OPTIMIZING SUSTAINABLE WASTE MANAGEMENT

IN SHENZHEN, CHINA

Part I: Short Term - Advancing the Collection and Segregation Processes

Part II: Long Term - Increasing the Recycling Rate and Advancing the Quality of Post-recycling Waste

By

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Optimizing Sustainable Waste Management in Shenzhen, China

EXECUTIVE SUMMARY

The rapid economic development and urbanization in China during the last few decades have brought municipal solid waste (MSW) management problems to prominence in all cities. Megacities like Beijing and Shenzhen had once faced garbage and open dumpsites surrounding the urban area. As the cost of urban and suburban land turned unaffordable for landfilling, the central government and municipalities started to support and enforce the development of MSW treatment facilities, especially by means of waste-to-energy (WTE) plants. In 2017, over 250 WTE plants were in operation in China, treating approximately 38% of the overall collected MSW.[1]

As the development of WTE technologies matures and sufficient capacity of treatment plants was established, additional facilities on top of the existing resources are looked into. Opportunities of existing WTE plants or cement plant plus pre-treatment facilities, such as Material Recovery Facilities (MRF) or Mechanical Biological Treatment (MBT) plants, are reliable in magnifying treatment capacity and gain recovered material at lower capital costs than building more WTE plants. Policies that provide incentives for waste synergy projects, for example, simple MRF and cement plant, have started to gain wide adoption.

This thesis includes preliminary financial and environmental analysis of WTE plants, cement plants, and pre-treatment facilities (MRF or MBT) combination options in Shenzhen, China. The target WTE plant is the Shenzhen East WTE plant, which will be the largest WTE plant in the world, starting at the end of 2018 and treating 5,000 tons (t) per day. The target cement plant is China Resource Shenzhen Cement Plant which China Resource has successfully operated using waste-derived fuels in Guangxi Province. All scenarios show that the combined plants are capable of providing promisingly high financial returns via material recovery or bottom ash recovery, biogas and electricity generation, and gate fee revenues. The use of MRF with either existing WTE or cement plants is more profitable than the MBT process. due to significantly lower capital cost and high material recovery return. When the WTE plant operates with no pre-treatment facility but including bottom ash recovery technology, it is more profitable even at though it has a higher capital cost. However, all the profit scenarios must rely on a stable electricity price and secondary market, as electricity and recovered material sales are the largest two revenue sources. Moreover, the environmental benefits are significant and have a compound effect in the long run. Also, all the materials-energy combination options can conserve land and abate millions of tons of greenhouse gases, by diverting waste from landfills.

In the long run, public recognition and participation are crucial to moving from landfill to WTE upward to composting and the 3Rs (reduce, recycle, reuse) in the sustainable waste management hierarchy. Also, the government must consider including the informal recyclers to the formal sector as the residents are familiar with these recycling professionals over the years. Ways of inclusion can be employed as waste sorters at pre-treatment facilities, waste managers in the housing estates for regulation compliance, and providing informal recyclers with uniforms and equipment that connect them with the communities. Only in this way, implementing both short-term and long-term action plans, the goal of attaining proper waste segregation and 35%

recycling rate; both of which require public participation that can be achieved within the next few decades, thus moving towards the entire society to the circular economy and sustainable waste management.

Acknowledgements

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Acronyms

MSW	Municipal Solid Waste
WTE	Waste-to-Energy
MRF	Material Recovery Facility
MBT	Mechanical Biological Treatment
t	tons/ton (note: tonnes is kept as tonnes)
LHV	Low Heating Value
HHV	High Heating Value
WEEE	Waste of Electric and Electronic Equipment
GHG	Greenhouse Gas
MC	Ministry of Construction
MEP	Ministry of Environmental Protection
MHURD	Ministry of Housing and Urban-Rural Development
RW	Restaurant Waste
EP	Environmental Park
RDF	Refused Derived Fuel
CFB	Circulating Fluidized Bed
APC	Air Pollution Control
NIMBY	Not-in-my-backyard
AD	Anaerobic Digestion
CLO	Compost-like Output
BOT	Build-Operate-Transfer
SZE	Shenzhen East

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1. Introduction

China has gone through unprecedented development for the past two decades. As the nation with the most population in the world with 191.4 million t of MSW generation, sustainable waste management becomes crucial in order to maintain the quality of life for the citizens in the long run.[1] Fast urbanization process has once contributed to the problem "cities besieged by garbage" in several megacities in China such as Beijing, Shanghai, and Shenzhen.[2] The Central Committee of China has been foreseeing and proactively remediating the MSW problems with "Five-Year Plans", "One Belt One Road" initiative, and many megacities environmental policy supports. In order to meet the short-term waste management goals that are set by the national, provincial, and municipality levels, MSW treatment facilities must be developed to achieve qualitative and quantitative requirements.

Shenzhen, as one of the first cities to achieve "zero waste to landfill" by the end of 2020 (the end of the 13th Five-Year Environmental Protection Plan), is proactively implementing programs and regulations to achieve a recycling rate of 35%.[3] The 11 million citizens of Shenzhen generated 5.7 million t of MSW, i.e. 0.51 t per capita, in 2016 and showed an increase of at least 6.1% per year.[4] A sufficient number of treatment plants have either built or under construction in Shenzhen, and the largest WTE plant in the world will be in operation starting 2019.

The aim of this Thesis is to assess the economic and environmental benefits of advancing the quality of the post-recycled MSW in Shenzhen for materials and energy recovery. A prevailing technique is to increase the low heating value (LHV) of the MSW that can be either disposed of in WTE plants or used as alternative fuel in the cement industry (short term target). In addition, the opportunities to integrate the informal recyclers to the formal recycling system and to educate the public for the benefits of recycling and sustainable waste management as a long-term target, are discussed. Two scenarios of mechanical treatment plants are examined: MBT and MRF. The post-recycled MSW produced is either combusted for the production of energy in WTE plants that use techniques for the recovery of resources from the WTE residues; or is used as an alternative fuel in the cement industry. The baseline scenario is sanitary landfilling of the post-recycled MSW.

Public participation is the key to achieve sustainable waste management, along with the political will and the development of sustainable infrastructure. As many studies and experience shown, to achieve circular economy, which promotes using disposed material as the raw material. It requires material recovery and separating different disposed material at source. In this way, the recyclable material is kept from further contamination before collection and it can be recovered in higher quality, which is used as the supply material for manufacturing. Enforcing regulation implementation and public participation are required to make efficient resource recovery plan to take place. Instead of the current one-bin collection in multifamily residential dwelling in urban areas, at least a two-bin system, “dry” and “other/wet”, should be in practice by the public through educational campaigns. The “dry” bin is referred to recyclables collection, i.e. Aluminum, glass, paper, etc.; while the ‘wet’ bin refers to the collection of food, yard and kitchen waste.

During curbside and residential community collection and transportation phase, the informal recycling sector plays a crucial role in keeping more recyclables from the MSW feedstock to the WTE plants. Similar to many other developing countries, China has a long history with the informal recycling driven by the market, since far before waste became a problem. Many Chinese municipalities, especially in the megacities, already have regulated the system to manage the recyclable collection chain from the door-to-door self-employed collectors to material recovery corporations. The recyclables collections include both the residential waste and the waste of electric and electronic equipment (WEEE). However, in order to promote a safe, resourceful, and manageable entity for the self-employed collectors and street scavengers, it is essential to engage both government supports and public recognition towards these groups. An enhanced integration between informal and formal recycling sectors improves the solid waste management with a more organized employee body and feedback system to track recycling situation at the source.

Raising public awareness and sectors integration can take a long time as some European countries used decades to increase their recycling rate. The goal of waste management in Shenzhen has been recognized as ambitious and exemplary to the whole country or even to other developing countries. Regulative and technological applications examined in this paper can be considered for Shenzhen and even other municipalities to meet goals of sustainable waste management.

2. Aim and Objectives

In Part I, by looking into the current WTE and cement industry development in Shenzhen, the aim is to recommend potential combinations of mechanical treatment facilities with the existing resources and facilities. The results consist of quantified economic and environmental benefits in term of maximizing energy recovery to further achieve sustainable waste management and circular economy.

Specific objectives are to:

- Identify the status of current waste-to-energy plants and cement plants in Shenzhen.
- Identify the status of current successful waste recovery facilities (MRF and MBT).
- Characterize the world's largest WTE plant, Shenzhen East, and identify the economic and environmental benefits of the plant with an MRF or MBT facility to pre-treat the waste as compared to having the WTE plant only.
- Characterize the China Resource cement plant in Shenzhen, and identify the economic and environmental benefits with of using an Alternative fuel recovered by the MRF or MBT.
- Compare the five scenarios with sanitary landfilling as a baseline.

The aim of Part II is to identify the environmental, economic and legal weaknesses of the current waste management model. Policy recommendations in solid waste reduction and recycling for the case of Shenzhen, China, are discussed.

Specific objectives are to:

- Analyze the urban waste management policy of China and Shenzhen.
- Characterize the collection and transportation system of the solid waste streams.
- Evaluate the contribution of the informal recyclers to the recycling and segregation targets.
- Propose ways for the safe inclusion of the informal recycling to the formal recycling system.

3. Demographics and Waste Management Policy in China

3.1. Economic Level

Since the 1980s as Chinese markets and industries have started to reform and open up to foreign investments, people's living standards have drastically improved through urbanization. In China, the GDP per capita has grown from ¥385 ($58) in 1978 to approximately ¥50,000 ($7,540) in 2015.[5] As a representative example, Shenzhen turned into a megacity with thousands of skyscrapers, the center of worldwide fashion and technology hub, and a financial and cultural melting pot in less than 15 years of development from a fishing village.

Alongside with all the development, solid waste disposal and treatment problems in the cities swiftly arose due to high population concentration and consumption upsurge.[6] China generates MSW at a higher rate comparing to other Asian countries, while 70% of the MSW is generated in China from the East Asia and Pacific region. In 2004, China topped the U.S.A. as the largest world waste generator.[7] In 2016, a total of 191 million t of solid waste has collected and transported in China.[1] The cities only managed to reach around 90% collection rate.[8] A large amount of waste that is likely more than the collected amount has left uncollected and untreated in the rural areas and some urban areas in China. Many cities are facing the problem of besieged by waste or no land to dispose of the waste due to expensive land.[9] A total of 640 landfill sites are in China, treating 344 million t each year.[1]

3.2. Policy Level

Mandated by the Five-Year Environmental Protection Plan, China has taken smart moves since the beginning of the 21st century in waste management and constantly and vastly invested in building WTE plants right outside of the major cities along the east coast. WTE technology significantly preserves land use, reduce waste out-coming, and cut down air pollution and greenhouse gas (GHG) emission from landfilling. In 2015, 220 WTE plants were in operation in China with a capacity of incinerating 219,080 t of MSW a day.[1] Additionally, many unsanitary landfilling sites and open dumpsites are gradually closed out and the waste is treated as sanitary landfill or directly delivered to WTE plants. In general, 94.1% of the MSW is treated, and 97.6% of the treated MSW is through landfilling or WTE.[1] The world largest WTE plant is being built in Shenzhen and expect to run by the end of 2018, and it will treat one-third of the MSW with a capacity of 5,000 t/day.[10] The total capacity will be required to deal with the overall quantity of waste disposal in China is sufficient and reliable, especially in the cities.

3.3. Waste Management Policy Framework in China

Development and environmental protection are the two main drivers of framing waste management policies in China. Usually, the central committees set the general goals and directions of MSW management in the plan for the upcoming years, then waste management departments in national, state, and municipality levels are responsible for executing and achieving the goals by obliging the environmental protection laws.

Ministry of Construction (MC) and Ministry of Environmental Protection (MEP) take charge of administering, supervising, and monitoring the entire process of waste generation from cleaning, collection, storage, transportation, to final disposal.[11] There are at least seven additional ministries involving in the MSW management. Figure 1 shows the different responsibilities and functions carried by the ministries and organizations. Note the Ministry of Housing and Urban-Rural Development (MHURD) is a department under MC.

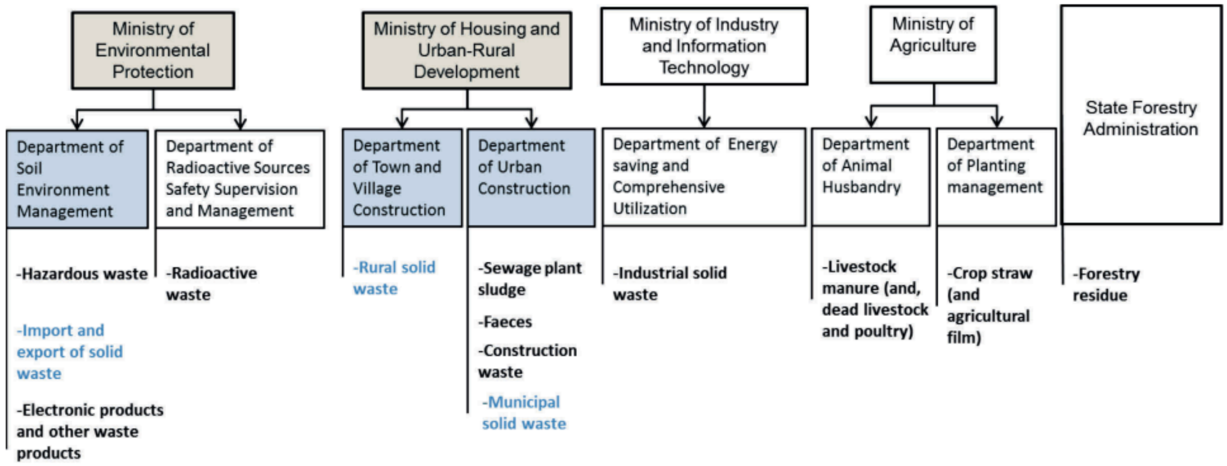


Figure 1: Authorities Relationship Involving in Waste Management Issues.[3]

To see the tiers of administrations more clearly, Figure 2 shows the organizational structure from central level to county level involving in the Chinese MSW management.

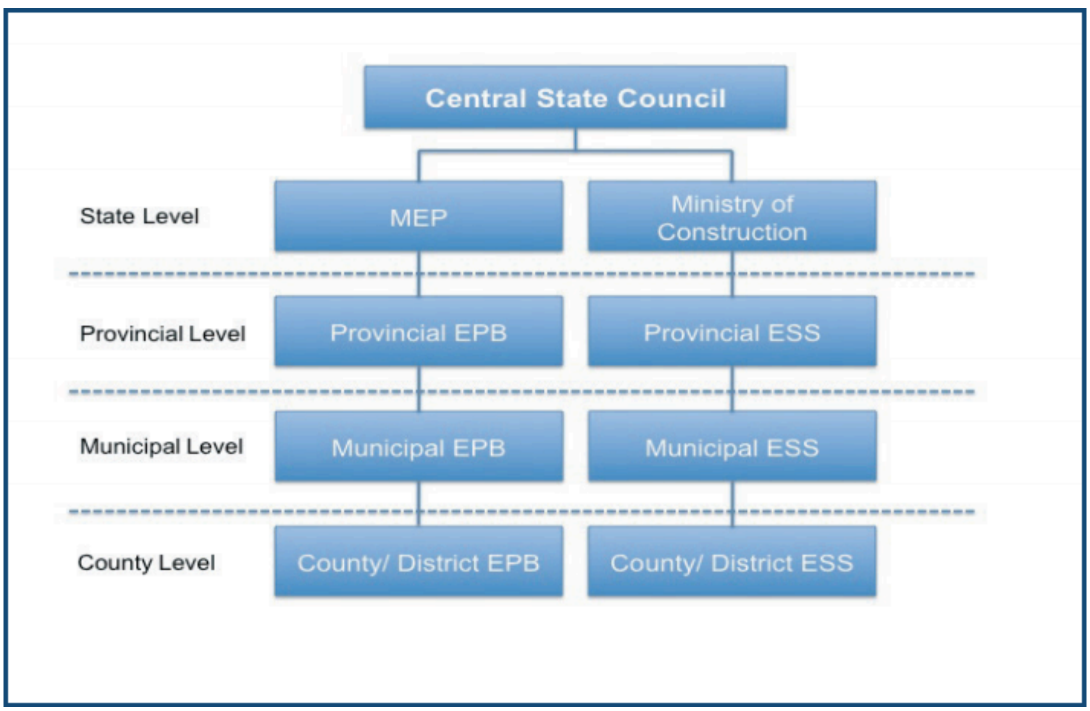


Figure 2: Political Organizational Structure in Chinese MSW Management.[3]

3.3.1. Policy for Integrated Solid Waste Management

As directed in the 13th Five-Year Plan published in 2016, the urban solid waste management is required to be regulated and improved towards waste reduction at source, harmless waste transportation, and waste to resource recovery.[12] The government favors the development of WTE technology and deployment, biological treatment development, and the synergy between cement plants and waste treatment facilities. By the end of 2020, the proper harmless collection and treatment rate in cities need to reach 95% of the MSW, with a ratio of 4:3:3 among WTE, composting and landfilling. In some greener and more advanced cities, the cities are moving from unsanitary landfilling to sanitary landfilling (harmless treatment) with methane recovery.

The landfilling sites in the urban areas are either gradually closing out, especially for illegal sites, or adapting methane recovery technology and shifting to sanitary landfilling sites. Landfill sites has decreased to a number of 2,500 from 6,500 since 1988, and the landfill treatment rate dropped to 50% from 80%.[13] In addition, it has been stressed to rapidly develop the treatment and disposal facilities and services for landfill leachate, WTE plants fly and bottom ash, and odor prevention. As the regulation of emission from WTE plants get more stringent towards development countries' standards, some outdated plants with low electricity generation and high emissions will be forced to shut down or entirely renovated to meet the standard.[14] The public can also monitor and report the WTE plants based on the real-time data of pollution emissions online and at the gate of the plants.

The government has been advocating the importance of involving every single citizen in the cities, not only the municipality and recycling sector, to recycle, reuse, and reduce waste at source in order to achieve higher efficiency of the entire process of resource recovery. During household waste disposal, residents are encouraged to sort waste into "wet" and "dry" bins. The Chinese Central Committee asked the municipalities to work closely with the community administrators to ensure sealed and safe collection and transportation of the MSW. In the meantime, the municipalities need to divert restaurant waste, textile, construction and demolition material, and WEEE from other waste streams from the MSW and accelerate the development of the treatment facilities.

3.3.2. Role of Local Government

On top of reaching the national goal of having 4:3:3 in WTE, composting, and landfilling, several megacities like Beijing, Shenzhen, and Nanjing, are picked as the 46 pilot cities in reaching ambitious goals of waste management, particularly in reaching 35% of recycling rate in the recent years.[15] The central committee required each pilot city to submit specific measures on how to by the end of 2017. The central government and municipalities/provinces work closely to oversee the general progress of the goal reaching, while the municipalities are responsible for the actual implementation and adjust policies based on outcomes and feedbacks over time.

4. Municipal Solid Waste Management in the City of Shenzhen

Up to 2016, Shenzhen MSW was mainly treated by WTE and landfilling, 43.4% and 56.6% of the total collected MSW, respectively.[4] Actions are required to meet the national goal of 4:3:3 with 30-35% recycling rate.

Shenzhen, as learned from the unsuccessful regulation enforcement since June 2015 on waste classification in households with only 20% public participation in recycling, has planned more detailed policies from general citizens' involvement to public treatment facilities. Figure 3 and 4 show the "short-term" and "long-term" plans released by Urban Planning & Design Institute of Shenzhen and Shenzhen Management Office in 2007 on MSW sorting and the specific treatment locations for each waste stream.[16] However, Shenzhen has recently released the waste management regulations according to the "long-term" plan while leaving the "short-term" plan unfinished.

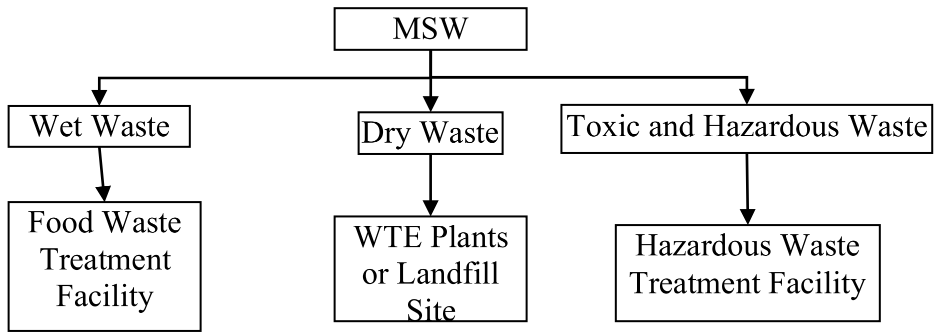


Figure 3: Urban Planning & Design Institute of Shenzhen Short-Term Plan (2006-2010).

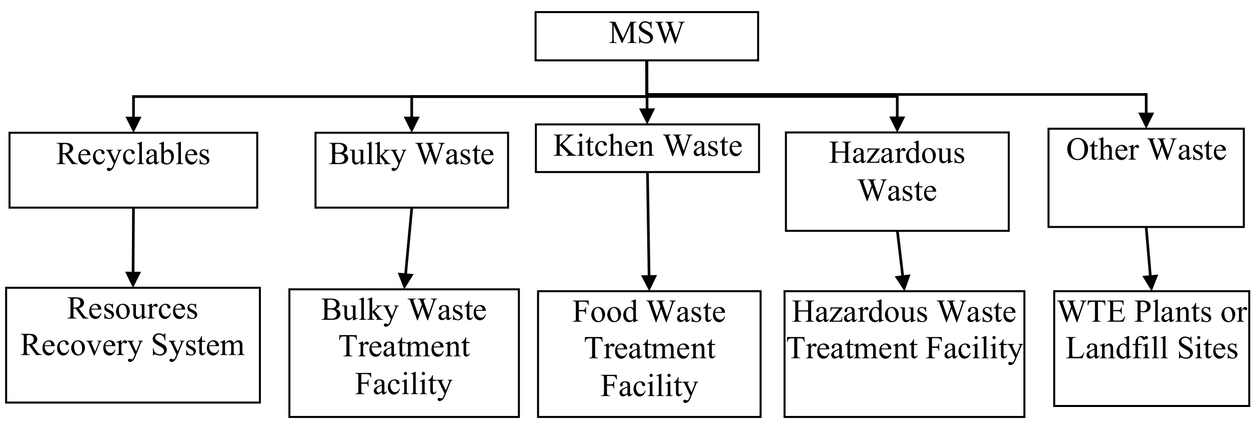


Figure 4: Urban Planning & Design Institute of Shenzhen Long-Term Plan (2011-2020).

Published in June 2017, the slogan of Shenzhen MSW management system is "Reduction at the source, sorting and diverting at the beginning, 'wet' and 'dry' separation in the middle, and integrated utilization at the end".[17] Bulky waste (i.e., furniture), green waste (i.e., plant and bonsai), textile (i.e., bedding and clothes), glass/metal/plastic/paper, and hazardous waste (i.e., e-waste and light bulbs) are required to be separated at each storage station in the housing estate ("Xiaoqu") before recyclables collection. The residual waste is categorized as MSW, and it is required to put into "wet" (kitchen waste) and "dry" (other waste) bins. This section discusses the current waste management status of Shenzhen in details.

Instead of encouraging the public to sort the waste at source voluntarily, Shenzhen government enforced the regulation to the public, as well as to the waste managers in every housing estate. The individuals who fail to follow the rules of sorting the disposals to specific bins will be fined from ¥50 (~$7) to ¥100 (~$14) and the housing estate waste managers who are responsible for the station will be fined from ¥2000 ($286) to ¥5000 ($714). Figure 5 shows one of the waste classification poster in the communities in Shenzhen.

Figure 5: Example of Waste Classification Poster Issued by the Shenzhen Waste Management Office in June 2017.[17]

4.1. Municipal Solid Waste Generation in Shenzhen

Most of the official data reflect the MSW harmless collection in Shenzhen, which represents 100% of the MSW generation (explained in "Status of Collection and Transportation of MSW"). According to Shenzhen Bureau of City Management, in 2016, Shenzhen generated on average of 15,636 t of MSW daily, approximately 5.7 million t annually.[4] At an increase of 6.1% MSW generation each year, the municipality is actively seeking and implementing more and various waste treatment facilities with sustainable and efficient outcomes.[18]

4.2. Characterization of MSW for Shenzhen

The collected MSW is send to treatment plants and landfill. Through recycling at the source, massive informal recycling throughout the collection and transportation phase, and limited formal recycling, many recyclable materials have been diverted from the MSW introduced to treatment plants and landfill sites. The characterization of the post-recycling MSW is what we are interested in this study and it has been referred as MSW in short throughout the article.

During the years of 2006-2007 and 2010-2011, four waste audits have been completed on the MSW feedstock of six existing waste treatment facilities (three WTE plants, two landfill sites, and one "Environmental Park," explained in the later section). Kitchen waste counts for 60-70% of the total MSW waste and the water content is 52-57%. The high food waste content among MSW comparing to developed countries is because of the Chinese dietary and eating habits, as well as the majority diverted recyclables picked by the informal collectors. From 2006 to 2011, the high heating value (HHV) has increased slightly from 7.2 MJ/kg to 7.8 MJ/kg over the years, while the LHV has increased from 5.4 MJ/kg to 6.2 MJ/kg, indicating the WTE technology can be wider implemented with high efficiency and effectiveness.[19]

Due to the outdated data from the source above and the unavailability of the current information regarding Shenzhen MSW characterization, two waste audits data from a China Everbright WTE plant in Boluo is used in this study (see Appendix) through personal contact with Staff Engineer Weifen Chen. Boluo area is adjacent to Shenzhen and the traits of the communities are exceedingly similar to an average Shenzhen community. Taking the average of two waste audits conducted earlier in 2017, the result shows a 47.6% food waste, 47.0% combustible material (i.e., paper, plastic, wood, textile), and 50.2% water content.

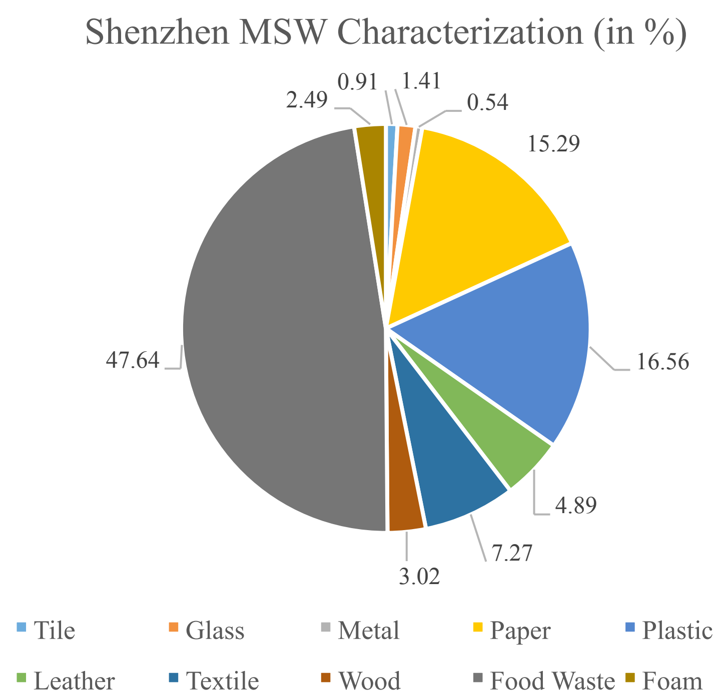


Figure 6: Shenzhen MSW Characterization. Data Acquired from China Everbright WTE Facility from Buolo Area near Shenzhen.

Table 1 shows Shenzhen MSW characterization and an estimated HHV, which is based on calculation method used widely in the waste management industry.

Table 1: Shenzhen MSW Characterization and the Estimated HHV Based on Industrial Method.[20]

Material	**Percentage in MSW**	**MJ/kg material (Technology Handbook)**	**HHV - MJ/kg MSW - Contribution to caloric value of MSW**
Tile	0.91	0	0.00
Glass	1.405	0	0.00
Metal	0.54	0	0.00
Paper	15.29	15.6	2.39
Plastic	16.56	32.4	5.37
Leather	4.89	16.1	0.79
Textile	7.265	18.4	1.34
Wood	3.015	15.4	0.46
Food Waste	47.635	4.6	2.19
Foam	2.49	4	0.10
Total	100		**12.63**

The estimated applications in Part I is based on another calculation method widely used in the academia, calculated from the heating values of material in the waste streams.[21] Note the HHV results from these two methods are slightly different.

WTE Full combustion: $C_6H_{10.1}O_{2.3} + 7.375\ O_2 = 6CO_2 + 5.05\ H_2O$
Heating Value_comb = 26.54 MJ/kg

$$HHV\ of\ MSW\ as\ WTE\ Feedstock$$
$$= Heating\ Value_{Comb} * X_{comb} - Heat\ Loss_{H2O} * X_{H2O} - Heat\ Loss_{Glass} * X_{Glass} - Heat\ Loss_{Metal} * Heat\ Loss_{Metal} - Heat\ Loss_{Tile} * X_{Tile}$$
$$= \mathbf{11.13\ MJ/kg}$$

To calculate the LHV, the process of moisture removal is considered. According to personal communication with Dr. Zhang of CEI, WTE plants at China can remove up to 20 wt.% of the moisture included in the MSW with the aid of a leachate treatment technique placed in the bunker. Based on this parameter and cases from operating facilities, in this thesis, 30% and 50% (almost all moisture) moisture removal rates are assumed for MRF with WTE and MBT with WTE, respectively. See Part I for detailed calculations.

4.3. Role of the Community

As inferred by the regulation, the main role of the community is to comply the rules in recycling and segregation of the waste. The residents and the management companies must work hand in hand with public awareness and educational activities. Understanding and collaboration between these two entities are crucial. Shown in the fining list, both the waste managers and individual residents are compliance with the regulations, but the managers also play roles as a guide in leading correct practices of waste sorting and a supervisor in overseeing the effects and collecting feedbacks. Figure 7 shows a demonstration of newly to-be-installed bins in residents' communities and the citizens are checking them out.

Figure 7: Newly To-be-installed Trash Bins in Residential Areas in Shenzhen.[17]

4.4. Current Waste Management Costs

Based on personal experience, depending on the service provided by the housing estate management company, a waste disposal fee of ¥2-6 ($0.3-0.9) per month is charged for each household. According to China Everbright International, landfilling site, and WTE plant charges the incoming MSW at a similar rate around $8-17 per t.[21] Since Shenzhen is a major city in China at high living cost, the landfill tipping fee (gate fee) is likely to be at the high end.

4.5. Status of Collection and Transportation of MSW

The current two modes are used for Shenzhen MSW collection and transportation scheme, transferring transport and direct transport. Unlike many developing countries residential curbside MSW collection, Shenzhen's MSW is mainly collected from stations in every housing estate ("Xiaoqu"), which is the source of MSW generation. A housing estate consists of a number of buildings with apartments or houses built by one developer and managed and maintained by a management company. Sometimes a company can be both the developer and the management company. Figure 8 and 9 compare the transferring transport and direct transport.

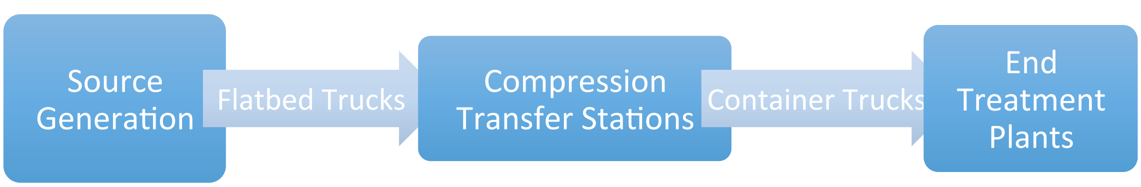


Figure 8: Shenzhen Transferring Transport Model.

Figure 9: Shenzhen Direct Transport Model.

Base on my own experience living in Shenzhen, the owners of the apartments usually discard their trash to the collection bins on the ground level of their building, and the management company workers will combine all the collected trash through those bins to a bigger bin or bags at a waste storage site in the housing estate, waiting for further collection and transporting off-site. In some rare case with a higher management fee, the management company provides the service of collecting the residents' trash from the bins on each floor. Next, trucks sent by the Shenzhen Department of Sanitation or its contractor companies will pick up the bins or bags from each housing estate and transport them to transferring stations or to treatment plants directly.

The transferring transport mode partakes lower energy and labor intensity due to a lower required frequency of collection. This mode has already covered 100% the MSW collection by the end of 2012 with 615 small-scale compression transfer stations, but it might still have dispersed special conditions for direct transport mode.[19] Up to April 2017, there are 965 MSW compression transfer stations in Shenzhen throughout the 10 districts, including mainly the small-scale stations supplementing by large-scale stations.[23] Figure 10 shows an example of the small-scale compression transfer station, which is designed and operated next to a public restroom.

Figure 10: An Example of a Small-scale Compression Transfer Station. [23]

Since the transferring transport mode represents nearly 100% of the collection and transportation case in Shenzhen, the process is further deliberated here in this section. The small-scale compression transfer stations are designed to intake at most 100 t/day of MSW in less than 500 square metered areas. Figure 11 describes the general process of Shenzhen MSW collection and transportation based on Urban Planning & Design Institute of Shenzhen and Shenzhen Management Office.

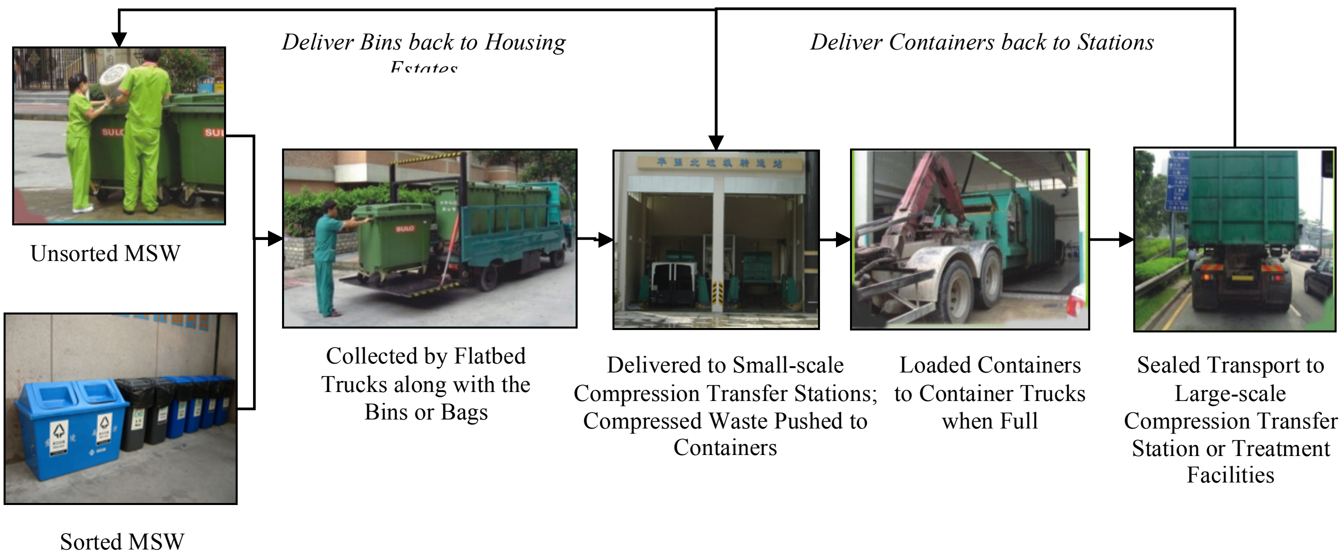
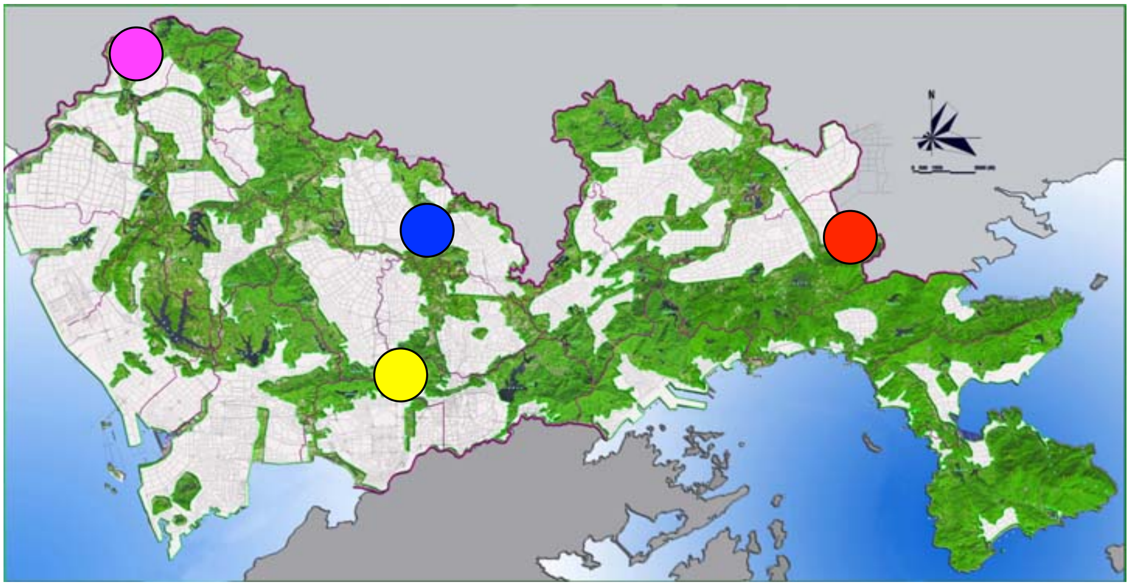


Figure 11: Demonstration of Collection and Transportation Process.[16]

The entire process of collection and transportation is required to strictly follow the health and safety regulations. It is prohibited to transport other recyclables, food waste, green waste, or any other categorized waste stream in the regular MSW trucks.

4.6. Other Pre-Treatment Facilities

The Shenzhen government also largely support the development of treatment facilities before the MSW be delivered to the landfilling sites. Based on Urban Planning & Design Institute of Shenzhen and Shenzhen Management Office, Shenzhen was planning to build a total of 18 waste treatment plants in 2007 including four food waste treatment centers, four waste sorting centers, four bulky waste treatment plants, and one composting sites.[16,24] Food waste treatment centers handle both the restaurant waste (RW) and kitchen waste collected and currently run at a capacity of 1,230 t/day, expecting to reach 2,100 t/day by the end of 2018.[25] The locations of those facilities are dispersed in all 10 districts but mainly clustered in the four "Environmental Parks" (EP), as shown in Figure 12. They mainly receive waste that is generated and collected within the districts or from nearby districts. The majority of the pre-treatment plants are utilized to reduce the weight and volume of the waste that would directly send to landfill sites from the diverted-at-source waste like the bulky waste, RW and recyclables, and recover material and energy through the process.



Qingshuihe EP Laohukeng EP Baihuge EP Pingshan EP

Figure 12: Waste Facilities Distribution in Shenzhen.[16]

4.7. Waste-to-Energy (WTE)

There are three types of WTE: combustion, pyrolysis and gasification. Combustion is the most widely applied type in the commercial scale, thus all "WTE" this thesis is referred to "WTE combustion".[20] WTE refers to a process that uses waste to generate electricity and/or steam through direct combustion or generate other products such as cement clinker through indirect combustion. WTE is also been referred to waste thermal treatment since solid waste is combusted and the pathogen in the waste completed destroyed. As a result, the weight and volume of the final residue that required to be landfilled are significantly reduced up to 90%.[20] An average case of 75% in weight reduction, while 25% is left as bottom ash and fly ash, among current operating plants is used in the analysis.[20]

According to the Sustainable Waste Management Hierarchy developed by the Earth and Engineering Center, WTE is regarded as the primary treatment method to divert disposed waste from landfill, while sufficient recycling and composting activities are in place that reduces the waste required for further treatment. Figure 13 shows the Waste Management Hierarchy.

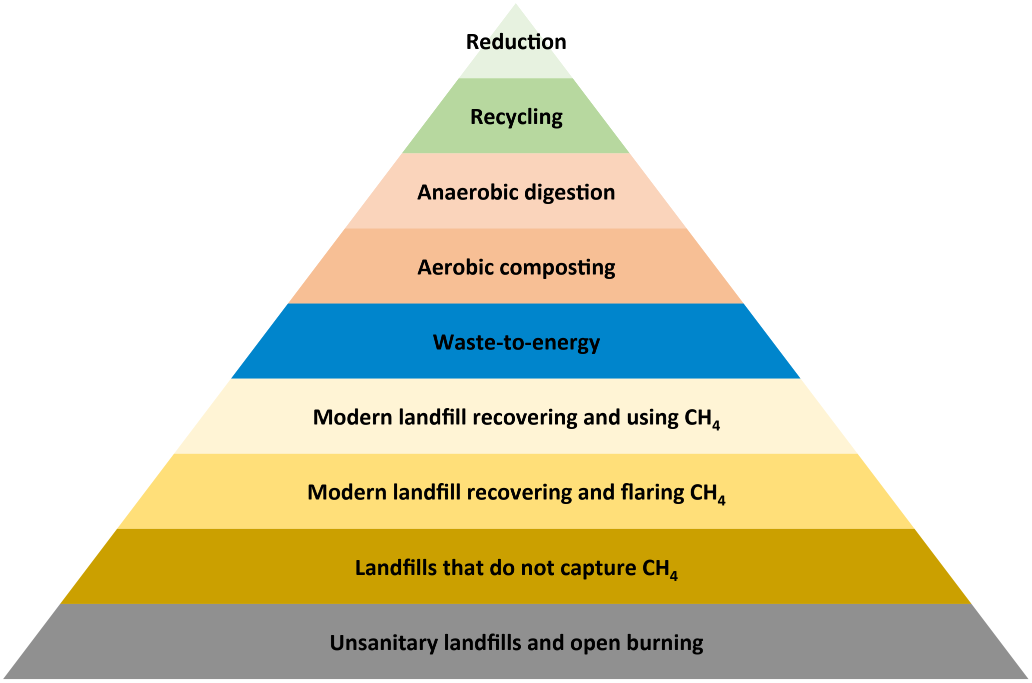


Figure 13: Waste Management Hierarchy.[20]

4.7.1. WTE Technology

There are three main WTE combustion technologies: grate combustion (aka full combustion), refused derived fuel (RDF), and circulating fluidized bed (CFB). Around 60% of the Chinese WTE plants use the grate combustion technology, mainly with Martin Moving Grates operations.[21] Grate combustion technology has 100-year development and it is the most reliable WTE technology that can accept various kinds of incoming MSW at a wide range of LHV. In this case, the Shenzhen East WTE plant is assumed to have the moving grate technology in the financial analyses.

As shown in Figure 14, MSW is brought in to the bunker of the facility. There leachate treatment will move up to 20 wt.% of the moisture before the received MSW enters the high-temperature combustion chambers, where one of the three types of combustion technologies is employed. The outcome ashes are divided to fly ash, which go through the Air Pollution Control (APC) system (bag house, scrubber, and monitoring system) before emitted to the surrounding air; the heavy part is collected as bottom ash where the heavy metal and mineral have high potential of recovery.

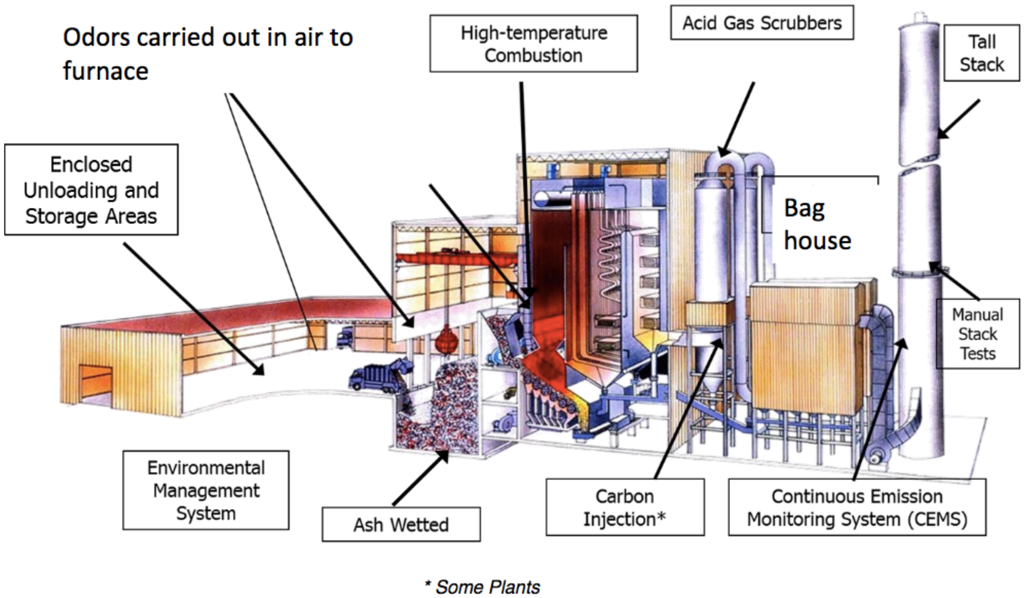


Figure 14: A Typical WTE Plant.[20]

4.7.2. Current WTE Status in Shenzhen

By the end of 2016, five (5) WTE plants are operating and four (4) are under construction in Shenzhen, including the future biggest plant at Shenzhen East.[4] According to Jinghao Liu, the Chief Engineer of China Urban Construction Design & Research Institute, the expected adding capacity is 10,300 t per day of the four developing plants.

4.7.3. Relevant Considerations for WTE

WTE technology receives significant amount of repulsive opinions and judgments from the society due to air pollution, especially in dioxins and Hg emissions, leachate, and odor concerns.[26,27] WTE projects usually face tremendous resistance due to Not-in-my-backyard (NIMBY) effect, especially in the major cities. The largest WTE project in Shenzhen East has received continuous and increasing protestors.[28] However, standard WTE plants must have APC system that complies with regulations and national standards. When operated properly, the odor is pressurized in the facility with no leak to the outside space and leachate is treated and transported with no damage to the surroundings.

Many so-called WTE plants in various sizes in China did not comply the environmental standards when the WTE industry started to boom. The Chinese environmental and construction officials have pointed out those incinerator plants had few or none APC and other related systems that strictly control the emissions.[29] Many newly built WTE plants in China are built following the EU emission standard. In addition, as the regulation towards WTE plant emissions come online, plants that are not able to comply will be gradually eliminated.[14] It is expected to gain societal acceptance towards WTE as stringent environmental regulations are implemented and the public are exposed to transparent information about plant operations.

4.8. Landfilling

4.8.1. Current Status of Shenzhen Landfilling

By the end of 2016, Shenzhen landfills 56.58% of the MSW at three (3) sanitary landfill sites at Luohu, Baoan, and Longgang districts. One unsanitary landfill site is already closed. All existing three sanitary landfill sites employ waste compacting, leachate treatment and gas recovering technologies. A 50% methane recovery at the landfill sites in the environmental analyses is a reasonable assumption based on the current technology in Shenzhen landfill plants.

4.8.2. Environmental Effect of Landfill

The amount of residue that sent to landfill determines the overall environmental effect. According to N.J. Themelis and P.A. Ulloa,[30] the methane and carbon dioxide production are calculated by the following chemical equation happening at the landfill site:

$$C_6H_{10.1}O_{2.3} + 2.325\ H_2O = 3.6875\ CH_4 + 2.3125\ CO_2$$

Table 2: Components of Shenzhen MSW. Rearranged from Figure 6.

Biomass components	%	Petrochemical components	%	Inorganic components	%
Paper	15.29	Plastic	16.56	Metal	0.54
Wood	3.015	Leather *	2.445	Glass	1.405
Food Waste	47.635	Textile *	3.6325	Tile	0.91
Leather *	2.445	Foam	2.49		
Textile *	3.6325				
Total	72.0175		25.1275		2.855

* Leather and textiles category of USEPA was assumed to be divided equally between natural and man-made products.

The typical MSW contains 72.02% biomass. The dry organics amount of the biomass components is 49.85% (1-50.15% moisture content), an estimate of 359 kg (3.019 kmol) of $C_6H_{10.1}O_{2.3}$ per t of MSW. Based on the landfill emission equation, 178.14 kg of methane and 307.22 kg of carbon dioxides are emitted per t of MSW.

Assume the landfill site can manage to recover 50% of the methane emission for biogas production, 89.07 kg of methane and 307.22 kg of carbon dioxides will be mitted per t of MSW incoming to the site. Use a factor of 21 as methane's carbon dioxide emission equivalent,[31] 2.177 t of CO_2eq emission is generated per t of MSW.

Besides GHG emission reduction, minimizing the MSW sent to landfill sites also free up land that can be used for other critical development in the urban areas. Urbanization has spiked up the housing and living costs due to land scarcity and exacerbating urban sprawl. On average, landfill requires 1 squared meter per 10 t of MSW.[20]

In addition, diverting waste from landfilling can also prevent additional landfill fires. Landfill fire usually happens spontaneously at the landfill site and generate dioxins and GHG emissions at an intensely high level. In the U.S., approximately 3,000 landfill fires were reported in 2011, creating over 200 times of total dioxins emitted comparing to all the WTE plants.[32]

Part I: Short term - Advancing the collection and segregation processes

5. Solid Waste Pre-treatment Technology

Shenzhen and China as a whole have boomed and entering maturity in WTE technology and deployment. Other facilities that work hand in hand with WTE also have emerged throughout the cities, for example, small-scale food waste processing centers, waste sorting centers, and composting sites. However, the majority of these facilities are utilized as end treatment plants paralleling to WTE plants, and the residual waste from the WTE plants and those facilities are sent to landfill sites. In the many European countries, a comprehensive and successful integration has been developed between pre-treatment facilities and WTE plants or cement plants. To cope with post-recycling waste with low caloric value, pre-treatment facilities, such as MBT and MRF, can produce higher quality fuel sent to WTE plants while optimizing energy and material recovery and minimizing the land usage for final residual disposal and the overall GHG emissions.

In this paper, a feasibility analysis is conducted to Shenzhen Energy, the developer of the under-construction Shenzhen East WTE plant, to see the potentials of expanding an MBT or MRF plant as a case study of WTE and pre-treatment plant integration for Shenzhen and Chinese industries. The developer can generate more revenue through gate fee with both the pre-treatment and WTE services and recyclable sell-backs and electricity generation by anaerobic digestion within the pre-treatment plants. Another parallel feasibility study is conducted to China Resources Honghe Cement Plant in Shenzhen to see the potential of utilizing the fuel produced by an MSW pre-treatment plant with either MBT or MRF instead of consuming the typical cement factory fuel, petroleum coke.

5.1. Mechanical Biological Treatment (MBT)

Mechanical Biological Treatment (MBT) is an integration that separates the input waste into material flows to get material and energy recovery through both mechanical and biological treatment. MBT typically contains four processes: material separation, mechanical biological stabilization with a biological drying process, mechanical-physical stabilization with a thermal drying process, and mechanical/biological pre-treatment.[33] The feedstock of each process is determined by the particle sizes, as explained in Figure 15 as an example. As a result, a fraction of recyclable material is recovered and sold to the secondary market; a combustible fraction called RDF is used to feed WTE and cement plants, which concentrated high calorific value; an organic fraction is composted and digested to be stabilized for landfilling, which concentrated low calorific value.[20] Figure 15 describes a typical MBT screening process by size.

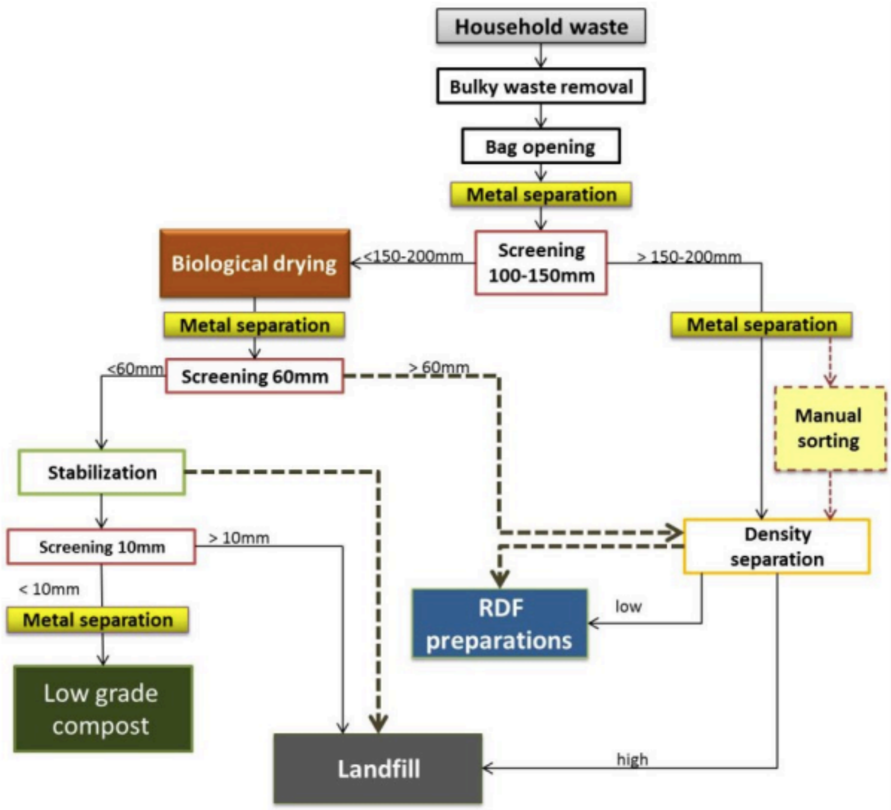


Figure 15: A Typical MBT Facility Screening Process by size.[33]

Even though the development of MBT has taken place in Germany and other European countries in the past twenty years, the technology has been adopted around the world based on local waste characteristics. Usually, an MBT plant comprises a MRF in the beginning and divert the recyclables from other waste streams before further cross-contamination. For a solid MBT model analysis in this thesis, anaerobic digestion (AD) and bio-stabilization/aerobic digestion (composting) are considered to fulfill the biological treatment method within the MBT plant. The main advantage of including AD is biogas production, which can be utilized to generate electricity as a stream of plant income. The composting process produces stabilized compost-like output (CLO) that sent to the landfill at the end of the process. The Figure 16 illustrates the process and flows in an MBT plant.

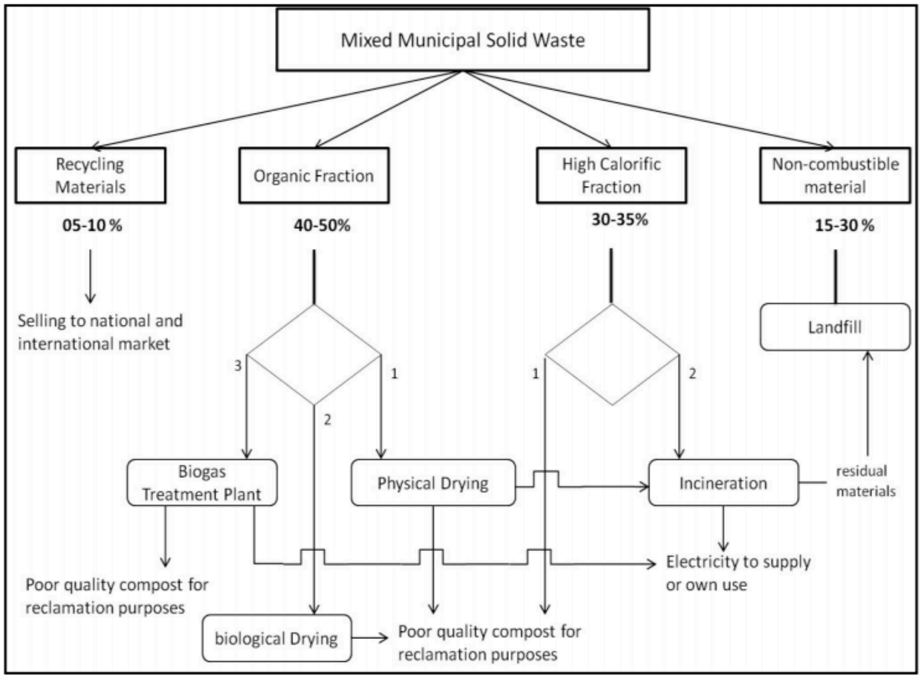


Figure 16: A Typical MBT Facility Process and Flows by Material Fractions.[33]

5.2. Material Recovery Facility (MRF)

MRF is a process of diverting valuable recyclables from the incoming waste. The recycled output materials sold in the secondary markets are paper, ferrous and non-ferrous metals, transparent and mixed film, glass, and a variety of plastics. The separation and sorting procedures may use either hand or automated systems, or the combination of the two.

Three types of MRF plants are mostly seen in the industry: clean MRFs, dirty MRFs, and specific purpose MRFs. The clean MRFs receive clean, source-segregated dry material from the dry bins to divert recyclables and produce fuel. The dirty MRFs receive mixed waste and the dry recyclables from the wet organics. Because the dry and wet are mixed with cross contamination when sending to the dirty MRF facility, material recovery rate is low, around 5-10%; some MRF with advanced segregation technology can reach up to 20% recovery rate (i.e., MBT plant at Larnaca, Cyprus). Dirty MRFs is the case considered in this thesis to treat the current MSW in Shenzhen when the clean and dry feedstock for the plants is still ideal and unrealistic under the newly implemented recycling regulations. The last type of MRF facility is for specific material such as e-waste, construction and demolition waste, or pure plastic waste. This type of MRF is common in small scale. As mentioned, many e-waste separation and sorting are done by the informal recyclers in Shenzhen.

Figure 17 explains the relationship between MBT and MRF plant in simplicity.

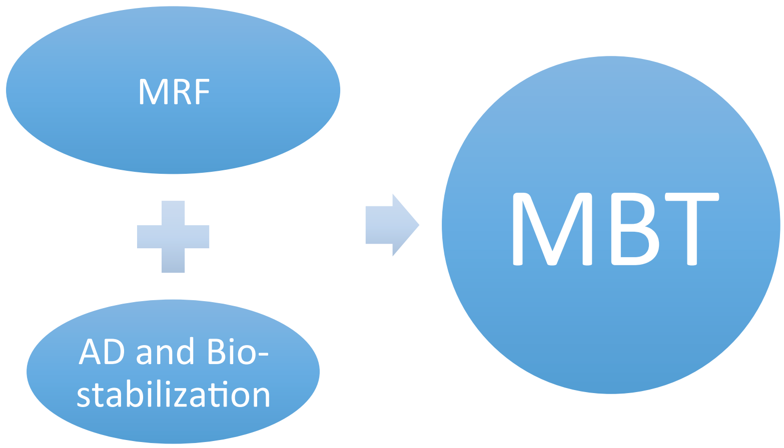


Figure 17: Relationship between MBT and MRF Plants.

5.3. Successful Case of MBT and MRF integrations

With WTE plants:

For this study, data from the successful operation of an MBT followed by a WTE plant, i.e. Mataro plant located in Barcelona, Spain were used. This plant includes processes of hand sorting of oversized items, bag openers, hand sorting of paper, plastics, and glass materials and trommels based on size fractions.[34] With respect to the post-recycling MSW incoming, the waste particles smaller than 200 mm is sent to the MBT facility (72.3%), otherwise directly to the WTE plants (12.7%). Within the MBT plant, particles between 70 to 200 mm are considered dry stream (approximately 35-40%) and recyclable products are recovered through magnetic/eddy current separator and ballistic and optical separator (~7.5%, relatively low overall recovery rate in the industrial applications). The remaining fraction of the 70 to 200 mm particles is conveyed to the waste pulping stage of the Biotechnische Abfallverwertung GmbH (BTA) process, where water is added to separate the floated light and sediment particles. The heavy particles are diverted as RDF for the WTE plant (41.7% out of MBT plant, 30.2% out of MSW incoming), while the light particles combined with particles smaller than 70 mm (around 40%). The light particles are considered wet material and further separated to anaerobic digesters (14.9% out of MBT plant, 10.8% out of MSW incoming) to recover biogas or to bio-stabilization /composting (32.2% out of MBT plant, 23.3% out of MSW incoming). The overall efficiencies from actual facility operations from the Mataro MBT plant part except MRF will be applied to the estimations in the pre-feasibility study.[35] The efficiencies applied in proposed models use the average of the year 2014 and 2015 from the Mataro plant operational data.

Another successful case of Larnaca MBT plant in Cyprus is considered in this thesis. The Larnaca MBT plant data is utilized and applied in estimating the projecting outcomes of the material recovery part (MRF) of the MBT study specifically in the subsequent sections. The treatment process of this plant involves bag opening, screening (material recovery, 20.5%) by ballistic, magnetic, eddy current, and near-infrared spectra optical separations, and separation of the organic fraction to aerobic stabilization with sizes < 70 mm (composting, 37.1%). The separation after the bag opening stage is operated by rotary screens, also called trommel, based on the sizes. The residuals of the MBT plant (26.3%) will send to sanitary landfill, while the stabilized organics can be used as covering material. During the screening, RDF (16.1%) will be separated from the waste as well. Refer to Appendix for detailed calculations of material recovery.

A relatively low acceptance rate, 30%, is applied when calculating the financial revenues of the proposed plants from materials recovery facilities. This is associated with the low acceptance rate, that affect the actual amount of recovered material sold to the secondary market.

Table 3 and 4 show the proposed models of the compositions and destinations for the entire MSW incoming based on the combined data from Larnaca and Mataro MBT plants.

Table 3: Proposed Compositions and Destinations of MSW Incoming through MBT Facility Followed by a WTE Plant.

MBT

Items	Composition	Destinations
Total material recovered	21.07%	Accepted: secondary market Unaccepted: WTE
RDF	30.16%	WTE
AD	10.79%	Remains in MBT, generate electricity, and reject landfilled
Bio-stabilization/Composting	23.31%	Remains in MBT, then a small amount landfilled
Other - un-combustible	14.67%	WTE
Total	100.00%	

Table 4: Proposed Compositions and Destinations of MSW Incoming through MRF Followed by a WTE Plant.

MRF

Items	Composition	Destinations
Total material recovered	21.07%	Accepted: secondary market Unaccepted: WTE
RDF	30.16%	WTE
Other	48.78%	WTE
Total	100.00%	

In China, the integration of MBT and WTE plant has been drawn into attention within this few years. An experimental integrated plant in Dalian, China is under construction and expected to operate by the end of 2017.[36] The Austrian-German WTE developer of the plant pointed out the ideal and promising technology as placing MBT as the pre-treatment for WTE in term of moisture content removal and heating value increase. High moisture content and LHV of the MSW in China have always been the critical obstacles in improving WTE plant efficiency. Now the Chinese market has started to gain interests in developing the integration from learning from the success. In the following sections, perspective scenarios will be presented utilizing the available data from the Mataro and Larnaca plants as a successful case to estimate the expected outcomes of the integration.

With cement plants:

China is the largest manufacturer of cement products, which it had caught attention of the regulators and the industry to value the integration of MRF or MBT plants with cement plants. RDF, as one of the outputs of MRF and MBT plants, can be used to power the cement kilns and produce clinker, the main component of cement production.[37] China Resources Cement Holdings and Honghe Cement Company had the vision about this technology and policy suitable integration since 2013 on its Binyang Cement plant in Guangxi Province, China. The cement plant with a production of 3,200 t/day is powered by a waste pre-treatment plant (biological drying) treating 300 t/day of sub-rural waste from the surrounding areas.[38,39] The calculated cement production over MSW feed in t per t is 10.7. Having more advanced waste pre-treatment facilities like MBT and MRF are likely to have a higher ratio. Referencing this successfully operating plant's efficiency to other existing cement plants which has the potential to receive MSW as fuel source is reasonable and reliable. Also, many professionals working in the waste management field have emphasized that the synergy use of RDF in the cement production process generates no residue unlike in the WTE plants.

Table 5 and 6 show the compositions and destinations of the entire MSW incoming after the proposed models.

Table 5: Proposed Compositions and Destinations of MSW Incoming through MBT Facility Followed by a Cement Plant.

MBT

Items	Composition	Destinations
Total material recovered	21.1%	Accepted: secondary market Unaccepted non-plastics: Cement plant Unaccepted plastics: Landfill
RDF	30.2%	Cement plant
AD	10.8%	Remains in MBT, generate electricity, then reject landfilled
Bio-stabilization/Composting	23.3%	Remains in MBT, then a small amount landfilled
Other - un-combustible	14.7%	Landfill
Total	100.0%	

Table 6: Proposed Compositions and Destinations of MSW Incoming through MRF Followed by a Cement Plant.

MRF

Items	Composition	Destinations
Total material recovered	21.1%	Accepted: secondary market Unaccepted non-plastics: Cement plant Unaccepted plastics: Landfill
RDF	30.2%	Cement plant
Other	48.8%	Landfill
Total	100.0%	

Successful Cases At-A-Glance:

- Mataro WTE and MBT Plant in Barcelona, Spain

- Larnaca MBT Plant in Larnaca, Cyprus
- Binyang Bio-drying Waste Pre-treatment and Cement Plant in Guangxi Province, China
- Dalian MBT and WTE Plant in Shandong Province, China (data not used in estimation)

6. Potential of Existing Plants with Pre-treatment Facilities (MBT or MRF) in Shenzhen, China

Shenzhen is building the biggest WTE plant in the world called Shenzhen East WTE Plant, expecting to operate by the end of 2018. Shenzhen East WTE Plant is located at Longgang District in East Shenzhen. Comparing other existing WTE plants in Shenzhen with 450-3,000 t/day capacity, Shenzhen East WTE Plant can treat 5,000 t/day of MSW as far beyond people's experience and practice. Excluding the benefits of engaging the informal recycling sector to the MBT and MRF plants mentioned in the previous section, the synergy between MBT or MRF with WTE plants is financially promising in the long run. The current Shenzhen East WTE Plant will sell electricity from WTE and 44,000 square metered solar PVs and collect gate fees as its only two sources of revenue other than government subsidies. However, having a MBT plant in addition to the WTE plant will increase the revenue with electricity sale from AD, recovered materials, and higher gate fees due to larger receiving capacity. If merely adding an MRF to the WTE plant, it could be more profitable with the sale of recovered material and higher volume of gate fees.

Primarily looking at the financial benefits and restrictions, two feasibility studies are preformed to show the opportunities of developing an MBT or MRF plant along with the existing Shenzhen East WTE Plant. As mentioned, the proposed MRF plant shares similar technologies and its efficiencies with the MRF part of the Larnaca MBT Plant; the rest of the plant shares similar technologies and efficiencies with the Mataro WTE and MBT Plant.

Except existing direct combustion WTE plants, cement plants synergies with MBT or MRF plants is also a sustainable example of waste to energy. As the largest cement producer with around 60% share of the worldwide production,[41] China is heavily looking into the energy efficiency and alternative fuel in the clinker production, a. Since rapid urbanization and rural development in China as a whole, the demand for cement is expecting to increase with no doubt over the next few decades, based on the cement consumption during 2011-2013 being larger than the entire consumption of USA in the past 20th century.[41] China Resources Cement Company has achieved successful operation at Binyang Waste Pre-treatment and Cement Plant, biological drying the incoming MSW, using it as the fuel for the cement plant, and producing clinker. The entire project costs 120 million Yuan (18 million US dollars). However, no more advanced pre-treatment facilities like MBT or MRF with cement plant operation has become available in China up to now. An existing cement plant in Shenzhen owned by the same company with a production of 300,000 cubic meter/year is chosen to be the target plant for the study of synergy with either MBT or MRF, using the Binyang plant as a reference.

The fuel used for cement plant has a higher requirement for chlorine content to avoid excessive formation of salts in the cement kiln and corrosion to downstream units. The chlorine content of the feed RDF has to be lower than 0.7%.[42] Because the feedstock of MBT or MRF plants is post-recycling MSW and the average chlorine content is 0.4%, assuming the same methodology applied in WTE scenarios from Larnaca and Mataro plants are sufficient at this time. However, as indicated in Table 5 and 6, the unaccepted recovered plastics and the composition categorized as "other" will not be sent to cement plant due to the risk of significantly lowering the RDF quality. The energy required by the proposed Shenzhen MBT plant is assumed identical to the Binyang plant but matching the scale of Shenzhen cement plant production. The technology and efficiencies are estimated based on the same methodology from Larnaca and Mataro plants as in the WTE scenarios analysis.

This study will investigate the financial feasibility and environmental benefits of the six scenarios and provide further recommendations. All analyses are divided into four sections, MRF, MBT except MRF part, the existing facilities, and landfill. Each section is projected with the same factors but to different scales based on applications. Figure 18 shows the sections where the flow of incoming MSW experience.

Figure 18: Proposed Incoming MSW Treatment Process.

<u>Scenarios:</u>

1. MRF and WTE
2. MBT and WTE
3. WTE only (with bottom ash recovery AND with no bottom ash recovery)
4. MRF and cement plant
5. MBT and cement plant
6. Sanitary landfilling with 50% methane recovery

For example, the MBT and WTE scenario will include all three sections in the analysis, the MRF and cement plant scenario will include the first and last sections, and the WTE only scenario will only have the last section analysis. The weight of residuals sent to landfilling will change for each scenario. Detailed explanations are included in Table 7.

A majority of the WTE plants in China are either Public owned or through Private Ownership business models, also called Build-Operate-Transfer (BOT) while in both cases, government supplies the site and the MSW sources. BOT model allows the private sector to design, build, and operate the plant for a term period, usually 20-25 years, and transfers the ownership back to the municipality. Figure 19 explains the relationship between different stakeholders in the BOT model. Only the construction and operational costs of the plant are included in the cost analysis, excluding the land acquisition and related costs.

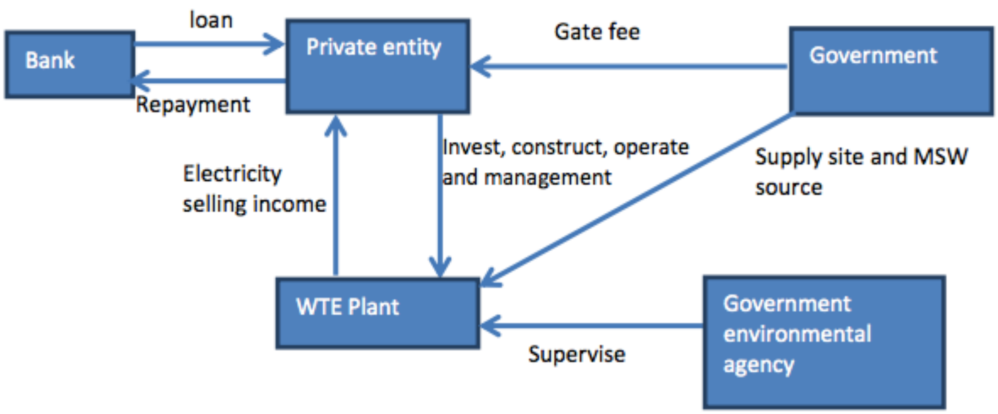


Figure 19: Relationship between Different Stakeholders in the BOT Model.[43]

The Table 7 illustrates the proposed first to fifth scenarios consist of economic analyses with cost and benefit comparisons for each scenario and environmental analyses comparing each scenario to the sixth scenario.