landfills most of its waste.

Mexico City has faced great challenges throughout the years. In 1985, the landfill Bordo Poniente was opened. By the time of its closure in December 2011, it had collected about 70 million tons of MSW, making it one of the biggest landfills in the world. Prior to its closure, almost all of the municipal wastes generated in the city were landfilled there, including construction and demolition wastes, contributing to its lifetime reduction.

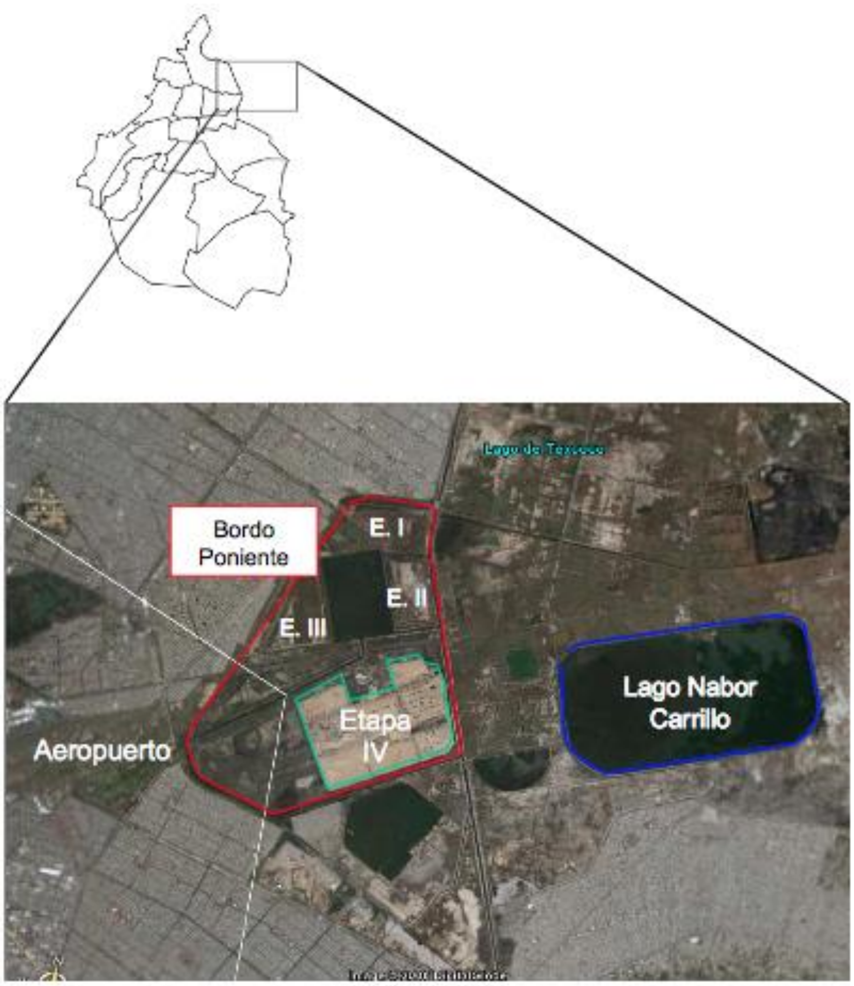

Figure 12 - Bordo Poniente Landfill Location and Satellite View (Secretaría del Medio Ambiente del Distrito Federal, 2006)

2.1. Waste Composition

According to a recent study by Moreno Duran (Moreno et al., 2013), the waste in Mexico City has the following composition:

Table 3 - Mexico City Physical MSW Composition (Moreno et al., 2013)

Category	**wt%**
Organics	49.50%
Plastics	13.16%
Sanitary Waste	10.77%
Paper	5.89%
Carton	4.03%
Textiles	3.64%
Glass	2.65%
Construction Material	1.88%
Special Waste	1.41%
Ferrous Material	1.16%
Fines	0.80%
Wood	0.45%
Aluminum	0.29%
Hazardous Waste	0.18%
Other	4.19%

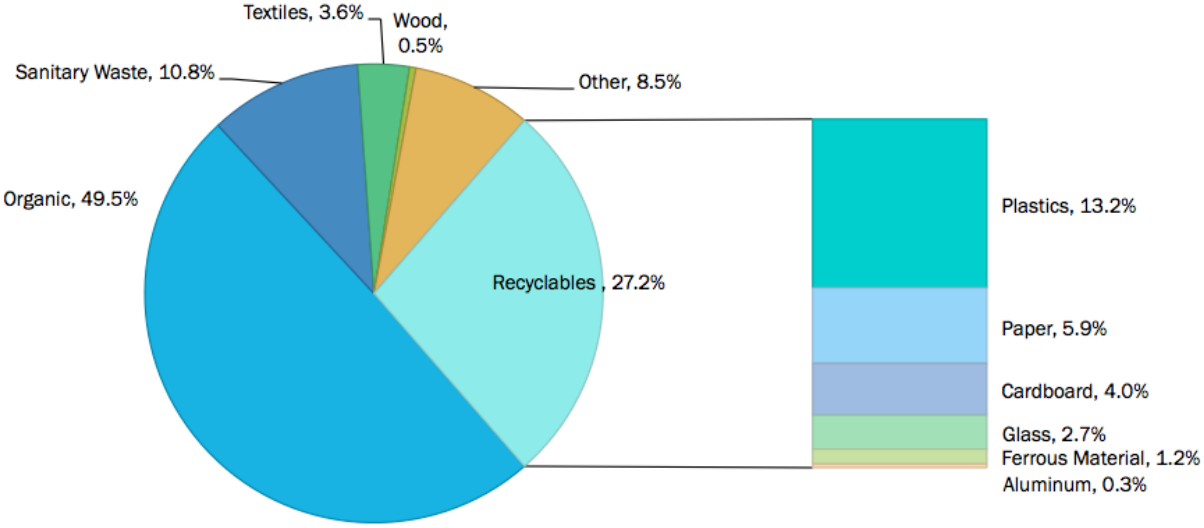

Figure 13 - Classification of the MSW in Mexico D.F. (wt%) (Moreno et al., 2013)

As mentioned earlier, the largest component is organic wastes (49.5%) and the second plastics (13.2%). The recyclables include plastics, a large part of which is not currently recycled due to economic or technical reasons, paper and cardboard, metals, and glass.

2.2. Waste Management Trends

Since 2006, the Federal District of Mexico City has published its Solid Waste Inventory. Its data has been used extensively in this study. Figure 14 shows the changes in the final disposal of the wastes from 2007 to 2012. It can be seen that waste management in Mexico City has improved continuously towards increased material recovery and reduced landfilling.

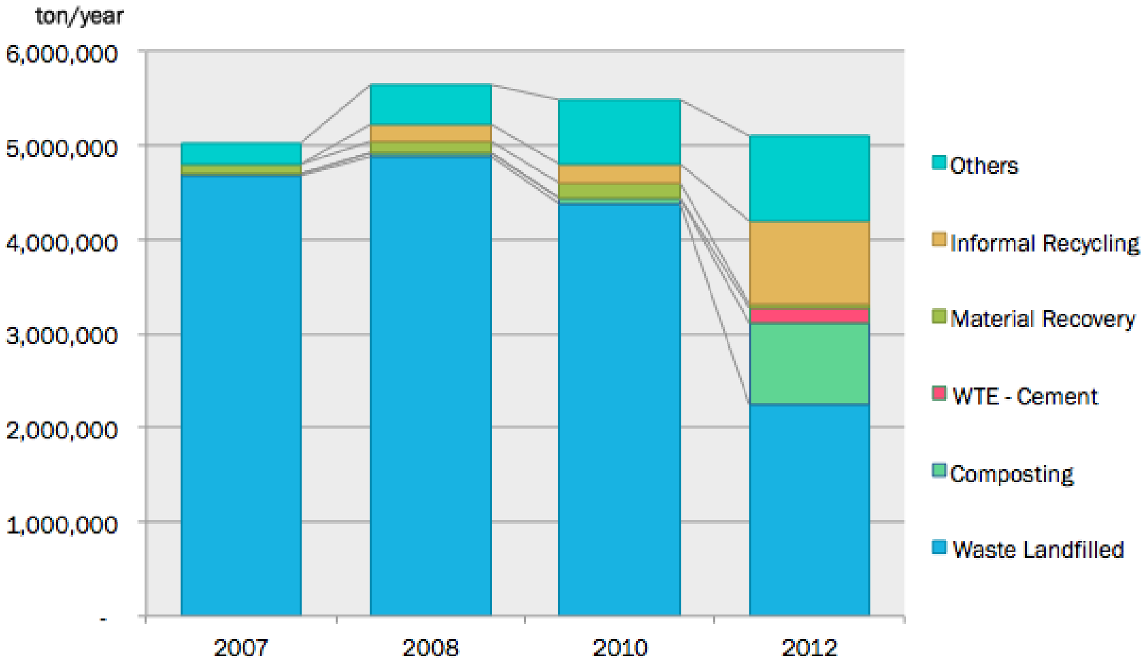

Figure 14 – MSW Final disposal changes from 2007 to 2012. Data: (Secretaría del Medio Ambiente del Distrito Federal, 2007, 2010, 2012)

Table 4 - Sources and flows of MSW

MSW generation	**2007**	**2008**	**2010**	**2012**
Mexico F.D.	4,000,000	4,740,000	4,600,000	4,650,000
State of Mexico	1,030,000	910,000	880,000	460,000
Total (tons/year)	5,030,000	5,650,000	5,490,000	5,110,000

MSW disposition	**2007**	**2008**	**2010**	**2012**
Waste Landfilled	4,679,000	4,891,000	4,387,000	2,245,000
Composting	21,000	38,000	50,000	867,000
WTE - Cement	-	-	-	163,000
Material Recovery	97,000	108,000	173,000	39,000
Informal recycling	-	196,000	196,000	881,000
Others*	230,000	412,000	681,000	918,000

Total (tons/year)	5,028,000	5,645,000	5,487,000	5,113,000
Percent Landfilled	93%	87%	80%	44%

Figure 14 and Table 4 show that by various means landfilling has been reduced drastically from 98% of the MSW, in 2007, to 44% in 2012. On its place, composting has increased by approximately 800,000 tons. Waste combustion at a cement facility is also being used, disposing of 163,000 tons. However, also Informal Recycling and the remaining balance "Others" increased significantly. Some possible causes for these differences are listed below.

The collected MSW increased from 5 million tons in 2007 to a maximum of 5.65 million tons in 2008. This increase can be explained by the way the totals figures are estimated. In 2007, the total amounts reported were obtained from the weight of waste measured at the first point of the collection system: The MSW transfer stations. In 2008, however, the process changed, the reported number is the based on the estimated MSW generation per capita, which is larger than the amount measured in the transfer stations. Therefore, the difference between the two numbers can be explained by:

- Informal recycling – This process begins in the waste collection trucks. As waste is picked up, collection personnel or other *scavengers* separate the recyclable waste such as PET bottles, aluminum cans, ferrous components and glass. This amount does not reach the transfer stations, as it is sold to recyclers, thus reducing the total amount of MSW recorded.
- Sorting recyclables – Separation of recyclables in the residential and commercial sector also reduces the amount collected.
- Use of non-regulated dumps – even though the F.D. government notes that 100% of the MSW is collected, there is a possibility that a fraction of the MSW may not reach the transfer stations or landfills and may be dumped in non-controlled sites. Open burning has also been discussed in other studies for less developed areas of the city.(Hodzic, Wiedinmyer, Salcedo, & Jimenez, 2012)
- An overestimation in the MSW generation per capita.

Another important variable is the amount of waste that comes from the State of Mexico. In 2007 the amount was 1 million tons/year. This amount was reduced in 2008 and 2010, and it was cut by one half in 2012, when the Bordo Poniente landfill stopped operating.

Also, an important and positive increase in composting was observed as a result of this strategy. Composting increased from 21,000 tons in 2007 to 867,000 tons in 2012. The results for 2013 were not published by the time this report was written but the composting status should be reviewed further at a later time to ascertain the amount of compost sold as this operation matures.

The landfills used in the year 2012 are all in the vicinity of the F.D., however all of them are outside the boundaries of the state. The six landfills used are the Cañada, Milagro, Xonacatlán and Cuautitlán in the State of Mexico, and Cuautla and Tepoztlan in the State of Morelos, where a lower amount of MSW is received (Figure 15)

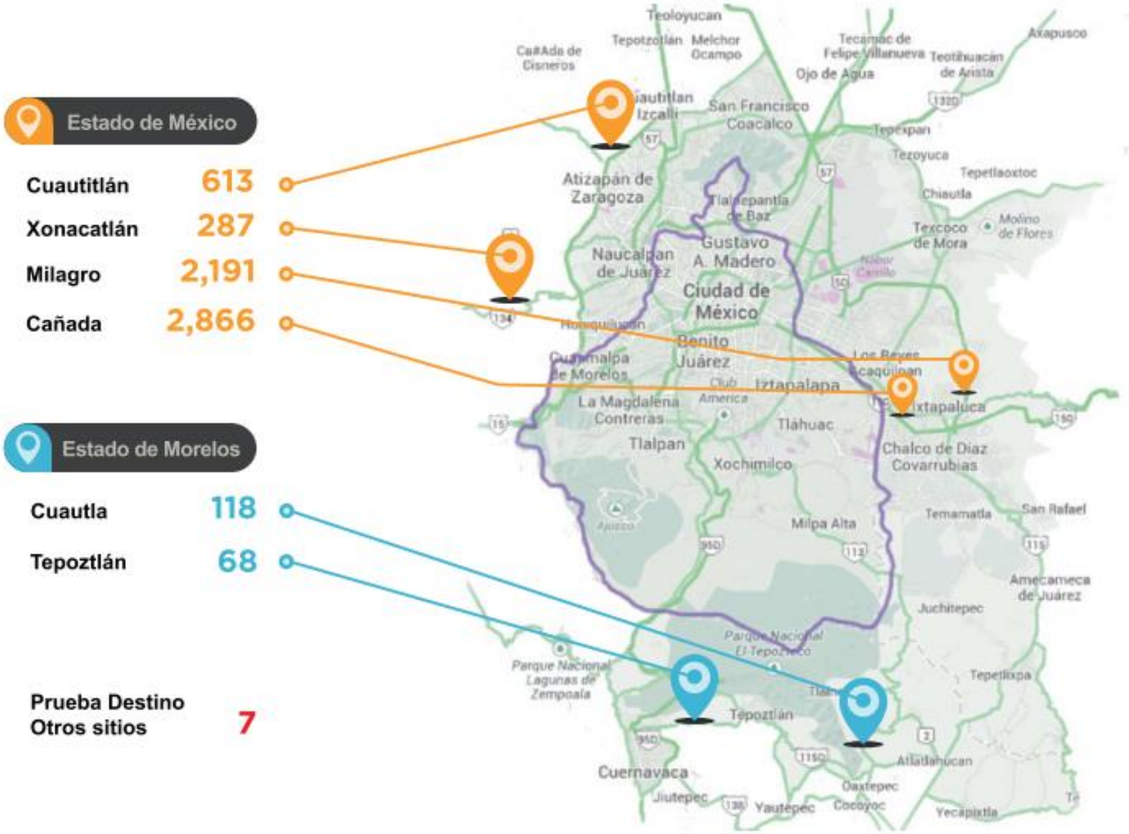

Figure 15 - Landfill locations used in 2012 (Secretaría del Medio Ambiente del Distrito Federal, 2012)

2.3. Recycling and Composting

In 2003, the Federal District Solid Waste Law was issued which required waste separation at the source. This law also stated that the local government set a waste management plan for Mexico City.

Afterwards, the government initiated a program where the population was required to separate their wastes into 2 streams: a biodegradable fraction, mainly food and green wastes, called the "organic" fraction, and the rest of the MSW, called "inorganic" fraction. This was part of the plan to improve the waste management process downstream, improve recycling and reduce landfilling. As the organic fraction is 50% of the MSW, this strategy has been useful for the transition into a better waste management structure. The efficiency of this separation ranged from 55% to 87% depending on the delegation. (Secretaría del Medio Ambiente del Distrito Federal, 2012)

Figure 16 – Current separation of MSW in Mexico: Organic: food and garden wastes; inorganic: paper, carton, glass, plastics, textiles, metals, and other trash. (SEMARNAT, 2014b)

The MSW collection process also transitioned to this separation scheme. This was achieved through different collection days: the organic fraction is collected Tuesdays, Thursdays and Saturdays, while the rest of the MSW is collected Mondays, Wednesdays, Fridays and Sundays.

The efficiency of separation varies from district to district. According to *Secretaría del Medio Ambiente* (Secretaría del Medio Ambiente del Distrito Federal, 2012)*, in 2012* the efficiency in separation in ranged from 55% to 87%, as shown in Figure 17. Despite the fact that the method for this evaluation was not mentioned, this data shows that more than half of the wastes are separated correctly.

This strategy is one of the reasons why Mexico City greatly increased its composting in 2012, as it is discussed in the following section. Another advantage of the source separation of the wastes is that the organic fraction contains more moisture than the inorganic fraction. Correctly separating these two fractions and disposing only the trash in a WTE facility can increase the heat capacity of the waste and the production of electricity per ton of waste.

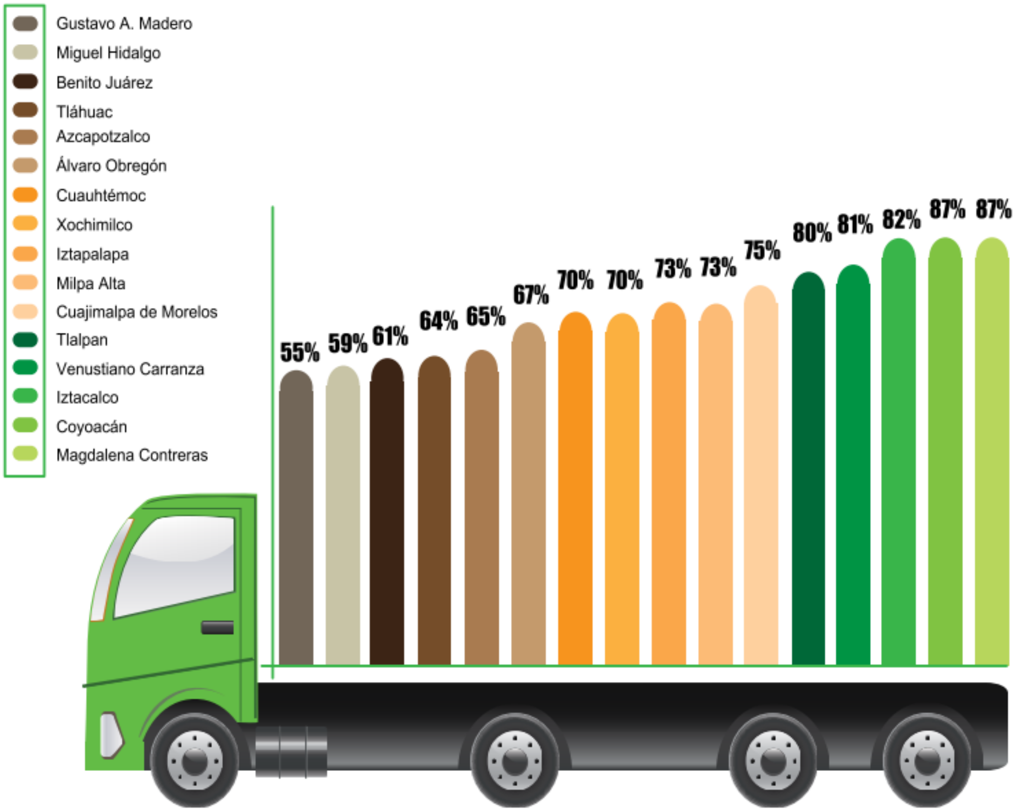

Figure 17 – Separation efficiency of organic wastes by delegation. Source: (Secretaría del Medio Ambiente del Distrito Federal, 2012)

Regarding composting, Mexico City has six operating composting plants. The biggest plant is the Bordo Poniente plant, shown in Figure 18, which handles more than 95% of the total composting capacity.

Figure 18 – Bordo Poniente Composting Plant in 2013, satellite view. (Image source: Google & DigitalGlobe, 2014)

The process that this plant uses is a windrow process. Windrow composting process is the most common practice for large scale composting globally (Van Haaren, 2009) As studied by Barron (2013), in the Bordo Poniente plant the organic waste is arranged in piles with a trapezoidal shape (Figure 19). Their average dimensions are a length of 120m, a large base of 5 m, a small base of 1 m, and a height of 3 m. The process lasts a total of 3 months, so this requires an area large enough to handle the inventory of material during the whole process.

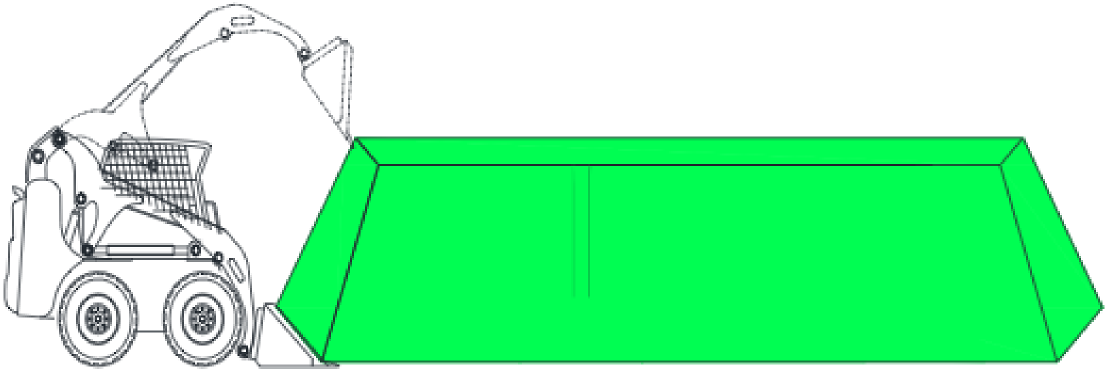

Figure 19 - Windrow composting cartoon. (Source: Barron Santos, 2013)

In 2007 these plants had a capacity of 79,000 ton/year (216 ton/day), which represents a low percentage compared to the 2.3 million tons/year (6,350 ton/day) of green and food wastes generated in the City. However, they were underutilized, as only 21,192 tons were composted in that year, accounting only a 27% capacity utilization. Gradually, the capacity utilization increased to 53% in 2010. By 2012, an impressive capacity expansion took place in the Bordo Poniente composting plant. This plant was expanded from 73,000 tons/year to 912,500 tons/year – a 13-fold increase in capacity. During the same period, the amount of waste composted in all six plants increased to 95% capacity utilization (Figure 20, Table 5).

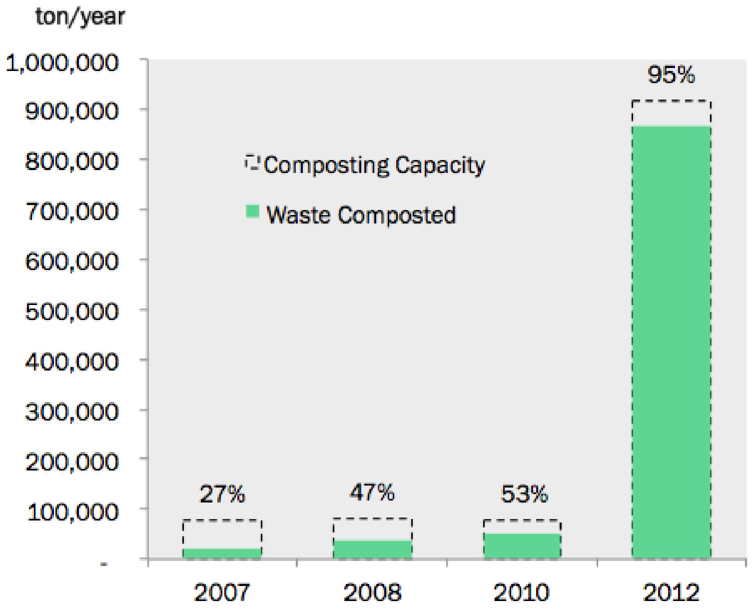

Figure 20 - Composting capacity, amounts composted (ton/year) and capacity utilization (%)

Table 5 - Waste composting information

	2007	2008	2010	2012
Capacity (ton/year)	79,020	80,151	78,739	916,980
Waste Composted (ton/year)	21,192	37,869	41,753	872,045
Capacity used (%)	27%	47%	53%	95%
Compost Generated (ton)	5,386	10,897	11,536	167,830
Compost Delivered (ton)	5,471	4,829	3,899	12,587
Number of Plants	6	6	6	6
Compost/Waste ratio	25%	29%	28%	19%
Compost Delivered/Generated ratio	1.02	0.44	0.34	0.07

Reviewing the numbers in Table 5, one can observe a big jump in the amount of compost produced from 2010 to 2012, corresponding to the increase in the waste treated. This poses certain administrative challenges: is there a market for that quantity of compost? Has the compost quality been maintained or has it decreased with the increased capacity requirement? According to Tovar *et al* (2013) composting quality has been maintained in a good level even as capacity was increased dramatically.

Certainly, the sudden increase in composting raises some questions on its viability, but overall it is an impressive step towards a more sustainable waste management. Studying with more detail in the composting process, such as odor reduction, ammonia emissions reduction and markets for the compost produced are suggested opportunities for further research.

2.4. Cost structure of waste management

In Mexico the municipalities are the responsible organisms to manage the sanitation and waste management for their territory. The population does not have to pay directly for these services as they are managed through the municipal budgets, so there is no direct monetary incentive for people to reduce the waste generation.

According to Tavares, *et al.* the cost of MSW collection may account for 70% or more of the total waste management budget, most of which is for fuel. They optimized the routes for MSW collection in two cities, taking into account distances, inclination, and vehicle weight, which yielded an 8-12% reduction of the fuel costs in those cases. (Tavares, Zsigraiova, Semiao, & Carvalho, 2009) For the case of installing a WTE plant, there will also be significant reductions in the time and distance the waste has to be transported to the landfills, as the WTE plant should be installed closer to the city than the existing and future landfills.

2.4.1. Transportation, treatment and landfilling cost update

To inquire about the current costs that the City is paying for their waste management services, the author contacted the delegations and the public works and services offices. Using the Infomex transparency system for the Federal District, which enables Mexican citizens to inquire about the processes, costs and other information about the government's operations.

The Public Works and Services office, which controls the transportation from the transfer stations to the MRFs, landfills and composting plants gave the summarized information shown in Table 6:

Table 6 - Cost of MSW management for 2012 and 2013.(Own calculations. Data from Secretaría de Obras y Servicios del Distrito Federal, 2014; Secretaría del Medio Ambiente del Distrito Federal, 2012. Exchange rate used: 13.50 MXN/USD)

Budget	**2012** (Thousand USD)	**2013** (Thousand USD)	MSW 2012 (tons)
Composting Plant	14,410*	4,776	866,510
Final Disposal	29,762	37,826	2,245,115
Transportation	39,150	43,253	4,650,100
Material Recovery Facilities	20,328	8,220	1,554,900

*In 2012 the Bordo Poniente composting plant had a large capacity increase.

The previously reported gate fees are between 120 and 210 mxn/ton (9-15.5 USD/ton).(Fernandez, 2012)

Throughout the country, landfill operation costs range from 25 to 80 mxn/ton; total landfilling costs range from 58 to 145 mxn/ton. (Instituto Nacional de Ecología, 2007). SEDEMA mentions a 360 mxn/ton ($26.50 USD/ton) cost for solid wastes of the D.F. that are disposed in landfills in the State of Mexico. This agrees closely with the data shared by the Public Works and Services office. Figure 21 and Figure 22 show the results of these costs, calculated per ton of MSW managed. This data is used in the financial calculations for the proposed WTE plant.

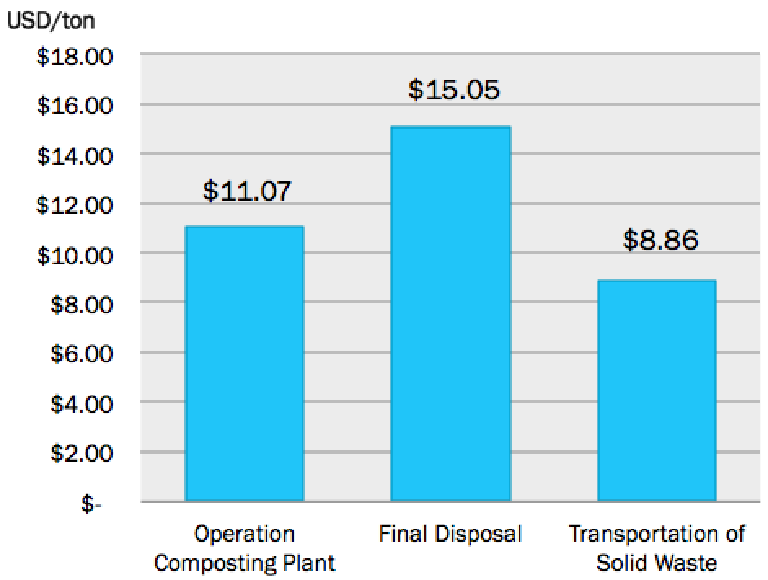

Figure 21 - Average costs for the FD MSW management for 2012 & 2013 (Own calculations, data from: Secretaría de Obras y Servicios del Distrito Federal, 2014)

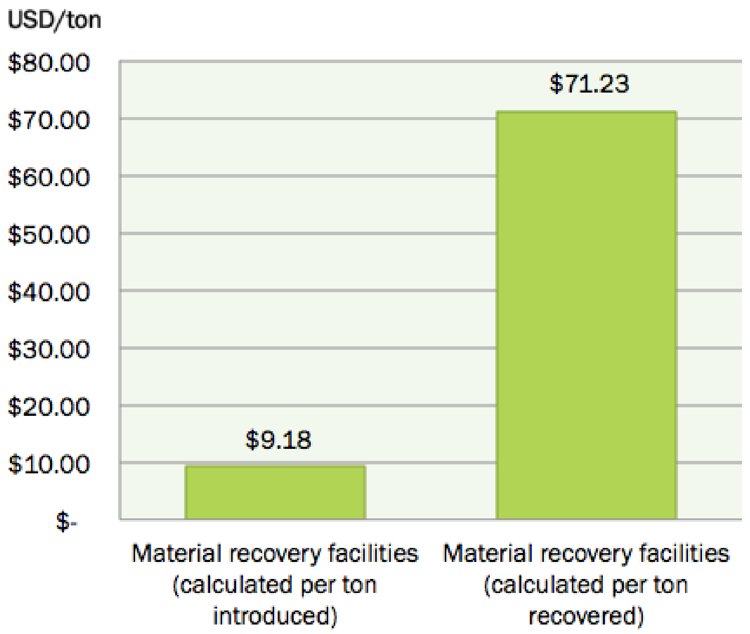

Figure 22 - MRF costs calculation comparison (Own calculations, data from: Secretaría de Obras y Servicios del Distrito Federal, 2014)

The Material Recovery Facilities budgets were also shared. In Figure 22 the cost per ton managed and per ton of material recovered is shown. If one calculated the value of the ton of recyclable materials recovered, it can be seen that the cost is very high. This requires further study, which was out of the scope of this thesis.

3. Waste to Energy

Recovering energy and materials from waste is an essential step to maximize the use of resources and obtain value from these materials. After waste is separated for recycling and composting, incineration is the alternative method for final disposal of waste - the other is landfilling. Waste incineration in a WTE plant is a thermal conversion process where waste material is combusted with excess air at temperatures between 850-1000ºC to release energy, producing gases and solid residues. This treatment effectively reduces the volume of the waste by 90% and its weight by 75%. The combustion process releases energy, which then can be recovered by heat exchangers to produce steam. The gaseous emissions are the largest risk of pollution from a WTE plant. These emissions include toxic organic compounds, heavy metals, as well as HCl, SO_2 and NO_x. Therefore, Air Pollution Control equipment is used to control these emissions reducing them to a minimum, as well as their impact to the environment and society.

Despite the benefits to the use of this process, this approach is only widely followed in some developed regions in the world. Japan uses WTE extensively to reduce landfilling, as land is scarce. Northern European countries use WTE for district heating in the winter. However, in developing countries, and also some developed nations, the waste seems to be treated mostly as a linear non-renewable flow, in which most materials are disposed of in landfills, posing a burden on the economy, burying useful materials and energy.

When landfills are used, there is also a means of recovering energy by capturing the biogas produced, which is composed by methane and CO_2. This also can reduce the environmental impact from landfills, as the biogas usually is flared. LFGTE is also discussed in this section.

3.1. Thermal energy stored in MSW

Evaluating how much energy can be recovered is an important part of the feasibility study. If the energy content in the waste is too low, the process is not viable and additional energy is required to combust the materials. The threshold on lower heat value that the World Bank stated in its Decision Maker's Guide document is 7 MJ/kg, never falling below 6 MJ/kg in any season (Rand, Haukohl, & Marxen, 2000). Despite the fact that those design parameters were established for the grate combustion type of reactor, they serve as a good heuristic indicator of economic and technical feasibility.

3.1.1. Moisture and ash content

Two important parameters in using MSW as fuel in WTE plants are *moisture* and *ash content*. Moisture of solid waste is defined as the material lost when a sample is heated for one hour at 105ºC. Ash is the residue that remains after combustion.

Moisture is important, as water requires a large amount of energy to vaporize which is then lost through the stack as water vapor. Therefore, waste materials with higher moisture are less desirable for WTE as less energy is available for recovery. Ash content is also significant as this is the amount of waste that will remain after the combustion process. This mass will have to be transported for reuse or final disposition in a landfill.

The large organic fraction is high in moisture content, which as mentioned earlier lowers the energy content of the materials. Reducing this moisture would enable a higher energy value per unit of mass. This can be attained by treating separately the organic fraction of the waste, which has the highest moisture, while combusting the remaining fraction. Also compaction to remove liquids from the waste has been studied previously, but it carries other difficulties, as the leachate generated has to be treated separately.

3.1.2. LFGTE

While less desirable in the waste management hierarchy, energy can also be recovered from wastes disposed of in landfills. The organic fraction of the wastes decomposes at the oxygen-deprived conditions it is exposed to when buried. This decomposition driven by methanogenic bacteria produces a biogas which is composed of 50-60% CH_4, 40-50% CO_2, plus other trace gases and water. This gas can be recovered installing a lining above the landfill cell, drilling holes and installing PVC pipes to collect the biogas. Also, there are active systems that also use blowers to inject air into the landfill, providing a pressure differential to extract the biogas with more ease. This gas is then collected, treated to remove impurities and pollutants, and then can be burnt in internal combustion engines for energy production. (Moreno et al., 2013) If not, usually it is just flared to avoid methane emissions.

Unfortunately, the gas production decreases with time. Biogas generation starts when the waste is buried and covered by soil in the landfill, and after oxygen depletes. However, the gas can't be collected until the landfill is equipped for gas recovery, so it is emitted to the atmosphere, with its corresponding GHG consequences. After the landfill cell is closed and the piping equipment is installed, an estimated 90% of the gas can then be collected and used. This gas generation is expected to last between 20-30 years, but, as there is a defined amount of organic waste inside the landfill, the generation of biogas will decline as the amount of organic waste decomposes. Techniques such as recirculation of the leachate within the landfill to increase the moisture in the waste and thus improve the decomposition process have been studied, which have increased significantly the gas production of these systems (Reinhart & Basel Al-Yousfi, 1996).

3.1.3. Emissions to the Atmosphere and Climate Change

Though there's interest to compare between different methods of waste management often comparisons can be subjective, which can result in skewed decisions. In the case of environmental impact, a tool called Life Cycle Assessment (LCA) was created. Following this rigorous LCA process helps quantifying the impacts to the environment of a complete process from "cradle to grave": from raw materials to final disposition. LCA's can evaluate several variables: greenhouse gases and climate change, water use, air pollution, effectively providing a basis for comparison of different processes.

An important concept to define in LCAs is the biogenic carbon and fossil carbon. In the environment, there are natural carbon fluxes the ground to the atmosphere with respiration and combustion; back and forth from the atmosphere to water bodies, as CO_2 is absorbed into carbonic acid; from the air to the ground in plants and algae in photosynthesis. This creates a carbon cycle where the balance of the fluxes and stocks remains the same for long periods of time.

However, with extensive fossil fuel use as well as changes in land use the balance is shifting. Since the industrial revolution, more CO_2 is emitted than can be absorbed by the natural sinks of carbon – mainly the ocean and vegetation - increasing its concentration in the atmosphere. As CO_2 is a greenhouse gas, an increase in its concentration in the atmosphere retains more heat, increasing global temperatures. This phenomenon has been thoroughly studied and is of great concern, as it is causing global climate change.

Then, to evaluate the impact in WTE processes it is important to differentiate the carbon sources into two groups: biogenic and fossil. The biogenic CO_2 comes from the combustion of biologically based materials, such as wood and biomass. The carbon in these materials was previously absorbed from the atmosphere by photosynthesis, so it is included in the natural carbon cycle. On the other hand, combustion of fossil fuels such as oil, gas and coal adds carbon to the atmosphere. This carbon had been underground for millions of years, so it increases the CO_2 of the pre-industrial carbon cycle. The IPCC has reported the carbon cycle numbers and stocks in their AR5 report.

In waste combustion, the stream of materials is a complex mixture so it is not straightforward to know what amount of the waste contains anthropogenic carbon and what is biogenic. The Earth Engineering Center at Columbia University has studied the content of biogenic carbon in waste to energy plants in the US. The difference between the biogenic and fossil carbon can be obtained doing a ^{14}C radiocarbon analysis. The carbon atom has two stable isotopes: ^{12}C and ^{13}C, but due to phenomena in the atmosphere where cosmic rays impact nitrogen atoms, there is a small amount of ^{14}C isotope created in the atmosphere, which is then used by living organisms (Beta Analytic, 2014). The fossil carbon has no ^{14}C content because after an organism dies, this isotope gradually decays; so in a timeframe of millions of years, the amount of ^{14}C is very low.

Using the procedure ASTM-D6866 to determine the biobased content of carbon by radiocarbon analysis, one can measure the amount of ^{14}C in the gas exhaust of a WTE plant and then correlate to the amount of biogenic carbon of the waste. The result of this research was that 66% of the carbon in the US waste stream is biogenic. Then, 66% of the energy obtained comes from the natural carbon cycle and can be considered as renewable. (Klinghoffer & Castaldi, 2013)

Kaplan *et al* (2009) studied the carbon emissions for different MSW disposal processes in the US, focusing on landfill gas to energy and WTE. An LCA comparison between them was made counting the quantity of CO_2eq emitted per MWh of electricity generated. The results from this study can be seen in Figure 23, with higher emissions from LFGTE than WTE. WTE performs in average as good as natural gas and better than coal and oil.

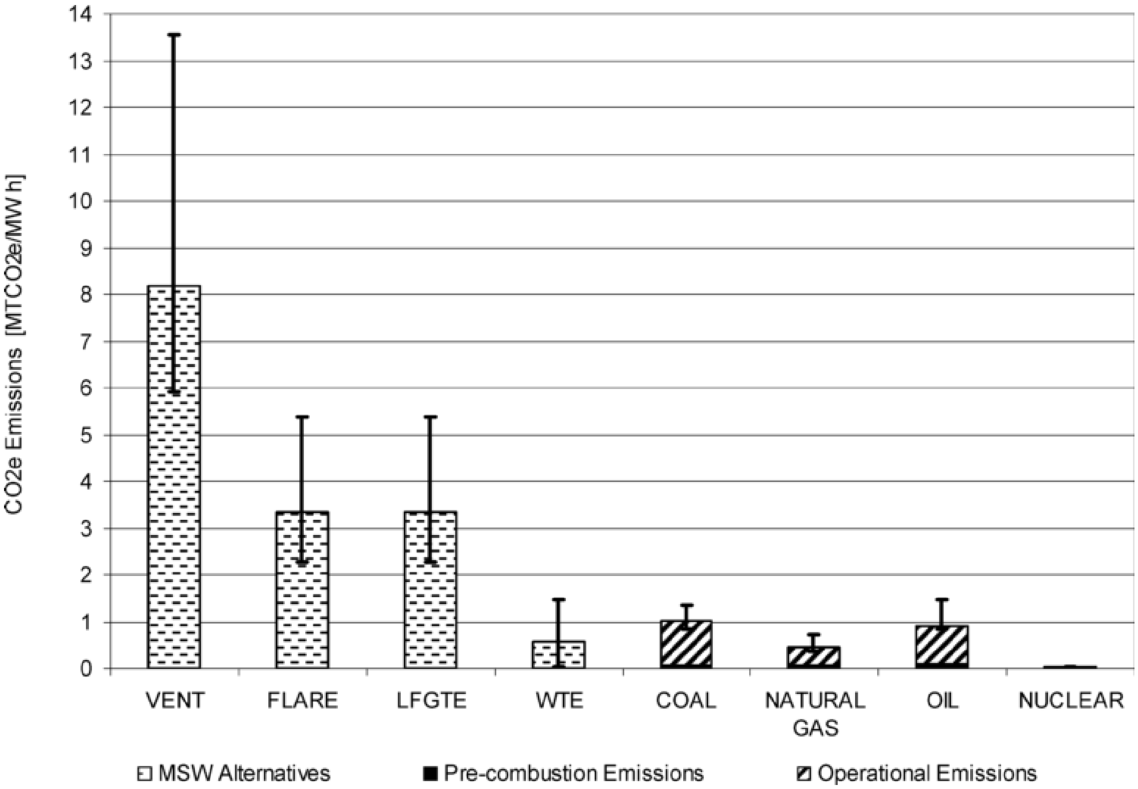

Figure 23 - CO_2eq emissions for different waste to energy methods and conventional energy generating technologies (P. O. Kaplan, Decarolis, & Thorneloe, 2009)

Also, there is an advantage to the amount of energy that can be generated. LFGTE uses the methane gas generated from organic wastes, however, a great volume of the gases, estimated from 60% to 85% of the total biogas generated is not collected, losing precious energy and emitting high greenhouse potential methane to the atmosphere. LFGTE also produces the biogas though a period of time so wastes are trapped in the landfill and their energy is freed in a long period of time as the methanogenetic processes take time. WTE uses the energy in organic wastes and other non-biodegradable wastes, such as plastics, recovering more energy per unit of mass. Also, the wastes are incinerated at the moment, compared to landfills where degradation takes place spread through several years, which makes it a more intensive process. It is then estimated that "WTE can generate an order of magnitude more electricity than LFGTE given the same amount of waste" (P. O. Kaplan et al., 2009).

3.2. Technologies used for WTE

Waste to Energy is a common practice in European countries, the US and increasingly in Asia. This practice started in the second part of the 19th century, with the "Destructor", the first incinerator built in 1876 in Manchester, UK. Since then, the technology has evolved to become more efficient, predictable and significantly cleaner. Current WTE plants usually have high plant availability (more than 90% of the time), which make them a good option for renewable base-load power electricity.

Several different technologies have been developed for WTE, evolving as science and technology advance and experience gives feedback to the design. For this analysis, we will compare the CFB reactor with the most widely used technology: the Moving Grate reactor. Other technologies such as RDF burning, plasma, rotating drum and other gasification technologies are not as widely used. Most of these technologies are studied with more detail by other authors. such as Themelis *et al, 2013;* Klinghoffer & Castaldi, 2013; Tchobanoglous & Kreith, 2002.

3.2.1. Mass Burn in Moving Grate Reactors

The most widely used type of MSW incinerator is called Moving Grate (MG) reactors. Mass burn MG incinerators burn the MSW as received, with little or no pretreatment. This makes it a less complex operation than other technology options.

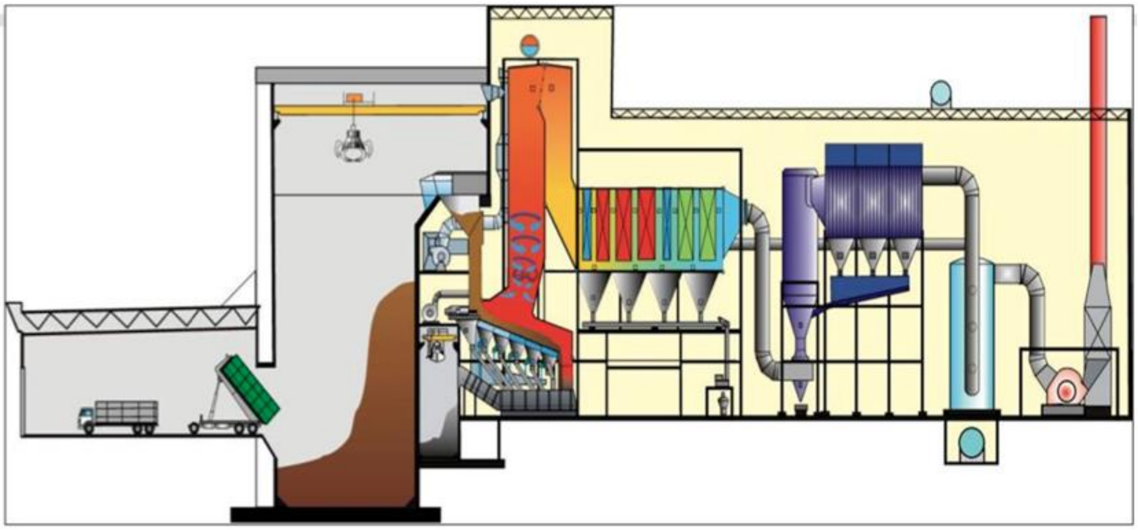

Figure 24 - Moving Grate WTE Process - Hitachi Zozen INOVA, Japan

The waste is received in a flat area called the tipping floor. Here the trucks unload the waste, it is examined by an operator for large items such as refrigerators, gas tanks, or other non-desired items for their removal or rejection. Afterwards, the waste is moved by a loader truck to a refuse pit or MSW storage area. This area provides a buffer to the process to ensure there is enough waste to fuel the process during all operating days, including weekends and holidays where no MSW is delivered to the plant. Afterwards, a claw crane picks up the waste and shuffles it around the pit to homogenize it and mix it with air, which helps the combustion process. Next, the waste is picked up with the crane and loaded into a hopper that connects it to the MG combustion chamber. The material is pushed with a large piston into the combustion chamber.

Figure 25 – A claw crane at Covanta's Essex plant taking MSW from the refuse pit, Newark, NJ.

The moving grate is an inclined surface that moves slowly to shuffle the waste and transport it towards the other end of the reactor while it oxidizes. This surface is inclined to help provide the movement towards the lower side of the grate. Primary air is injected in the bottom of the grates to aid combustion, which also helps move the waste. A layer of waste sits on top of the grate. This layer cannot be very deep as then air cannot penetrate the layer, so mainly the area of the grate determines the capacity of the plant. An excess air of around 80% is used to help complete the combustion.

The ashes are extracted from the bottom part of the grate and quenched with water for cooling. The hot flue gases are transported to the top of the reactor where combustion is completed. The flue gases pass through several heat exchangers for heat extraction. This heats up water into superheated steam that can be used to generate electricity through a turbine, while cooling the flue gases. The flue gases finally go through Air Pollution Control (APC) equipment, where the acid is scrubbed, solid particulates are removed either through Electrostatic Precipitators or bag-house filters and the air is emitted through a stack. Also activated carbon may be used to remove heavy metals from the exhaust.

The moving grate process is the most widely used and trusted around the globe. Therefore, the Guidebook for the application of Waste to Energy in Latin America and The Caribbean, as well as the World Bank and the recommend this technology as for the introduction of WTE in countries new to this practice. However, the MG technology is expensive, as it requires high quality materials for moving parts exposed to high temperature as well as the size of its reactors. The investment cost has prohibited its use for developing countries.

3.2.2. Circulating Fluidized Bed Reactors

The circulating fluidized bed is a type of reactor that uses air at a high velocity to blow the solid particles up the reactor, creating a very turbulent solid-gas mixture, where a chemical reaction - in this case combustion - takes place. These type of reactors have are used in other applications involving solids and gases, such as coal combustion, biomass combustion. Also, they are used in refining processes in the oil & gas industry, such as Fluid Catalytic Cracking.

3.2.2.1. Particle classification and fluidization regimes

Particle movement inside the reactor is important, as a good mixing and flow is essential in FB reactors. Geldart (1973) classified particles in 4 different groups consistent on their characteristics for fluidization as seen on Figure 26. The different groups are:

- Group A – Aeratable – Low to moderate density. E.g. FCC particles.
- Group B – Bubbling – Particles are larger and heavier than group A. E.g. sand, glass particles.
- Group C – Cohesive – Particles are smaller and lighter. Strong interparticle forces. E.g. flour, talc.
- Group D – Spouting – Particles are larger and heavier than group B. E.g. Coffee beans, metal ores, other large or heavy particles.

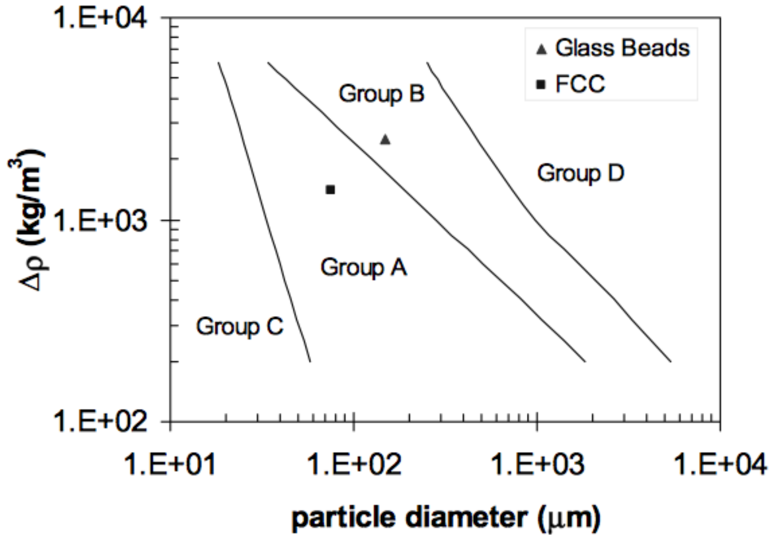

Figure 26 – The Geldart group classification according to particle diameter and density difference between particles and fluidizing gas (O'Hern et al., 2006)

The fluidized bed is formed when the solid/gas mixture is set in conditions that make it behave as if it were a fluid. This is done by blowing air from the bottom of the vessel at a speed high enough to cause movement in the particles. As the air changes its speed, different regimes form, as shown in Figure 27.

To describe its effect we can imagine the following experiment. At the start, a vessel contains a "bed" of solid particles. Air is introduced through the bottom of the chamber. As a higher air speed is achieved, the solid particles bed changes its behavior. At first air blows through the spaces between the particles, causing the particles to increase the space between them. This increases the bed height. After a threshold is reached, an amount of air cannot flow through the channels between particles and bubbles begin to form. This regime is called bubbling bed, as shown in Figure 27 letter b. When the air speed is higher, the bubbles begin to become larger and large passageways begin to form, in a turbulent fashion. Particles begin to mix with more violence as air and particles flow upwards in the center of the vessel and downwards in its edges. When the speed is high enough, some particles are carried with the air over the top of the vessel, which requires a recovery and injection. This is the fast fluidization regime and when particles are circulated back to the vessel, the Circulating Fluid Bed regime is formed. If air speed is increased further, more particles are carried with the air, forming a pneumatic transport regime. This is not desirable for the operation of a CFB as the particles should have a turbulent movement but they should stay as much as possible within the main chamber.

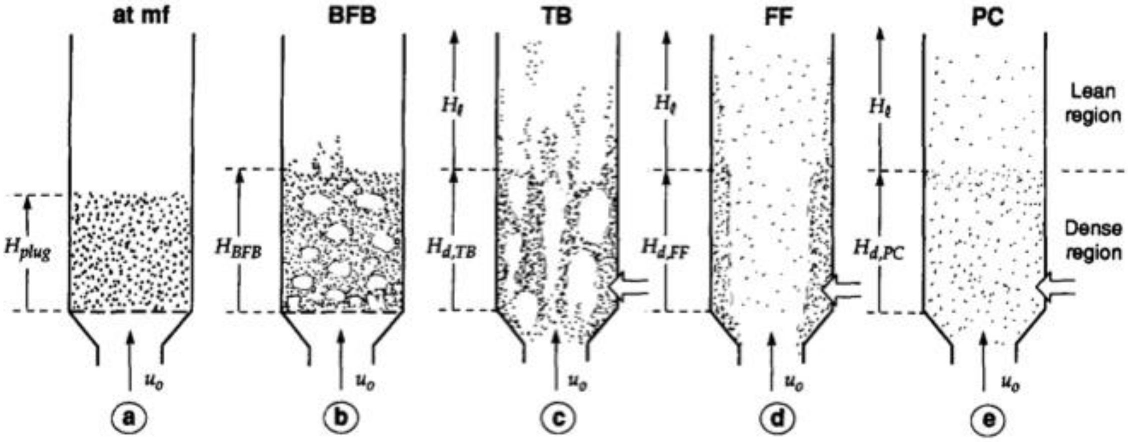

Figure 27 – Particle flow patterns depending on airflow. Source: (Kunii & Levenspiel, 1997)

The airflow and highly turbulent environment within the chamber make the fluid bed a very desirable environment for chemical reactions, such as combustion and catalysis, as at high turbulences the air and solid particles mix better. The stagnant layer at the interface between the bulk of air and the solid particle reduces as air speed increases allowing better mass and heat transfer between the air and the solid particles leading to higher speeds of reaction.

One of the downsides of this reactor design is the particle carryover. As air flows upwards and mixing with the particles is encouraged, particles are carried over the reactor vessel and have to be separated from the air exhaust and returned to the reactor as much as possible. This operation, which is usually done by a cyclone, allows some of the particles to go through, requiring more air pollution controls in the followings steps. Usually baghouses are used to filter out the remaining particles from the air before it is returned to the environment. A higher amount of particles cause the life of the baghouses to be lower, as these filters clog sooner and have to be cleaned more continuously.

3.2.2.2. CFB History in China

The studied CFB technology for WTE was developed in China. It is of interest to study how this technology evolved in the country, as it was first used, and is still used extensively for coal boilers.

The CFB combustion reactors have a long history in China. Starting in the 1960s, China started developing their Bubbling Fluidized Bed (BFB) boilers to burn coal for electricity generation. By 1980, there were more than 3,000 operating BFB in the country. In 1982, after the success of a CFB Boiler in Germany, Chinese researchers started the R&D on the CFB.

As Yue *et al* mentions (Yue, Yang, Lu, & Zhang, 2010), the history of Chinese CFB can be divided into 4 periods. The first period was between 1980-1990, where the previous BFB combustors were modified to have a separator and an extended furnace and s-shaped or louver type separators, which had low separation efficiencies. This limited the amount of coal that could be used so the capacity of the boiler usually was between 35-75 t/h. This also limited the air velocity in the upper region of the furnace, which didn’t reach a fast-fluidized bed regime, reducing the combustion efficiency and heat transfer.

In the second period, from 1990-2000, together with government aid, research of gas-solid flow was improved. More than one hundred CFB boilers were put in operation with a capacity between 75-130 t/h. Cyclone separators with cooled walls were used to achieve high particle collection efficiencies.

In the third period, from 2000-2005, the technology was mature and it expanded its market in China. Technology was developed in-house and also imported and licensed from European companies, which allowed the country to escalate their plant capacities to 135-200 MW boilers.

In the period after 2005, 300MW boilers emerged and also the development of 600MW supercritical steam CFB took place. By 2008, there were more than 63,000 MW of installed capacity using CFB technology in China, which was more than 10% of the total coal fired power plant capacity.

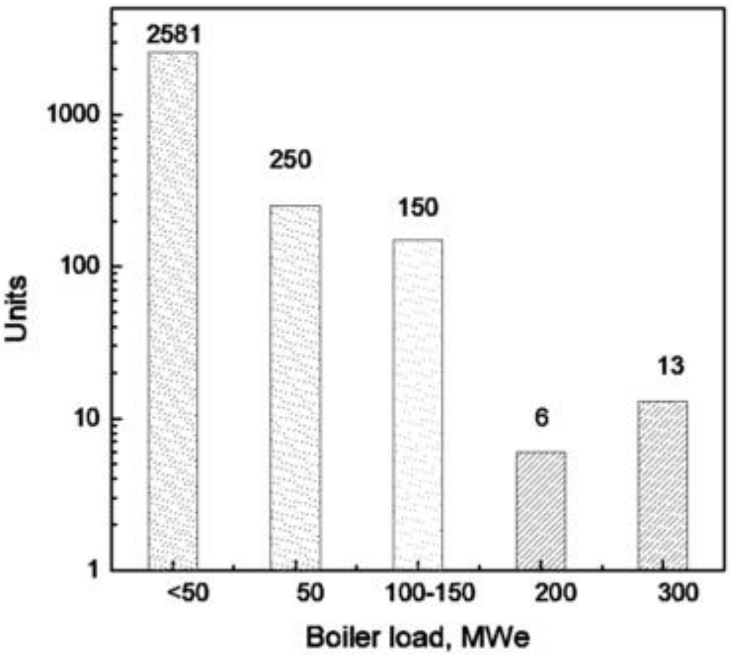

Figure 28 – The market of CFB boilers in China by the end of 2008: (Yue et al., 2010)

WTE reactors evolved from the coal CFB design as the Chinese government dedicated resources to develop a lower cost and high moisture WTE technology to reduce landfilling and generate electricity. Three main CFB technologies evolved: the Zhejiang University, the Chinese Academy of Sciences and the Tsinghua University reactors. We focus on the Zhejiang University technology in this study.
By 1998, a full-scale demo was available with a 150ton/d capacity. Throughout the years, the technology evolved, a commercial demo was available in 2000, and by 2008 a commercial application with >600 ton/day was available. (Quinxing Huang, Chi, & Estrada, 2014)

China experienced an important growth in CFB technology for WTE. By 2012, there were 47 CFB WTE plants with a total capacity of 40,000 ton/day. This accounted for 47% of the total WTE capacity.(Qunxing Huang, Chi, & Themelis, 2013)

3.2.3. Size reduction

A fundamental difference the CFB process has compared with the Mass Burn process is the requirement for a pre treatment of the waste to reduce its size and allow a more homogeneous fluidization in the reactor. Bags full of MSW and other large bulky items can’t be introduced in the reactor as received as they are too heavy to be elevated by the airflow. Then commonly the waste is shredded as a pretreatment. This also has other benefits, such as 1) breaking the raw MSW into its basic components; 2) allowing for a smaller particle that has more solid-air interfacial contact area, which helps the combustion process in the reactor; and 3) components are broken into different size distributions to be more easily separated by air knives, screens and optical sensors; this is manly used in Material Recovery Facilities and recycling.

Fitzgerald and Themelis (Fitzgerald & Themelis, 2009) studied the 2 most common shredder types in the market: High Speed Low-Torque (HSLT) and Low Speed High Torque (LSHT). The latter is preferred for WTE applications for several reasons explained in the following section.

3.2.3.1. High Speed Low Torque Shredders

HSLT shredders, also called hammer mills, operate at high rotating speeds. The operation principle is to induce breaking and size reduction of the materials by impacting the materials with several hammerheads at a high speed, providing a strong impact force. The shredder is comprised of rotating head hammers attached to an axis that turns powered by an engine. The hammers are pinned to the axis free to swing, so they carry a kinetic energy component. The materials enter the shredder from a chute above, are impacted by the hammerheads, and leave the shredder from below through the sizing bars as shown in Figure 29.

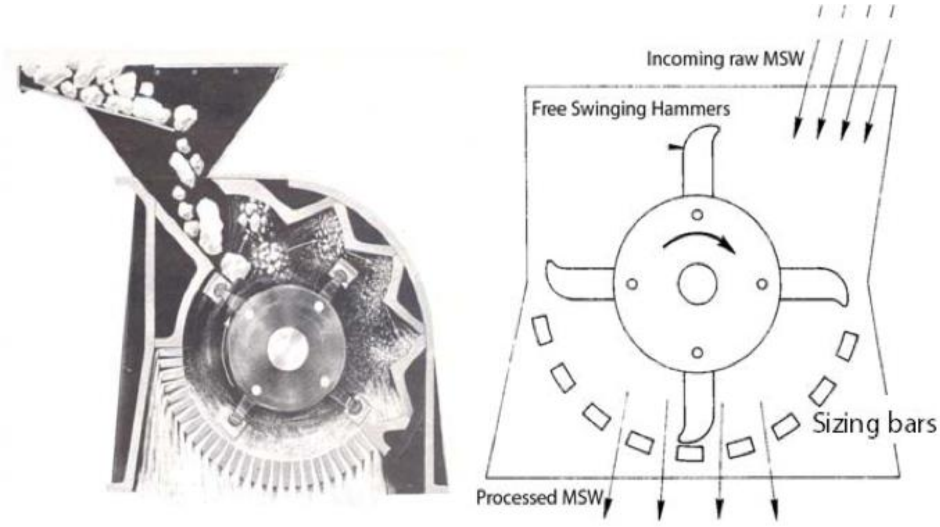

Figure 29 – Internal arrangement of a Hammer mill shredder (Fitzgerald & Themelis, 2009)

This type of shredder works best with brittle and hard materials. This type of treatment is used in the mining sector for minerals and other hard non-elastic materials. However, because of its diverse composition, MSW contains materials that are not brittle and hard, such as plastics, rags, and paper.

Another problem is that material can break into lower sizes than required, creating dust. Maintenance requirements are high, as the hammers impact with the materials makes superficial damage to the heads. This has to be continuously inspected and repaired. Energy use is in the range of 6-22 KW/ton.(Fitzgerald & Themelis, 2009)

3.2.3.2. Low Speed High Torque Shredders

LSHT shredding uses a different for size reduction. These shredders (Figure 30 and Figure 31) use high shear forces instead of impact forces to break the materials. These forces are more adequate than impact forces to break the moist and more flexible materials in the waste stream, which makes these shredders more suitable than hammerheads for MSW pre-treatment.

Figure 30 - Metso LSHT shredders for MSW. Image from metso.com

Figure 31 - LSHT Shredder used in CFB WTE plant at Cixi, China. (Image shared by Dr. Quinxing Huang, 2014)

The power drive uses hydraulic transmission, which helps lower stress on engines when compared to direct linkage. Additionally, the shredders from Metso can have an automatic reverse motion of the rotors, which can help reject materials that are hard to shred, by reversing the direction of the shredding. This is done continuously through the operation, which can also help unclog the shredder without manual intervention.

The capacity for commercial LSHT shredders usually is lower than HSLT shedders, but still is highly scalable as demand for these types of shredders increases. Typical sizes are in the 70ton/h range. These shredders operate in speeds between 10 to 50 rpm. (Fitzgerald & Themelis, 2009)

3.2.3.3. Particle size and shredding operation

To properly fluidize the solid waste in the reactor, the particles have to be smaller than as received from the MSW stream. Trash bags have to be broken to be able to mix their contents. Still, the particle sizes need not be very small. According to experience from Zhejiang University and the operating WTE CFB plants, the WTE reactor performs correctly with maximum particle sizes of 15 cm, which is the gap between the blades of the LSHT shredder.

A very convenient improvement for the pre-treatment, which was implemented by the Zhejiang University design, is the location of the shredders. Previous RDF plants had a designed space to receive the waste, shred it and store it shredded, which was later used at the WTE facilities. The shredders of the Cixi plant in China are located in the pit where the waste is received and stored as shown in Figure 32:

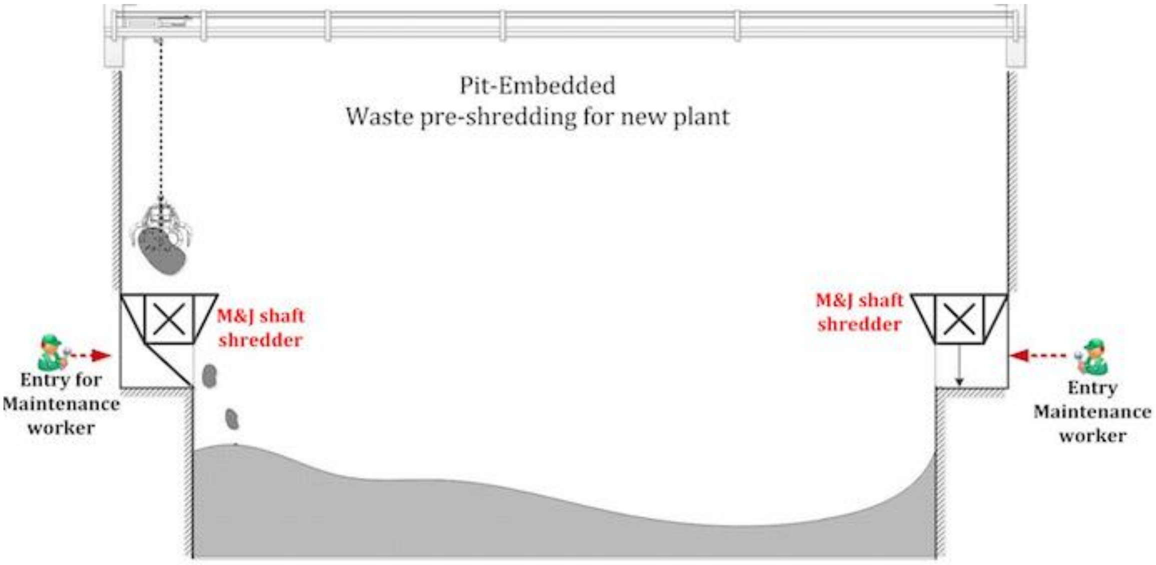

Figure 32 –Location of the shredders in Cixi CFB Plant, China.

The operation is as follows: the waste as received is deposited towards the center of the pit. The crane picks up this waste and is shredded in one of the two installed shredders. These two shredders serve the 2,300 ton/day plant. The shredded waste then will be located close to the sides of the pit. Two shredders are installed, as one used mostly as a backup to allow for preventive maintenance of the other shredder. This helps provide a continuous operation of the plant.

3.3. Air Pollution Control (APC)

The APC is the last part downstream the process. This part is similar in all WTE plants, as there is special attention to clean the flue gases and ensure air quality is maintained around the plant. There is an important attention on this point as previously when WTE plants were developing in the late 1970's and 1980's, they lacked proper operation and air pollution controls, which led to toxic emissions and public response. WTE plants shut down and implemented improvements in combustion practices and APC technology. Now WTE plants are one of the cleanest energy production plants with low pollutant emissions.

3.3.1. Dioxins and furans in WTE

WTE plants were seen as producers of toxic compounds called dioxins and furans. This may have been the case in 1980s and 1990s, but current technology has reduced the emissions to a low amount, making WTE plants a low generator of dioxins, as detailed below.

Dioxins or polychlorinated dibenzodioxins (PCDDs) and polychlorinated dibenzofurans (PCDFs) are chemical compounds formed by two benzene rings and a number of chlorine atoms. These different compounds have different toxicity levels, but are called dioxins as a group. They became known widely after a chemical plant accident in Seveso, Italy where a large amount of the toxic compounds were emitted (Buser, 1982). After that accident, studies were done to study emissions on MSW incinerators and the dioxin compounds were detected in their emissions. Several organizations also made studies to understand what factors and what chemical reaction mechanisms produce these chemicals.

Based on results surveyed by Vehlow (2012), it is clear that managing a complete combustion is key to minimizing dioxin production, as Products of Incomplete Combustion (PICs), such as soot particles, are the main precursors of these toxic compounds. The boiler should be cleaned to avoid deposits of these particulates.

Temperature is also critical as shown in (Figure 33) where it was detected that exposure of soot or other PICs to the critical temperature range between 200°C and 600°C leads to generation of dioxins. Above 600°C these compounds are destroyed. Thus, filters should operate at a temperature below 200°C. Results also showed that at normal combustion conditions, the formation of dioxins is controlled by PICs and not by the composition of the waste such as the amount of halogens.

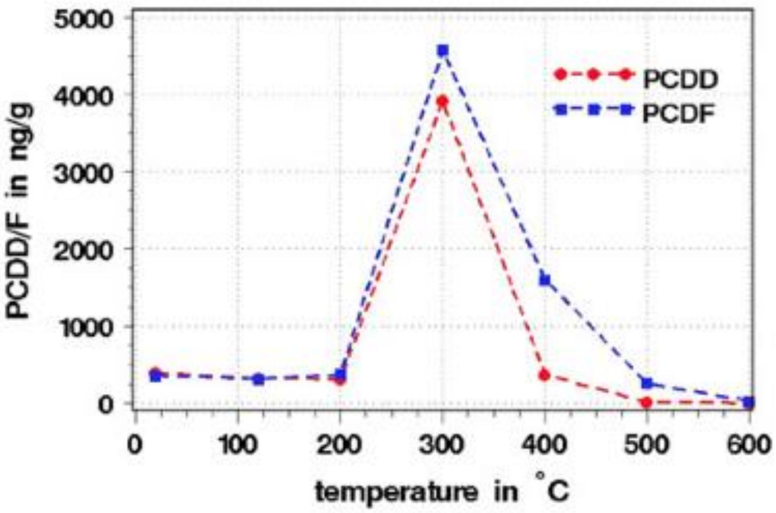

Figure 33 - Formation of PCDD and PCDF in fly ashes heated in air atmosphere. (Vehlow (2012), adopted from Vogg and Stieglitz (1986))

Additional to these combustion guidelines, other secondary measures such as activated carbon injection, the use of catalysts in baghouses or in selective catalytic reduction processes, used for NO_x reduction in other processes, can also reduce the emissions of dioxins up to 99%.

Vehlow (2012) summarizes: “It can be concluded that dioxins are no longer to be seen as a barrier to waste incineration. A significant impact on health or environment can be excluded if all technical knowledge is applied.”

3.4. Mass Balance

According to the Guidebook for the Application of Waste to Energy Technologies in Latinamerica and the Caribbean (Themelis, Elena, Barriga, Estevez, & Velasco, 2013), the mass balance for the waste stream in a moving grate WTE facility is shown in Table 7. From the total mass of the waste, 75% is consumed during combustion, leading mainly to CO_2 and H_2O production. For moving grate plants, in average the ash remaining is split between the bottom ash (22.5%), which flows from the bottom of the furnace and the fly ash (2.5%), collected in the baghouses or the ESP. For the CFB plant studied, the process carries more ash through the air, 16% of the initial weight exits the reactor as bottom ash and 11.6% as fly ash.(Jiang, 2013)

Table 7 – Average mass balance in a WTE Facility. Source: WTE Guidebook(Themelis et al., 2013)

Mass input (tons)		**Mass consumed during combustion (tons)**		**Remaining mass (tons)**	
Waste	1	Mass consumed during combustion	0.75	Bottom ash	0.225
				Fly ash	0.025
Total	1	Total	0.75	Total	0.25

3.4.1. Combustion chemistry

As any other combustion process, the combustion of the MSW requires oxygen, as the objective of the process is to oxidize the content in the waste materials. This is an exothermic process: it releases energy as heat. The heat will be then recovered by a series of heat exchangers connected to a boiler. The efficiency of the reactor is directly related to the maximum and minimum temperatures in the system, as temperature is the driving force in the heat exchange process.

3.4.1.1. Moisture and Composition

The energy available in the materials to combust has to be quantified. However, there are some differences in the way this calorific value is reported. To identify them, energy measurements can be reported in several ways:

- *Dry Basis High Heating Value (HHV)* – A sample has its moisture removed (the sample is heated up to 105ºC until its weight is stable. The difference in weight is the Moisture). Next, the dry sample is combusted until it cools again and reaches room temperature. As the final temperature of the sample is below 100ºC the water produced in the combustion reaction will be liquid in its final state. This means that the latent heat of vaporization of the water produced by the combustion, a significant amount of energy required to change the state of water from liquid to vapor, is included in this heat value.

This calorific value is the highest amount reported compared to the rest, and usually is the one reported in the US, Canada and the UK. (Liu & Liptak, 2000)

- *Low Heating Value as received (LHV)* – The sample is combusted as received: its moisture is not removed prior to this measurement. Also, the measurement ends at a temperature higher than 100ºC. Then, the moisture and the water produced in the final state are vapor. This value is lower than the HHV and is more practical in terms of the combustion in a WTE plant, as the final temperature of the exhaust gases in the process will be above 100ºC. This is true for most power plants.

These heat values can also be approximated if the chemical composition and moisture of the sample is known.(Liu & Liptak, 2000; Pichtel, 2014)

3.4.1.2. Air Balance

Air is an important variable as it is one of the reagents in the chemical reaction: air will provide the oxygen the combustion reaction needs. However, the amount of air that is fed to the reaction is important. One would like to include enough excess air for most of the combustion to take place, but not so much that the combustion energy is lost heating this excess air. The minimum amount needed to convert all elements to their oxidized states is the stoichiometric amount. This can be calculated assuming that all organic elements are oxidized to CO_2, H_2O, SO_2 and NO.

However, using the stoichiometric air value is theoretical and using this amount of oxygen will not lead to a complete combustion, as the combustion will be limited by the oxygen mass transfer to the waste materials. To help a complete combustion, an excess amount of air is always used. An estimated 50% to 100% excess air is often used in grate mass burn processes, so equipment should be sized for a 100% excess air. The CFB process however, as it improves the contact area and thus the combustion efficiency, excess air can be reduced to approximately 30-40%, thus reducing the air blower equipment size, cyclone or other particle separation equipment and losses in efficiency due to heat loss in the exhaust air.

In a moving grate reactor, the air required for the combustion of the MSW is injected into the furnace from different sources. In moving grates, 50% to 70% of the air is injected from bottom of the reactor and the remaining amount is injected from above.(Klinghoffer & Castaldi, 2013)

3.5. Reactor design and operation control for CFBs

2 CFB reactors are analyzed: the Strömberg Coal reactor and the Zhejiang University CFB WTE reactor. Differences and similarities are underscored to help understand its operation.

In both reactors, a low particle speed is required in the bottom part of the reactor to increase residence time.

3.5.1. Coal CFB

A coal combustion CFB reactor was studied as described by Stromberg (1987). This process combusts coal particles with 0.1-0.5 mm diameter.

The reactor has 2 parts:

- A bottom section, which is 2 times wider than the reactor (so to provide 2x the cross sectional area). This allows for a lower air speed to increase the residence time in this section. This serves several purposes: mixing, sub-stoichiometric combustion, dynamic dampener. Primary air distribution is injected from the bottom into valves that don't allow backflow of particles.
- Above the bottom section, the vertical reactor is enclosed with cooled walls (in this case, pipes with vertical fins). There is a secondary air intake just in the connection between the bottom and the reactor sections. The mean air speed in the reactor is recommended to be between 5 and 10 m/s, using 30% excess air. Pressure drop is around 3 kPa. The reactor top is a slightly rounded 90 degree bend that connects with the particle separation sections.

The particle separation is a critical step, as particles are carried over continuously and are circulated. This requires a series of particle separation techniques listed below.

- After the reactor a 1 stage of fixed mechanical non-centrifugal type of separator is included such as U beams. Air flow has to cross in a zig-zag trajectory encountering resistance and walls. The particles impact these walls and fall into a particle storage section. These can be 1 or 2 particle separators, the second one is inclined 60º or more to avoid particle buildup, and are adjacent to the reactor as they share a wall to make a more compact design. Separated particles then fall to a storage section.

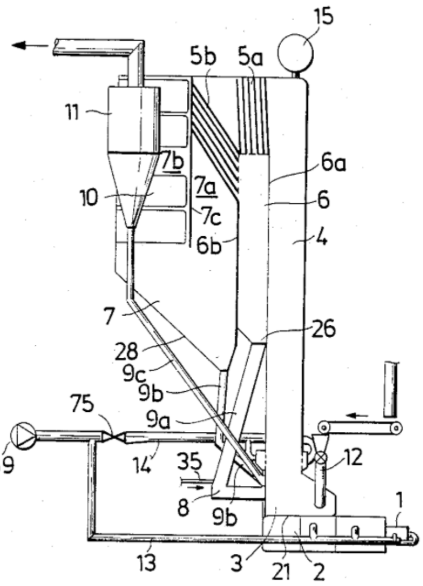

Figure 34 - Drawing of the Strömberg CFB process (Stromberg, 1987)

- A U shaped settling chamber with cooled walls follows slowing down flow, recovering particles and reducing temperature. The upflow passageway has a heat exchanger. The chamber bottom, where particles are collected, is connected to the bottom section of the reactor.

- A high efficiency cyclone follows afterwards, where the temperature is now lower than 250ºC. The cyclone bottom, where particles are collected, is connected to the bottom chamber of the reactor.

- The particle storage section is important as a large volume of solids is accumulated here. According to Stromberg (1987), with a 1 ton loading in the reactor, an approximate 500 kg of particle storage is required. The walls of the storage are also cooled for heat recovery. The bottom of the storage is a distributor plate with holes for the fluidization of the particles. The air required is only 0.2% of the main air supply. The ashes can also be drained from this chamber.

- The particle circulation is a crucial part of the reactor. It is one of the 2 main controlling variables, the second one being the fuel introduction to the reactor. This is controlled by an L-valve, called after its shape. It is connected from the top to the particle storage chamber and in the bottom leg to the bottom chamber of the reactor. To control the flow of particles an air supply valve is connected slightly above the elbow of the L. The feedback control for his valve may be linked to the pressure of the boiler or to a bed temperature sensor inside the bottom chamber. This control scheme allows for flexibility in the fuel type used, as the recirculation rate can be regulated accordingly without additional changes to the boiler or fuel intake.

3.6. Zhejiang University CFB

The CFB process for Zhejiang University shown in Figure 35 is slightly different than the Strömberg design, as this has been specifically designed for MSW.

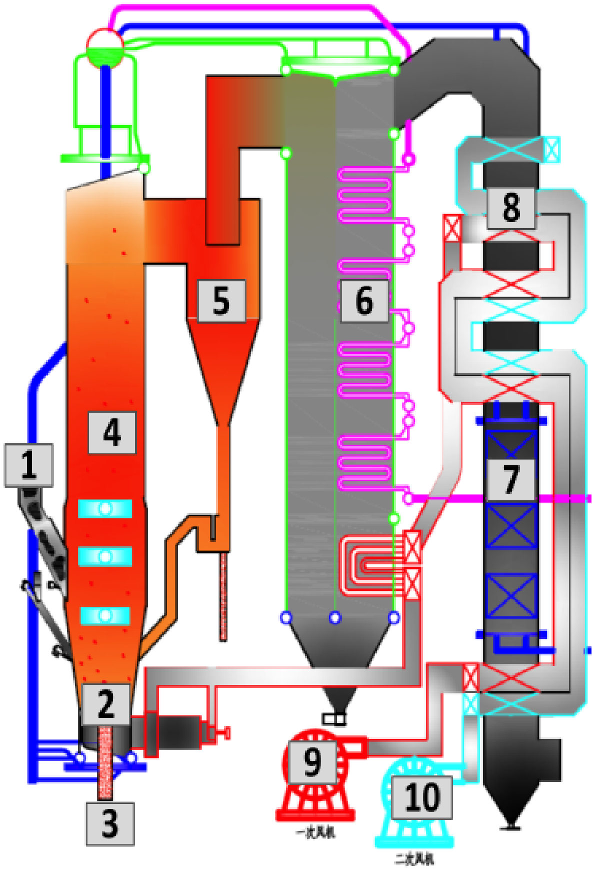

Figure 35 - Process Diagram for the Zhejiang University CFB (Qunxing Huang et al., 2013; Jiang, 2013)

A reactor with a smaller bottom section (2) is used. The bottom of the reactor operates as a bubbling bed reactor, where the larger, heavier, non-combusted particles and ash remain. This bed is useful as it has a high thermal inertia, which helps the waste inflow to mix, heat up and evaporate its moisture. It also has a longer residence time within the reactor, helping the waste to completely combust. This allows for a more uniform temperature control.

The reactor (4) operates between 850°C and 950°C (Jiang, 2013). Above the reactor, the primary particle separation technology is a cyclone (5), which separates the particles from the flue gases through a centrifugal force and circulates these solids back to the reactor. The control valve in the bottom of the cyclone is a J-valve.

Below the reactor there is an ash circulation system (3), which separates the larger particles of the bottom ash to be quenched with water and discarded. The rest are circulated back into the reactor.

The U shaped settling chamber is located after the cyclone, which makes an additional particulate collection followed by an air preheater (8), superheaters for the boiler (6) and an economizer (7). The intake of air is pre-heated in 2 stages: the first with the excess heat from the flue gases (8); second in the first stage of the superheater section, allowing a 450ºC air temperature at the intake of the reactor.

It is important to note that no auxiliary fuel is used for the continuous operation of this CFB WTE plant, even though the Chinese MSW is high in moisture and low in heat content.(Jiang, 2013)

4. Pre-Feasibility Analysis of a Mexico CFB WTE Plant

After reviewing the current status of Mexico City's waste management and the different technologies available for WTE plants, a specific analysis of heat content, precedents and a financial perspective is detailed in this section.

4.1. Advantages of using Waste to Energy

Despite landfilling remains the most widely used method for after-recycling waste disposal because of its lower cost, there are several clear disadvantages that this landfilling produces:

- Emissions of GHG and pollutants to the atmosphere
- Landfill fires
- Water lixiviate production
- Low or no material recovery
- Health risks
- Costs of operation after landfill is closed
- Property devaluation with proximity to the landfill
- Space availability

In Mexico City, several cases have been seen just in the last few months (Jimenez Jacinto, 2014) (NOTIMEX, 2014) where the current landfills have been temporarily closed due to noncompliance with the local or environmental laws. These problems are common with landfills and create additional complications for the local governments and their citizens.

Waste-to-Energy facilities provide several clear advantages when compared to landfilling, analyzed in this section. Lower GHG emissions to the environment, energy recovery and material recovery are a few of the benefits of using WTE.

4.2. WTE Precedents in Mexico

Mexico City installed a pilot MSW incinerator plant in 1992, but it was closed soon after, as it did not meet the emission requirements. Other studies have been made. The EEC studied the case of Toluca for a WTE plant. However, with the lower amount of waste generated in that city as well as a higher investment cost of the technology, the plant was not financially viable. Landfill Gas to Energy is already been done in several places with good results. MSW co-processing in CEMEX plants has had mixed results due to complaints from the public.

4.2.1. Landfill Gas to Energy

Mexico already has a number of projects using the biogas from landfills for energy recovery, which is higher in the waste management hierarchy than sanitary landfilling with or without CH_4 flaring. A noteworthy example of the use of LGTE in Mexico is the Metropolitan Zone of Monterrey. A public organism, separate from the state's government called SIMEPRODE (Solid Waste Processing Metropolitan System) is the main administrator of the waste management. This organism manages the cleaning, waste collection and final disposition of the city, coordinating the labor. Monterrey pioneered the WTE in Mexico and installed in 2003 the first project in the country and in Latin America for biogas capture from a landfill for electricity generation. The project initially generated 7.4 MW of electricity, and it increased its capacity in 2008 to 12.7 MW. Currently is seeking a 3rd increase to 16.24 MW.(BENLESA, 2013)

The project had financial support from the World Bank as part of a set of Carbon Offset projects, to achieve a reduction of 3,000,000 tons of CO_2eq by 2015.(The World Bank, 2012) It has obtained positive results, however electricity generation has not been as large as expected as shown in Figure 36:

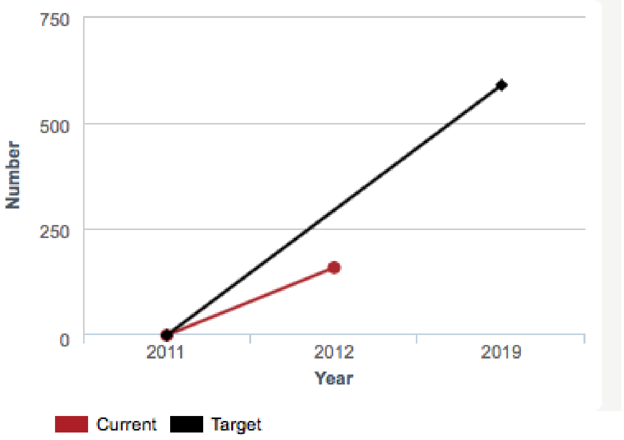

Figure 36 - Estimated electricity generated and exported to the grid (GWh) (The World Bank, 2012)

Following the successful startup of the first project, additional projects have been executed for biogas capture from landfills in Mexico. By 2006 there were more than 1,100 gas recovery projects worldwide plus 4 recently executed projects in Mexico: Monterrey, Guadalajara, Leon, Saltillo, and Mexico City.

4.2.2. MSW Co-processing in the Cement Industry

As we know, with correct combustion conditions MSW can be used as a heat source. Heat intensive industries, such as cement manufacturing, can use this heat to substitute the use of fossil fuels, which can have a large impact as cement manufacturing accounts for 5% of all GHG emissions. Using MSW as a fuel also provides the additional advantage of reducing the burden on MSW management systems and landfilling.

Jiao Zhang (2013) and the EEC have already studied the energy, environmental and greenhouse gas effects of using alternative fuels, such as MSW in cement production. this co-processing and published a MS. Thesis with this research.

CEMEX, the largest cement manufacturer in Mexico and one of the largest in the world, signed a contract with Mexico City's government to purchase sorted MSW, transport it and use it as fuel for their cement manufacturing facilities in neighboring plants: Huichapan in the State of Hidalgo, and Tepeaca in the State of Puebla.

In Huichapan plant however, there were complaints about smells and health effects on the neighboring population supposedly related to the co-combustion of MSW in the plant (Cruz Sánchez, 2013). This caused major uproar in the neighboring town, which got support from anti-incineration groups. The result was a change in the state legislation banning solid waste and special waste incineration within the state. (GOBIERNO DEL ESTADO DE HIDALGO, 2009) This resulted in all waste going to Huichapan being redirected to Tepeaca plant, in Puebla.

This case is important as it may set a precedent on WTE, as the then Governor for the State of Hidalgo is now State Secretary for the country. For following projects in the cement industry and WTE, information sharing with the government and the communities with up to date information about WTE will be a requirement to avoid this kind of confrontations.

4.3. Evaluating Using Waste as a Fuel

A useful reference guide from the World Bank established a framework to determine the viability of using waste as a fuel, shown in Figure 37:

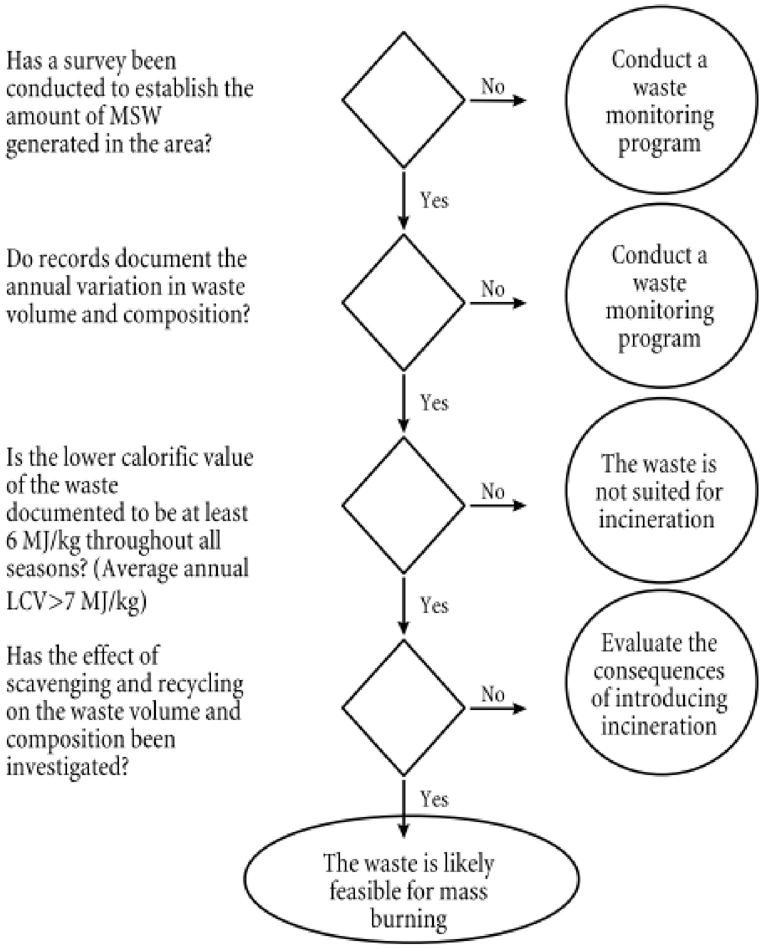

Figure 37 - Assessment of Waste as a Fuel (Rand et al., 2000)

4.3.1.1. Conduct a Waste Monitoring Program

The government of Mexico D.F. is required by law to provide a yearly inventory of the MSW generation, treatment and its disposal. This analysis has been available since 2006, and has been published every two years. This data has proven to provide a great deal of information to evaluate the current state of waste management and improvements.

The inventory report includes a flow diagram with estimations of the waste stages from its generation, collection, transport, sorting, and final disposition. Still, this flow diagram needs improvement, as the sources and sinks of the wastes do not match. A large amount of waste now pre-sorted and collected by scavengers at the collection truck. This pre-scavenging accounts for more than 38% of the estimated waste generation and the final disposition of this fraction of the waste is not reported in this study. The most probable scenario is that all the waste collected is recyclable material, sold to private recycling businesses.

4.3.1.2. Waste volume and composition

Using the monthly data from the transfer stations in Mexico D.F. in 2012 we can assess variations on the volume of waste generated throughout the year. After calculating the average amount of waste received per day in each month, the lowest amount collected was in April: 7,174 tons/day, and the maximum was in August: 8,345 tons/day. Studying the seasonality of the waste, in Figure 38 we can observe that in the summer a higher amount of waste is generated, peaking in August and reaching a low in January, increasing back again. In this year, the waste generated in April was lower than March and May, changing the overall trend. We would have to study if this is the case in other years.

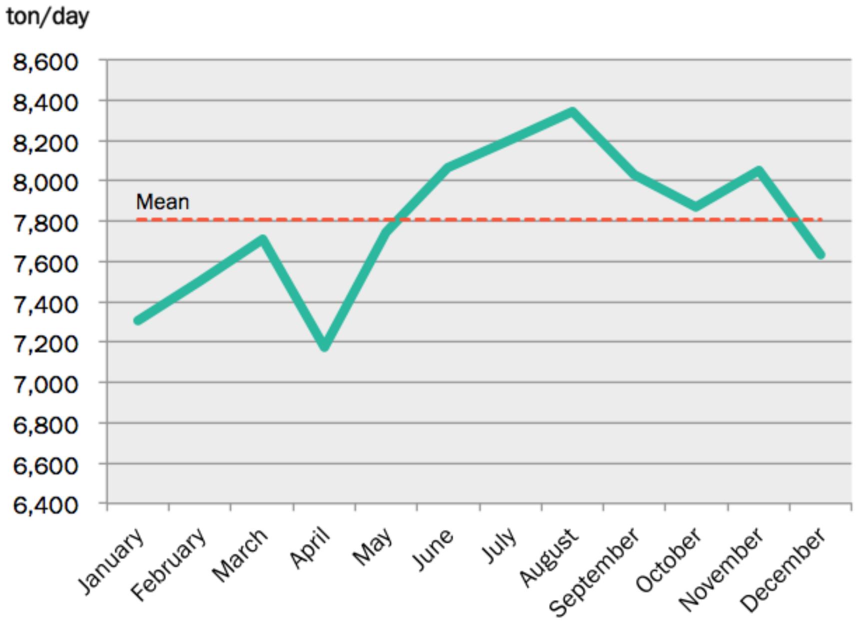

Figure 38 - Monthly variations of the waste received at Transfer Stations in Mexico D.F. (Data from: Secretaría del Medio Ambiente del Distrito Federal, 2012)

The waste amount does not vary significantly from the mean, as it was 8% lower in April and 7% higher in August. As a result, one can expect a steady flow of MSW throughout the year, allowing a secure fuel supply for a WTE plant.

It is important to note that this data accounts only for the D.F.. The information for the State of Mexico's neighboring municipalities is not available with this amount of detail, but the urban areas surrounding the D.F. are expected to have a similar generation pattern and an amount of waste equivalent or larger than Mexico D.F., as there is a higher population in the metropolitan area than in the D.F. itself.

4.3.1.3. Calorific value suitability

Waste combustion obtains its energy from organic combustible material. The amount of combustible organic matter as well as of moisture, ashes, metals and glass contents determines the heat value of the waste. As stated by Moreno *et al*, 2013, the LHV of the MSW in Mexico was determined to be 6.7 MJ/kg. This is lower than the recommended threshold of the World Bank, which is 7.0 MJ/kg in yearly average and never lower than 6.0 MJ/kg. However, a more thorough analysis was done as the quality of waste is lower than expected from a medium GDP/capita city. This is addressed in a section afterwards.

Other calculations using Tchobanglous Handbook data and the composition of the waste from Mexico City lead to a calorific value of 9.5 MJ/kg and 9.2 MJ/kg, depending on the composition used as shown on Table 8 and Table 9.

Table 8 – Heating value (calculation using MSW composition from Moreno et al (2013))

Material	**Percentage in MSW (Moreno *et al, 2013*)**	**Heating Value (Tchobanoglous, 2002)**	**Contribution to Calorific Value (MJ/kg)**
Organic wastes	49.5%	4.6	2.3
Paper and cardboard	9.9%	15.6	1.5
Wood	0.5%	15.4	0.1
Plastics	13.2%	32.4	4.3
Textiles	3.6%	18.4	0.7
Glass	2.7%	0.0	0.0
Metals	1.5%	0.0	0.0
Sanitary waste	10.8%	4.0	0.4
Construction material	1.9%	0.0	0.0
Fines	0.8%	4.0	0.0
Other	4.2%	4.0	0.2
Special waste	1.4%	0.0	0.0
Hazardous waste	0.2%	0.0	0.0
Total	**100.0%**		**9.5**

Table 9 – Heating value (calculation using MSW composition from Arvizu (2006))

Material	Percentage in MSW (Arvizu, *2006)*	Heating Value (Tchobanoglous, 2002)	Contribution to Calorific Value (MJ/kg)
Organic wastes	40%	4.6	1.8
Paper and cardboard	20%	15.6	3.1
Textiles	1%	17.4	0.2
Plastics	11%	32.4	3.6
Glass	11%	0.0	0.0
Ferrous metal	2%	0.0	0.0
Non Ferrous metal	2%	0.0	0.0
Others	13%	4.0	0.5
Total	**100.0%**		**9.2**

4.3.1.4. Effect of scavenging on the waste volume

There is a high presence of informal recycling in Mexico City and throughout the country, from the collection routes, the MRFs and the landfills. The introduction of a WTE plant will probably reduce part of the income that these informal workers obtain with the recovery of materials, as landfills will receive less MSW. This labor issue will have to be addressed helping introduce a more formal and structured approach to recover recyclables, while offering a better and safer working environment.

Also, by removing some of the recyclable plastics, there will probably be a reduction in the heat value. There is also another opportunity to increase the heat value, which is the removal of moist organic contents in the waste, as Mexico City already has separate collection of the organic and inorganic wastes. This would separate food and green waste into composting plants, which is higher in the waste management hierarchy.

In Table 10 and Table 11 a scenario to calculate the heating value of an MSW stream with high composting and recycling is evaluated.

Table 10 - Scenario with high composting and recycling

Activity	Diversion amount
Composting	50.0%
Recycling metals	40.0%
Recycling paper & carton	50%
Recycling plastic	50.0%

Table 11 - Heat value calculation with a high composting and recycling scenario (calculated)

Material	MSW High compost and recycling scenario	Heating Value (Tchobanoglous Handbook)	Contribution to Calorific Value (MJ/kg)
Organic wastes	39.2%	4.6	1.8
Paper and cardboard	7.9%	15.6	1.2
Wood	1%	15.4	0.1
Plastics	10.4%	32.4	3.4
Textiles	5.8%	18.4	1.1
Glass	4.2%	0.0	0.0
Metals	1.4%	0.0	0.0
Sanitary waste	17.1%	4.0	0.7
Construction material	3.0%	0.0	0.0
Fines	1.3%	4.0	0.1
Other	6.6%	4.0	0.3
Special waste	2.2%	0.0	0.0
Hazardous waste	0.3%	0.0	0.0
Total	**100.0%**		**8.6**

The results show a lower heating value as high calorific plastic and paper were reduced. However, the result obtained, 8.6 MJ/kg, is still within the recommended values from the World Bank.

4.3.2. Projected WTE Power Plant Costs

According to Kaplan(S. Kaplan, 2009), the factors that drive power plant costs through their building and operation are:

1. Government Incentives
2. Capital costs, including construction costs and financing
3. Fuel costs / Operating costs
4. Air emissions control

4.3.2.1. Government Incentives

Mexico's government offers a series of incentives to promote renewable energy generation. There is an investment tax accelerated depreciation, which allows for the investment in equipment and machinery to be depreciated in the first year of operation, counting there is enough taxable income. If this is not the case, the depreciation can be done in the following years.

4.3.2.2. Capital Costs

WTE plants can be very expensive. According to the EEC plants usually cost between 500 USD to 1,000 USD per ton of annual capacity, depending on its total capacity and location. Capital costs of a WTE plant include:

- Land plot
- Plant construction
- Equipment purchase – some of it can be imported (moving grates, shredders)
- Services – electric tie up to the grid
- Other Infrastructure

However, the CFB process has had a lower capital intensity compared to traditional moving grate plants. The experience from plants in China has shown a possible 200-300 USD/ton of capacity, however this has to be benchmarked further to ensure a proper comparison is made. (Qiu, 2012)

4.3.2.3. Financing costs

The major cost element of WTE facilities is the repayment of the capital costs so financing is critical for the project's viability. In Mexico, the government can offer financing to renewable energies with debt to projects in operation or construction maxed at 25% of the total of the project.(SENER, 2012) This offers an advantage vs. other financial sources as the government takes part of the risk of the project. This makes debt a low interest financing. Other resources such as long time debt sales in the stock market, or custom support are available for evaluation by the NAFIN (National Financing organism in Mexico). Funding through the World Bank, German Development Bank KfW, and IFC are also available.

4.3.2.4. Operating Costs

Based on the WTE Guidebook (Themelis et al., 2013), the operating costs are between US$32/ton for a 1,000,000 ton plant and US$47 USD/ton for a 160,000 ton plant. This depends on the size of the plant, decreasing the costs as the plant size increases. A US$35/ton value will be used for the calculation of the NPV of the project.

Operating costs include ash disposal, chemicals, gas cleaning, maintenance and other miscellaneous costs, personnel, a 5% contingency fund and insurance.

4.4. Plant Capacity

To size the WTE plant for Mexico City, a review of current waste trends was done. In 2012, still 44% of the MSW was landfilled, which was 2,245,000 ton (6,151 ton/day). To allow for improvements in recycling and composting, which would reduce the amount landfilled eventually, the plant capacity was established at 700,800 tons/year. The plant would be made up of 3 x 800 ton/day units operating at 80% plant availability. This plant would reduce by 30% the amount of waste landfilled, still leaving much space for further improvements in recycling and materials recovery to reduce landfilling.

4.5. Plant Location

The recommended area to build the WTE plant is in the location of the previous Bordo Poniente landfill. There are several reasons for this selection:

- Access to waste collection routes
- Proximity to the city and roads
- Large area available
- It currently houses the Bordo Poniente composting plant

According to the Guidebook for the Application of WTE Technologies in Latin America and the Caribbean (Themelis et al., 2013), a WTE plant for a capacity of 960,000 tons/year, similar to the one we are studying in this document, requires a land area of 460 x 250 meters (115,000 m^2). For size reference, this was marked in the aerial view of Bordo Poniente Landfill in Figure 39. The location of the plant within the landfill site is only a proposal based on the proximity to roads but could also be situated in a different place within the perimeter. However, the plant location is close to the Benito Juarez International Airport, seen on the lower corner of Figure 39. This interaction may be worth to review, as there may be aerial norms on building and smokestack heights that could restrict the building of the plant.

This site selection should be evaluated with city planning as other development plans for the same area may conflict with this plan.

Figure 39 - Possible size and location of WTE plant inside the Bordo Poniente Landfill area (Google & DigitalGlobe, 2014)

The location of the WTE plant should also plan to get the best calorific quality of waste within the region to try to maximize the energy recovery. Also, there could be an opportunity to choose which areas should supply the plant, as only 700,000 tons will be used in the plant from the 2,245,000 tons of MSW each year that get landfilled. Based on the work from Moreno *et al,* 2013, the transfer stations that have the highest calorific content in the city are the ones shown in Figure 40:

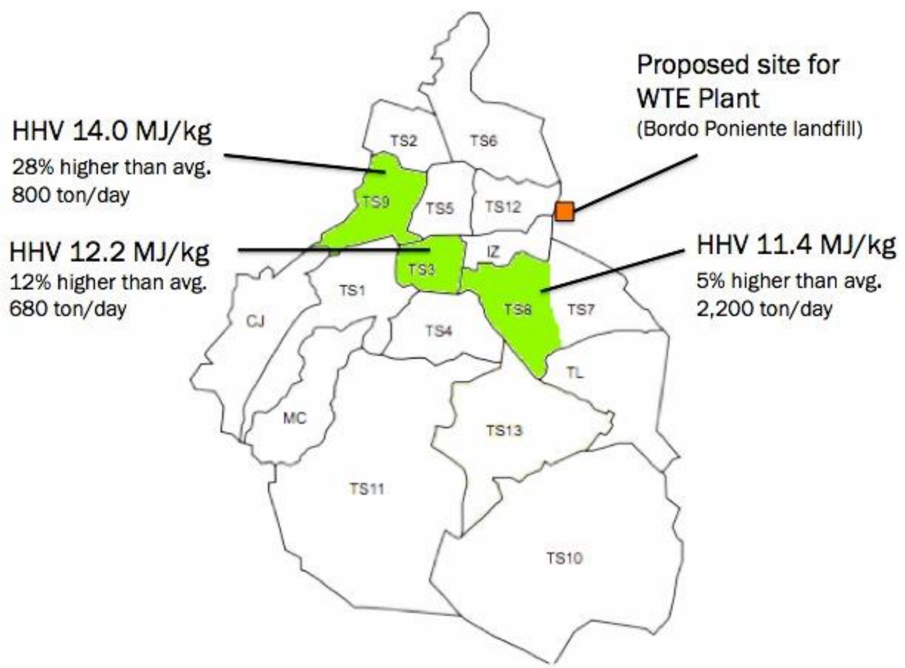

Figure 40 - Proposed transfer stations, HHV and MSW produced to supply MSW to WTE plant. Data from (Moreno et al., 2013; Secretaría del Medio Ambiente del Distrito Federal, 2012)

4.6. Capital Investment Estimation

One of the most important benefits that the CFB reactor would have over the moving grate technology is the lower capital cost, as this is the main cost involving a WTE plant investment and operation.

To address the capital cost estimation, we contacted Zhejiang University’s Dr. Quinxing Huang to provide a cost estimation on the cost of the plant provided their experience on the WTE plants that have been built in China using Zhejiang University’s engineering design and process. In a private communication, Dr. Huang form Zhejiang University in Hangzhou, China, shared a +/- 30% Capital estimate of 125 million USD for the proposed 2,400 ton/day Mexico City plant (Table 12). This leads to a 52,000 USD/daily ton estimated with all equipment and labor in installed in China. (Quinxing Huang, Estrada, & Themelis, 2014)

Table 12 - Cost and capacity data for CFB WTE Plant

CFB Plant – Cost in China		
800 ton/day x 3 units	2,400	ton/day
300 days operation per year	700,800	ton/year
Plant availability	80%	plant availability
Estimated cost of plant (in China)	125	Million USD
Cost per annual ton of capacity	174	USD/annual ton

The steam production characteristics are 60 ton/h at 3.89 MPa, 400ºC providing a 20% electric efficiency.

The calorific value waste scenarios (Table 13), the electricity generation was escalated maintaining the electric efficiency. The remaining capital costs were maintained equal for this analysis.

Table 13 - Calorific value and electricity generation scenarios

	Low LHV	Mid LHV	High LHV	
LHV	6.7	8.5	9.5	MJ/kg
MSW capacity per line	800	800	800	ton/day per line (3 lines)
Total heat content of fuel	62.0	78.7	88.0	MW - total heat content
Electric Efficiency	20%	20%	20%	Electric efficiency
Electricity generation per line	12.4	15.7	17.6	MW
Total electricity generation	37.2	47.2	52.8	MW
Electricity generation per ton	372	472	527.8	kWh/ton

Compared to previous case studies done by the EEC, similar kWh/ton values were obtained as with the High LHV (9.5 MJ/kg) scenario. The results of this study are compared with previous case studies from the WTE Guidebook in Annex 1 - IDB Latinamerica WTE Guidebook case study comparison.

4.6.1. Cost Estimate Analysis

As the source for the cost estimate was provided in China, a useful comparison can be done to other WTE plants in China. In Figure 41 several WTE plants were plot using data from Ling Qiu (2012).

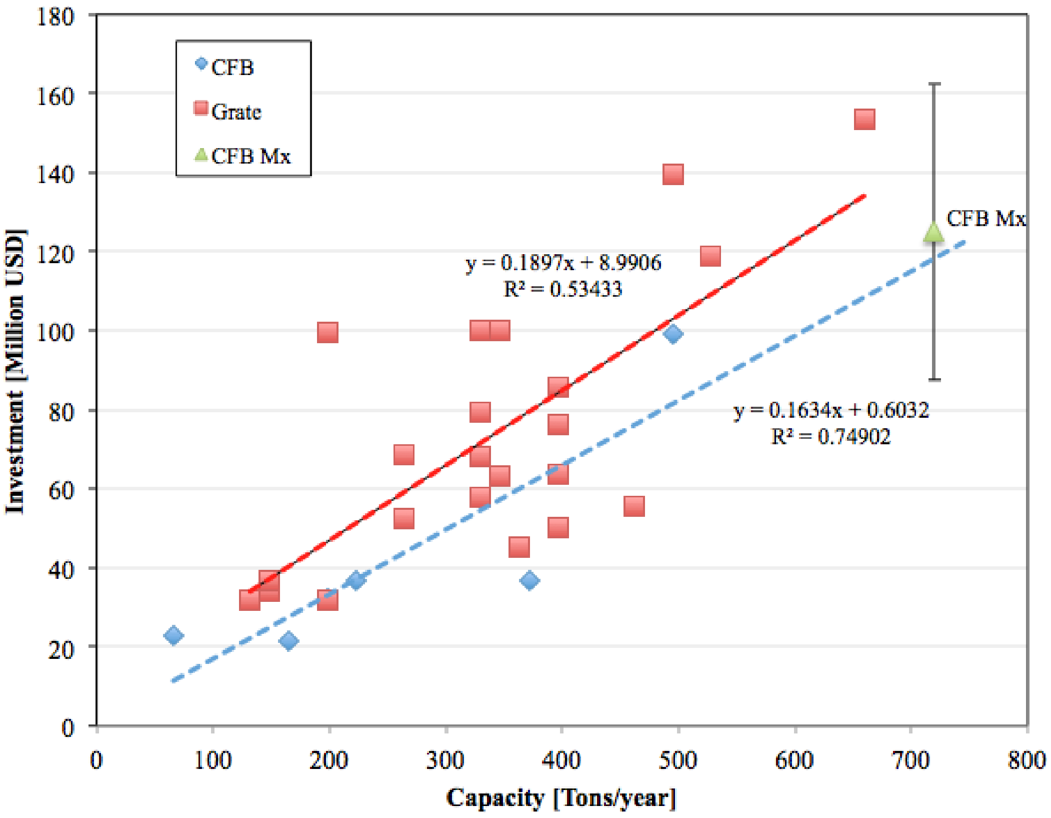

Figure 41 - Plant Capacity (thousand tons/year) vs. Capital Investment (million USD) in China. Data: (Qiu, 2012)

From Figure 41, we can see two trends of capital intensity. Comparing the mass burn technology vs. the CFB process, the average cost per ton is significantly lower using CFB.

The proposed data points are all from new China WTE facilities. Inflation effects due to different startup years for the plants were not included. The technologies used in the Chinese plants are varied and include imported Martin Grates, Belgium multistage grates, USA pulsed grate furnaces, Japanese EBARA CFB technologies; as well as local CFB and moving grate technologies.

The data from Qiu however should be detailed further with the complete scope of the plant, as there are several plants with the same capacity, technology, and different cost. Some of them are only projects for expansion of an existing plant while some are greenfield projects.

4.6.1.1. Cost estimate adaptation from China to Mexico

Cost changes depending on the country a project is installed due to several factors:

- Price of building materials
- Price of labor

- Skill of labor
- Freight and taxes for imported equipment
- Exchange rate

The cost estimation for this stage of the project will follow a conservative approach: the cost in China will be escalated an additional 50% to allow for cost increases in labor, materials, transportation and import taxes on equipment as the plant will be installed in Mexico. Also the transfer of technology and support for the construction and installation has to be included in the cost and startup estimates. This detail will have to be developed in further estimates as the project moves along.

The original estimate in China was US $125 million. Multiplied by a factor of 1.5 and rounding, the cost in Mexico used to evaluate the project at this stage will be US $185 million.

4.6.2. Projected WTE Plant Revenues

The WTE plant can have several sources of revenue. The main source for this plant will be the sale of electricity followed by the gate fee. The main assumptions for number are listed below:

- A 90 USD/MWh price for the electricity sales
- Electricity generation using a MSW calorific value of 9.5 MJ/kg.
- Gate fee of 20 USD/ton

The rationale for these assumptions is explained in the following section.

4.6.2.1. Electricity pricing

In the recent months the country moved to an open electricity market, the electricity price will then have some variability. Previously, the state owned CFE had the monopoly of the electricity market from generation and transmission to sales. According to a Levelized Cost of Electricity (LCOE) analysis done by CFE, the cost for their electricity generation varies significantly between technologies as seen in Table 14. The cost figures include investment cost, fuel, operations and management, and water for each technology. The % of total generation is an approximation of the real value, as private parties generation for auto-consumption is included which may not reflect the same cost structure of CFE. However, Table 14 provides a ballpark estimate for the costs of electricity in Mexico and their prices. This was used to calculate a weighted average electricity production price to use for the financial analysis.

Table 14 - LCOE for different technologies and a weighted average cost. Calculated with data for costs from CFE (2012) and % Generation from CIDAC (2013)

Technology	LCOE USD/MWh	Average LCOE USD/MWh	% of Total Generation	Share of Cost
Combined Cycle Natural Gas	55 - 68	61.5	45.10%	27.7
Coal thermoelectric	66 - 71	68.5	6.80%	4.7
Geothermal	70 - 118	94	2.20%	2.1
Nuclear	91	91	3.40%	3.1
Hydroelectric	58 - 123	90.5	12%	10.9
Conventional thermoelectric	121 - 160	140.5	23.50%	33.0
Turbo industrial natural gas	118 - 145	131.5	6.20%	8.2
Turbo natural gas	151 - 162	156.5	-	-
Internal combustion	145 - 173	159	0.10%	0.2
Wind	75 - 86	80.5	0.70%	0.6
Solar PV	190	190	0.00%	0.0
Turbogas aeroderived diesel	252	252	-	-
Weighted average USD/MWh				90.3

Another important source of information for electricity pricing are tariffs. In Table 15 the tariffs for industrial and residential users are shown, for Mexico, the US and the OECD average. Industrial tariffs in Mexico are significantly higher than the US and the OECD average. Also for residential users, electricity tariffs are higher than for US users, though lower than the OECD average. However, it is important to note that the residential tariffs in Mexico are subsidized: tariffs for industrial users help pay for the subsidies for residential users.

Table 15 - Electricity tariffs in Mexico, United States and OECD Average (CIDAC, 2013)

Country	2011	2012	2011	2012
Electricity Tariff	Industrial (USD/MWh)		Residential (USD/MWh)	
Mexico	175.2	180.5	145*	142*
United States	68.2	67.0	117	119
OECD Average	118.1	125	163	165

*The residential tariff in Mexico is subsidized.

The costs of electricity are subject to be reduced as the use of natural gas for electricity generation increases. Natural gas pipelines are currently being built across the country to help supply this fuel to power plants and substitute the use of fuel oil, which accounts for 18% of electricity production, and is more expensive and polluting.

After the review of costs and tariffs of electricity in Mexico, a $90/MWh electricity price can be considered a conservative assumption for electricity sales. A sensitivity analysis was also done to study the financial impacts of a lower or higher electricity price.

4.6.2.2. Gate Fee

The gate fee objective for this plant was set with the current waste management costs of Mexico City. As mentioned previously in this study, the average cost of final disposal of solid waste in the Federal District is $15.05 USD/ton. However, there is additional spending on the transportation of the MSW to the landfills, which are located 20 or more miles away of Mexico City. The average cost of transportation from the transfer stations to the landfills is $8.86 USD/ton. Together, the cost of hauling and final disposal of waste is $23.91 USD/ton (Figure 42).

Figure 42 - Transportation and final disposal costs for Mexico City (Calculated with data from Secretaría de Obras y Servicios del Distrito Federal, 2014) Exchange rate used: $13.5 MXN/USD

With the WTE plant, the transportation costs will be reduced due to several reasons:

- The WTE plant will be closer to the TSs, so the travel distance will be more than 50% shorter. Also, the garbage trucks could deliver the waste directly to the WTE plant, reducing even more the cost.
- The waste amount is reduced by 90% in volume (70% in weight).

We are assuming that these factors will help reduce in more than half the costs of the transportation. So, a total cost of transportation and disposal of $20 USD/ton for the gate fee will be similar to the current waste disposal fees of the City. The cost for the disposal of the ash is already included in the operations

4.6.2.3. Other Assumptions

Other assumptions that also contribute to the WTE plant financial analysis are:

Ferrous metal recovery – 50% of the metal will be recovered and sold at a price of US$100/ton

Aluminum recovery – With an eddy current non-ferrous metal separator, approximately 8% of the metal can be recovered. The assumption is that they will be sold at a price of US$1,500/ton. Total recovery of both ferrous and non-ferrous metals yields an income of 590,000 USD/year.

Carbon credits – The United Nations Framework Convention on Climate Change allows for developed countries to fund carbon emissions reduction projects in a developing country. This resource requires the use of a Clean Development Mechanism. These carbon credits are included in the assumption of the financials of the project as WTE helps reduce the emission of CO_2 and methane from landfills and also from the combustion of fossil fuels to generate electricity. "One ton of MSW combusted rather than landfilled results in decreasing carbon emissions by 0.5 to 1 ton of carbon dioxide, depending on the efficiency of landfill gas collection."(Themelis et al., 2013)

These credits are assumed to yield an income of US$3.8 million/year, with a price of carbon of $10.8 US/ton of CO_2. These assumptions were similar to the ones used by the Guidebook for the application of WTE technologies in Latin America.

4.7. Financial sensitivity analysis

With the assumptions mentioned previously, a Net Present Value analysis model was run for the construction and operation of the CFB WTE plant in Mexico City. The construction of the plant will be executed in 2 years, with 30% of the capital expenditure in the first year and 70% expenditure in the second year. The startup of the plant will occur in year zero and the plant will operate 20 years with 80% plant capacity factor, meaning that it will run 80% of the 365 days of the year.

The base assumption discount rate is 5%, which would be a low interest rate loan, available for government projects. Higher discount rates would be used for a private enterprise or a public-private partnership. A sensitivity analysis for higher discount rates is shown in Table 16.

Table 16 – NPV analysis varying the discount rate (calculated)

Discount rate	5%	10%	15%
NPV (million USD)	153.8	42.0	-12.8
IRR	13.5%		

Disregarding the discount rate and using the Internal Rate of Return, the results shown in Figure 43 and Table 17 are obtained doing a sensitivity analysis on the calorific value of the waste and the electricity prices:

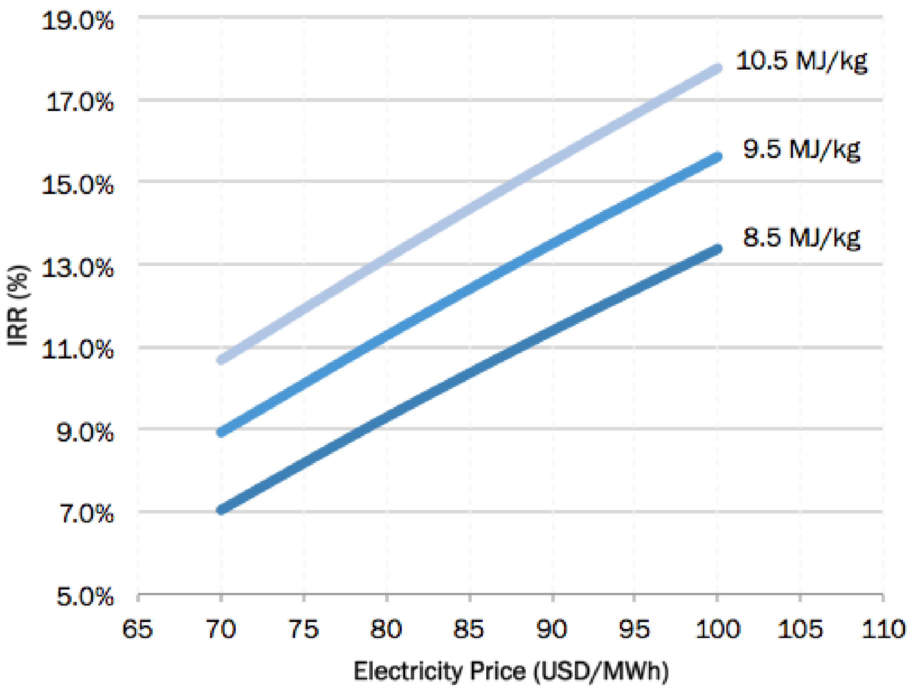

Figure 43 - IRR Sensitivity analysis varying electricity prices and MSW calorific value (calculated)

Table 17 – IRR Sensitivity analysis varying electricity prices and MSW calorific value (calculated)

IRR (%)		Electricity Price (USD/MWh)			
		70	**80**	**90**	**100**
Heat Value (MJ/kg)	**8.5**	7.0%	9.3%	11.4%	13.4%
	9.5	8.9%	11.3%	13.5%	15.6%
	10.5	10.7%	13.2%	15.5%	17.8%

The results show that even with an electricity price of US $70 and a heat value of 8.5 MJ/kg, the plant would break even at a 7% rate of return. This being the worst scenario studied here. However, the best scenario in case of a higher heat value and a higher electricity price, the IRR would reach 17.8%, which would yield a profit with a more expensive capital.

5. Conclusions and further work

Waste generation in Mexico is growing at 3.3% per year, as the economy is expanding and population is increasing. As in other areas of the world, cities are growing at a faster pace than rural areas. The waste management sector has improved significantly since the beginning of this century, moving from unregulated dumps to sanitary landfills in most of the country, even though small cities and rural communities still mostly use dumps rather than sanitary landfills.

Mexico city has improved much more in response to its main landfill closing. Landfilling decreased from 93% to 44% of the total, yielding to informal recycling and composting. Composting, aided by source separation of food and green wastes, now treats nearly half of the organic fraction of the waste and 17% of the total MSW reaching the City. The largest composting plant is located within the city, which reduces transportation, and its operation costs are lower than landfilling. Proven its success, it may be expanded to use a larger share of the organic compounds to generate compost. Challenges to continue having a good source separation should continue to be addressed, sharing the good news with the population. The sale and use of the larger production of compost are still to be resolved. However, it is proven to be a high quality product meeting the required standards.

Recycling is still mainly informal, however, more than half of the paper and carton is currently recycled. PET plastic collection from bottles, led by private parties, is also in a good shape, recovering 60% of the bottles. Attention should be put to expand to other types of plastic and to improve the conditions of the informal workers.

Waste to Energy is currently being used by cement manufacturers, in specific CEMEX, to reduce their use of fossil fuels. However, there has been citizen opposition in one of the two CEMEX production plants, Huichapan, leading to all MSW being directed to Puebla's plant, further away from the City. The state of Hidalgo, where the Huichapan plant is located, as a result banned waste incineration in the state.

As for the technologies used for WTE, using Moving Grates is the most widely used technology across the world. However, China, with great experience using CFB for coal combustion, has developed in the past 30 years the CFB for WTE, using moist and lower energy content MSW. The technology has worked well and now almost half of the Chinese WTE capacity uses CFB reactors. The technology is inherently less capital intensive than MG due to a smaller reactor.

The Zhejiang University CFB design has key design improvements: the use of LSHT shredders and their location in the refuse pit has allowed the pretreatment without high investment on a new area dedicated to this activity. Additionally, energy efficiency of the plant is industry average, approximately 20%, and air pollution controls allow emissions to meet EU standards.

Evaluating a 700,800 ton/year WTE project for Mexico City, the plant would reduce landfilling by 30% of the 2012 value. This would allow for further improvements in recycling and composting in the future, without reducing the availability of MSW for the energy plant.

The heating value of the MSW was calculated at 9.5 MJ/kg, however other sources were also studied and a sensitivity analysis was performed to evaluate how this value impacts the profitability of the project. This value is critical and needs to be studied with actual samples throughout a year in the feasibility stage of the project.

The Guidebook for WTE in Latin America and the Caribbean was used as a guide for the pre-feasibility analysis, using as a reference previous case studies. The capital cost for the plant was estimated with information from Zhejiang University, with an additional 50% as a location factor, totaling US $185 million installed in Mexico City. Financially, after the capital cost, the most important assumptions are the price of electricity and the gate fee. The gate fee of US $20 was estimated after reviewing the current costs of the City in disposal and transportation in a survey to the government. The electricity price of US$ 90 was estimated based on current cost of production of the electricity plants in Mexico and the prices to the final users. Also, a sensitivity analysis was done to evaluate the financial impact due to changes in these assumptions.

The WTE plant has an IRR of 13.5% and a positive NPV with a 5%-10% discount rate. Financing options have to be detailed in the feasibility stage of the project.

Overall, the lower capital cost of the CFB WTE technology, with adequate pricing for gate fees and electricity makes this a profitable project, which could improve the waste management in Mexico City and lead WTE introduction in the country.

6. References

Arvizu Fernandez, J. L. (2010). La basura como recurso energético. Situación actual y prospectiva en México. *Ingeniería Civil*, (496). Retrieved from http://www.iie.org.mx/boletin012011/inves.pdf

Barron Santos, F. (2013). *Optimización del Proceso de Composta Producida a partir de la Fracción Orgánica de los Residuos Sólidos Urbanos que se Generan en la Ciudad de México*. Centro Interdisciplinario de Investigaciones y Estudios sobre Medio Ambiente y Desarrollo (CIIEMAD), Instituto Politecnico Nacional (IPN).

BENLESA. (2013). Monterrey III: Proyecto de ampliación de generación de energía eléctrica a través de la basura.

Beta Analytic. (2014). Radiocarbon dating: An introduction. Retrieved November 25, 2014, from http://www.radiocarbon.com/about-carbon-dating.htm

CFE. (2012). *Costos y Parámetros de Referencia para Formulación de Proyectos de Inversión del Sector Eléctrico* (p. 4.9). Retrieved from http://www.iadb.org/projectDocument.cfm?id=38271058

CIDAC. (2013). *Luz a la Competitividad Nacional - Propuesta de Reforma al Sector Eléctrico Mexicano* (p. 18). Retrieved from http://cidac.org/esp/uploads/1/Luz_a_la_Competitividad_-_Reforma_al_sector_electrico-_Final180813.pdf

Consejo Nacional de Población. (2013). Delimitación de las Zonas Metropolitanas de México 2010. Retrieved July 25, 2014, from http://www.conapo.gob.mx/es/CONAPO/Zonas_metropolitanas_2010

Cruz Sánchez, A. (2013, May 14). Incinerador de Cemex provoca afecciones en 30% de habitantes de Huichapan, Hidalgo. *La Jornada*. Pachuca, Hidalgo. Retrieved from http://www.jornada.unam.mx/2013/05/14/estados/032n1est

Diario Oficial de la Federación. Ley General de Cambio Climático. , Pub. L. No. DOF 07-05-2014 (2012). Mexico. Retrieved from http://www.inecc.gob.mx/descargas/2012_lgcc.pdf

ECOCE. (2014). Datos Estadísticos. Retrieved from http://ecoce.mx/informacion/datos-estadisticos-2/

EIA. (2014). Mexico - Country Analysis. Retrieved September 08, 2014, from http://www.eia.gov/countries/country-data.cfm?fips=MX

Fernandez, E. (2012, February 8). Edomex paga $210 por tonelada de basura en El Milagro. *El Universal*. Ixtapaluca. Retrieved from http://movil.eluniversaledomex.mx/otros/nota27244.html

Fitzgerald, G. C., & Themelis, N. J. (2009). *Technical and Economic Analysis of Pre-Shredding Municipal Solid Wastes Prior to Disposal*. Columbia University in the City of New York.

Gaviota, M., Pérez, V., & Themelis, A. N. J. (2011). GENERATION AND DISPOSITION OF MSW IN MEXICO AND POTENTIAL.

Geldart, D. (1973). Types of gas fluidization. *Powder Technology*. doi:10.1016/0032-5910(73)80037-3

GOBIERNO DEL ESTADO DE HIDALGO. QUE ADICIONA LA FRACCIÓN XXXI BIS AL ARTÍCULO 4 Y UN ARTÍCULO 133 BIS A LA LEY PARA LA PROTECCIÓN AL AMBIENTE DEL ESTADO DE HIDALGO. (2009). Hidalgo. Retrieved from http://intranet.e-hidalgo.gob.mx/NormatecaE/Archivos/DECRETO_269.pdf

Google, & DigitalGlobe. (2014). Bordo Poniente Satellite View. *2/22/2013*.

Gutierrez Avedoy, V., Ramirez Hernandez, I. F., Encarnación Aguilar, G., & Medina Arévalo, A. (2012). *Diagnóstico Básico para la Gestión Integral de los Residuos Sólidos 2012*. (INECC, Ed.) (1st ed., p. 200). Mexico.

Hodzic, A., Wiedinmyer, C., Salcedo, D., & Jimenez, J. L. (2012). Impact of Trash Burning on Air Quality in Mexico City.

Huang, Q., Chi, Y., & Estrada, A. (2014). WTERT 2014 Bi-annual meeting. In *Rapid growth of CFB WTE technology in China*. New York, NY, USA. Retrieved from http://www.seas.columbia.edu/earth/wtert/meet2014/Proceedings/presentations/Huang_Estrada.pdf

Huang, Q., Chi, Y., & Themelis, N. J. (2013). A Rapidly Emerging WTE Technology : Circulating Fluid Bed Combustion. In *Proceedings of International Thermal Treatment Technologies (IT3) San Antonio, TX*. Retrieved from http://www.seas.columbia.edu/earth/wtert/sofos/Rapid_Emerging_Tech_CFB.pdf

Huang, Q., Estrada, A., & Themelis, N. J. (2014). *Private communication with Dr. Huang*.

Instituto Nacional de Ecología. (2007). Residuos sólidos urbanos. Retrieved June 25, 2014, from http://www2.inecc.gob.mx/publicaciones/libros/495/residuos.html

Jiang, X. (2013). International Conference on Applied Energy. In *Design and application of a A 800T/D circulating fluidized bed incinerator for firing pure low heating value chinese MSW*. Pretoria, South Africa.

Jimenez Jacinto, R. (2014, May 21). Cierran relleno sanitario en Naucalpan. *El Universal*. Mexico. Retrieved from http://www.eluniversal.com.mx/ciudad-metropoli/2014/clausura-propaem-relleno-sanitario-en-naucalpan-1011906.html

Kaplan, P. O., Decarolis, J., & Thorneloe, S. (2009). Is it better to burn or bury waste for clean electricity generation? *Environmental Science & Technology*, *43*(6), 1711–7. Retrieved from http://www.ncbi.nlm.nih.gov/pubmed/19368161

Kaplan, S. (2009). *Energy Policies, Politics and Prices : Power Plant Characteristics and Costs*. New York, NY, USA: Nova Science Publishers, Inc. Retrieved from http://site.ebrary.com/lib/columbia/docDetail.action?docID=10661686

Klinghoffer, N. B., & Castaldi, M. J. (2013). *Waste to Energy Conversion Technology*. (N. B. Klinghoffer & M. J. Castaldi, Eds.). Woodhead Publishing Limited.

Kunii, D., & Levenspiel, O. (1997). Circulating fluidized-bed reactors, *52*(15), 2471–2482.

Liu, D. H., & Liptak, B. (2000). *Hazardous Waste and Solid Waste*. (C. Press, Ed.). Lewis Publishers.

Moreno, A. D., Rodríguez, M. G., Velasco, A. R., Carlos, J., Enriquez, M., Lara, R. G., … Hernández, D. (2013). MEXICO CITY'S MUNICIPAL SOLID WASTE CHARACTERISTICS AND COMPOSITION ANALYSIS. *Revista Internacional de Contaminación Ambiental*, *29*(1), 39–46. Retrieved from http://www.scielo.org.mx/scielo.php?pid=S0188-49992013000100004&script=sci_arttext

NOTIMEX. (2014, March 9). Clausuran relleno sanitario en Tepotzotlán. Mexico. Retrieved from http://www.centinela.mx/nota/7948/edomex/clausuran-relleno-sanitario-en-tepotzotlan.html

O'Hern, T. J., Trujillo, S. M., Torczynski, J. R., Tortora, P. R., Oelfke, J. B., & Bhusarapu, S. (2006). *Circulating Fluidized Bed Hydrodynamics Experiments for the Multiphase Fluid Dynamics Research Consortium (MFDRC)*. Albuquerque, New Mexico. Retrieved from http://prod.sandia.gov/techlib/access-control.cgi/2006/064914.pdf

Pichtel, J. (2014). *Waste Management Practices: Municipal, Hazardous and Industrial*. CRC Press. Retrieved from http://dx.doi.org/10.1201/b16576-7

Qiu, L. (2012). *PART I : ANALYSIS OF THE ECONOMICS OF WASTE-TO-ENERGY PLANTS IN CHINA PART II : MSW SORTING MODELS IN CHINA AND POTENTIAL FOR IMPROVEMENT*. Columbia University in the City of New York.

Rand, T., Haukohl, J., & Marxen, U. (2000). Municipal solid waste incineration: a decision maker's guide. *Municipal Solid Waste Incineration: …*. Retrieved from http://bases.bireme.br/cgi-bin/wxislind.exe/iah/online/?IsisScript=iah/iah.xis&src=google&base=REPIDISCA&lang=p&nextAction=lnk&exprSearch=32702&indexSearch=ID

Reinhart, D. R., & Basel Al-Yousfi, a. (1996). The Impact of Leachate Recirculation On Municipal Solid Waste Landfill Operating Characteristics. *Waste Management & Research*, *14*(4), 337–346. doi:10.1177/0734242X9601400402

Secretaría de Desarrollo Urbano y Ecología, & Departamento del Distrito Federal. (1992). *NORMA MEXICANA NMX-AA-61-1985*. Retrieved from http://legismex.mty.itesm.mx/normas/aa/aa061.pdf

Secretaría de Energía. (2012). *Estrategia Nacional de Energía 2012 - 2026*.

Secretaría de Energía. (2013). *Balance Nacional de Energía 2012*. Retrieved from http://sener.gob.mx/res/PE_y_DT/pub/2012/Balance Nacional de Energia 2012 (Vf).pdf

Secretaría de Medio Ambiente y Recursos Naturales. (2013). *Inventario Nacional de Emisiones de Gases de Efecto Invernadero 1990-2010*.

Secretaría de Obras y Servicios del Distrito Federal. (2014). *Public Inquiry*.

Secretaría del Medio Ambiente del Distrito Federal. (2006). *Inventario de Residuos Sólidos del Distrito Federal 2006*. Retrieved from http://www.sma.df.gob.mx/rsolidos/inventario_residuos_solidos.pdf

Secretaría del Medio Ambiente del Distrito Federal. (2007). *Inventario de Residuos Sólidos del Distrito Federal*. Distrito Federal.

Secretaría del Medio Ambiente del Distrito Federal. (2010). *Inventario de Residuos Sólidos del Distrito Federal 2010*.

Secretaría del Medio Ambiente del Distrito Federal. (2012). *Inventario de Residuos Sólidos del Distrito Federal*.

SEMARNAT. (2014a). Base de Datos Estadísticos - Badesniarn. Retrieved September 06, 2014, from http://www.semarnat.gob.mx/temas/estadisticas-ambientales/badesniar?De=SNIARN

SEMARNAT. (2014b). Guia de diseño para el manejo integral de los residuos sólidos urbanos. Retrieved from http://www.semarnat.gob.mx/archivosanteriores/temas/residuos/solidos/Documents/guia-diseno.pdf

SENER. (2012). Incentivos y Financiamiento. Retrieved August 25, 2014, from http://www.renovables.gob.mx/portal/Default.aspx?id=1660&lang=1

Stromberg, L. A. (1987). Fast Fluidized Bed Boiler and a Method of Controlling Such Boiler.

Tavares, G., Zsigraiova, Z., Semiao, V., & Carvalho, M. G. (2009). Optimisation of MSW collection routes for minimum fuel consumption using 3D GIS modelling. *Waste Management (New York, N.Y.)*, *29*(3), 1176–85. doi:10.1016/j.wasman.2008.07.013

Tchobanoglous, G., & Kreith, F. (2002). *Handbook of Solid Waste Management* (Second Edi.). McGraw-Hill.

The World Bank. (2012). Mexico: Waste Management and Carbon Offset Project. Retrieved August 06, 2014, from http://www.worldbank.org/projects/P088546/mexico-waste-management-carbon-offset-project?lang=en

The World Bank. (2014a). Data. Retrieved from http://data.worldbank.org

The World Bank. (2014b). Urban population (% of total). Retrieved July 28, 2014, from http://data.worldbank.org/indicator/SP.URB.TOTL.IN.ZS

Themelis, N. J., Elena, M., Barriga, D., Estevez, P., & Velasco, M. G. (2013). *GUIDEBOOK FOR APPLICATION OF WTE IN LATIN AMERICA* (p. 1–228).

Van Haaren, R. (2009). *Large scale aerobic composting of source separated organic wastes: Environmental impacts, costs, and contextual effects.*. Retrieved from http://www.seas.columbia.edu/earth/wtert/sofos/haaren_thesis.pdf

Vehlow, J. (2012). Reduction of dioxin emissions from thermal waste treatment plants: a brief survey. *Reviews in Environmental Science and Bio/Technology*, *11*(4), 393–405. doi:10.1007/s11157-012-9296-5

Yue, G. X., Yang, H. R., Lu, J. F., & Zhang, H. (2010). Latest development of CFB boilers in China. In *Proc. 20th International Conference on Fluidized Bed Combustion*.

Zhang, J., & Themelis, N. J. (2013). *Energy, environmental and greenhouse gas effects of using alternative fuels in cement production*. Columbia Univeristy in the City of New York.

6.1. Annex 1 - IDB Latinamerica WTE Guidebook case study comparison

	Reference Guidebook for WTE Case Studies (Themelis et al., 2013)				
	Valparaiso, Chile	Buenos Aires, Argentina	Toluca, Mexico	Mexico City, Mexico	Comments for Mexico City case
Pop. (Millions)	1	9.9	0.82	8.9	
GDP per capita, USD (Country data)	15,732	14,725	10,307	10,307	World bank, 2013
GDP per capita, PPP, USD 2011 (Country data)	21,714	N/A	16,290	16,290	World bank, 2013
MSW generation per capita tons/year	0.38	0.3	0.36	0.55	
Total MSW tons /year	380,000	2,970,000	295,000	4,650,100	
MSW Recycled & composted tons/year	20,000	70,000	68,000	1,786,675	Includes informal recycling and composting
MSW LHV MJ/kg	9.4	10.3	10	9.5	
Landfilled MSW, tons/year	360,000	2,900,000	227,000	2,250,000	
WTE plant capacity, tons/day	1,000	3000	480	2,400	
WTE plant annual capacity, tons/year	336,000	990,000	158,000	700,800	80% Plant capacity factor
Electricity production, kWh/ton MSW	540	600	600	530	20% electricity efficiency
Electricity to the grid, MWh/year	182,000	600,000	96,000	370,000	
Electricity price, US$/MWh	90	102	62	90	Estimate based on LCOE analysis and industrial tariff rates
WTE plant annual capacity, tons/year	336,000	990,000	158,000	700,800	
CAPEX, US$ million	225	600	120	185	Cost estimate is 1.5 times Chinese cost
CAPEX, US$/ton MSW	670	595	750	264	
OPEX, US$ million	13.1	32	7.6	25	
OPEX , US$/ton MSW	39	31.8	47.5	35	Estimate based on Guidebook
Current gate fee, US$/ton MSW	14	20	13	20	Estimate based on final disposal and transportation offset
Electricity revenue, US$/ton MSW	46	61	37.2	47.7	
Recovered metal, US$/ton MSW	3.9	0.96	0.93	0.85	
Carbon Credits, US$/ton MSW	5	7.7	5	5	

6.2. Annex 2 – NPV analysis

Table 18 – NPV and IRR analysis assumptions and results

Discount rate	10.0	%
Plant capital cost	(184,000,000)	$
USD per ton of capacity	263	USD/ton
Operating cost	35	USD/ton
Tons per year	700,800	tons/year
Gate fee	20	USD/ton
Electricity sales	380,000	MWh/year
Price of electricity	90	$/MWh
Ferrous metal recovery (50%)	3,504	tons/year
Price of ferrous metal	100	USD/ton
Aluminum recovery (8%)	163	tons/year
Price of aluminum	1500	USD/ton
CO2 emission reduction	0.5	ton CO2/ton MSW
Price of carbon	10.0	USD/ton CO2
Metal recovery	0.85	USD/ton

NPV (USD)	41,999,398
IRR	13.50%

Table 19 - Yearly balance for financial analysis

	Construction	Startup						
Year	-2	-1	0	1	2	3	4	5
Plant Construction	(55,200,000)	(128,800,000)						
Operation costs			(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)
Gate Fee			14,016,000	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000
Electricity Sales			34,200,000	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000
Metal sales			594,278	594,278	594,278	594,278	594,278	594,278
Carbon credits			3,506,803	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803
Total	(55,200,000)	(128,800,000)	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082

Year	6	7	8	9	10	11	12	13
Plant Construction								
Operation costs	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)
Gate Fee	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000
Electricity Sales	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000
Metal sales	594,278	594,278	594,278	594,278	594,278	594,278	594,278	594,278
Carbon credits	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803
Total	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082

Year	14	15	16	17	18	19	20
Plant Construction							
Operation costs	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)	(24,528,000)
Gate Fee	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000	14,016,000
Electricity Sales	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000	34,200,000
Metal sales	594,278	594,278	594,278	594,278	594,278	594,278	594,278
Carbon credits	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803	3,506,803
Total	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082	27,789,082

6.3. Annex 3 – Air requirement calculations

The MSW has a very heterogeneous composition, but if averaged over the days of the year, the chemical formula is surprisingly homogeneous. For mass balance calculations in combustion, one can assume that the waste is mainly one hydrocarbon molecule averaging the composition of the combustible wastes. For Mexico city, Moreno et al measured the composition of MSW in Mexico city and found a chemical formula of $C_{7,125}H_{22,066}O_{938}N_{309}S$. (Moreno et al., 2013)

Element	wt. dry	MW	Moles
C	0.612	12	5.10E-02
H	0.154	1	1.54E-01
O	0.0745	16	4.66E-03
N	0.0292	14	2.09E-03
S	0.0002	32	6.25E-06
Ash	0.1301		

Table 20 - Waste composition in weight % and moles

After calculating the moles, one can calculate the amount of oxygen needed to complete the following theoretical reactions:

$C + O_2 \rightarrow CO_2$ $2H + \frac{1}{2}O_2 \rightarrow H_2O$ $N + \frac{1}{2}O_2 \rightarrow NO$ $S + O_2 \rightarrow SO_2$

Oxygen content in the waste is assumed to react and provide oxygen for the combustion reaction, so the amount of oxygen is subtracted from the oxygen content in the air. Once calculating the stoichiometric oxygen amount, the amount of air can be calculated by multiplying this factor by 4.32.

The calculation results are listed in Table 21:

Table 21 - Stoichiometric air calculation requirement

Reaction	O_2 moles	O_2 mass	Air mass	
CO_2	0.051	1.632	7.05	
H_2O	0.0385	1.232	5.32	
O_2	-0.002	-0.075	-0.32	
NO	0.001	0.033	0.14	
SO_2	0	0.0002	0.00	
Total		**2.82**	**12.20**	kg/kg of waste