Carbon Mitigation Cost of WTE and Comparison with Other Waste Management Methods

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Executive Summary

Global warming is associated with adverse effects on biodiversity, human survival and development and the earth environment. It is therefore necessary to reduce the Greenhouse Gas (GHG) emissions that are associated with climate change. Among various methods to slow down greenhouse effect, waste management can play a key role, directly or indirectly.

The proper and efficient management of municipal solid waste (MSW) is vital to achieving sustainable development, since poor waste management impacts on public health and the environment and may affect the development and quality of life of future generations. The primary waste treatment options, recycling (including composting), waste to energy (WTE) and landfilling are associated with different environmental burdens. The waste management hierarchy prioritizes the means of managing wastes and is widely accepted by organizations and legislative bodies across the world. However, the waste hierarchy by itself cannot be used to quantify the level of sustainable solid waste management attained by a nation.

In this study, five waste management scenarios were investigated: sanitary landfilling, sanitary landfilling with gas collection and flaring, sanitary landfilling with electricity generation, Waste to Energy (WTE), and Mechanical and Biological treatment (MBT) combined with WTE were used to compare the carbon mitigation cost of various waste management techniques and provide supporting arguments for decision makers. The baseline scenario was sanitary landfilling without energy recovery. Data were derived from the literature and industrial contacts and the GHG reductions, net present costs and carbon mitigation cost of each scenario were calculated.

The computed carbon mitigation cost followed the same order as in the generally accepted hierarchy of waste management. Among the five target scenarios, MBT plus WTE indicated the lowest carbon mitigation cost (-$27.3/MTCE without CER and -$43.4/MTCE with CER). WTE ranked second in mitigation cost (-$26.5/MTCE without CER and -$42.5/MTCE with CER) but offered the highest GHG reductions (1.06MTCE/ton MSW). Also, two landfilling mitigation measures exhibited economic benefits for reducing GHG. The introduction of carbon credit schemes is beneficial for decreasing carbon mitigation cost in all cases.

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1. Introduction

Climate change is a serious international environmental problem and one of the major concerns for humanity in the 21st century. The increased amount of greenhouse gases in the atmosphere (primarily CO_2, CH_4 and nitrous oxide) retains solar radiation that would otherwise be radiated into the space and has led to a warmer planet. Without this so-called greenhouse gas (GHG) effect, the average temperature on earth would be 2 degrees Fahrenheit lower than the current 57 degrees Fahrenheit [1]. The global warming has already caused some environmental changes such as sea level rising, glacier and snow cover melting, reduced biological diversity, and agricultural shifts, all of which pose significant risks to the natural system and human society. The majority of scientists believe that this increase is derived, at least in part, by human activity, especially the burning of fossil fuels to generate electricity and drive cars. However, carbon dioxide concentration is still arising and projected to increase to a nominal 500 ppm in less than 40 years according to business as usual models. Among the efforts to slow down global warming, waste management options provide many opportunities, directly or indirectly [1].

Landfilling is the most widely used waste management method because of its very low technology and cost. However, landfilling is one of the largest anthropogenic sources of GHG emissions since it produces methane (CH_4), in combination with other landfill gases (LFG) through the natural process of decomposition of organic wastes. CH_4 makes up approximately 50% of LFG, the other 50% is carbon dioxide and small amount of other gases, including volatile organic compounds (VOCs). Methane is recognized as a big GHG source that has over 20 times the global warming potential greater than that of the same volume of carbon dioxide according to IPCC's estimation. Notably the United States is the largest emitter of landfill CH_4 in the world, accounting for over twice the emissions of the second large emitter, China. The amount of methane produced by landfill is determined by some key factors, like waste characterization, the quantity waste disposed per capita and LFG technology applied in the LF.

Despite efforts to control the landfill gas emissions, it is still a significant source of methane emissions because of increasing waste streams in developed countries [2].

However, other waste management methods with energy recovery may be more environmental friendly and cost-effective. Landfill gas collection and utilization or flaring has been applied to many sanitary landfilling to reduce gas emissions. There is an increasing tendency to use landfill gas for electricity production also. Besides, waste to energy is now transforming the definition of what it means to waste management. When waste is combusted, the amount of waste to landfill is reduced and waste is transformed to energy in the form of electricity and heat. The energy produced is provided for industry or house using and thus conserves fossil fuels used in power plants. Furthermore, Recycling reduces energy-related GHG emissions in the manufacturing process and also avoids emissions from landfill. It is notable that different options may not be mutually exclusive: for example, recycling can recover materials and reduce GHG emissions, which in turn may affect the economics of the market.

Although GHG emission is an important factor when proposing a new project, the economic factor is always a key concern that can even kill the project. According to the World Bank's World Development Report, the cost of climate action globally reveals the financial burden between climate change mitigation and society [3]. The maximum estimated available funding for climate action in the future through United Nations Framework Convention on Climate Change (UNFCCC) and other funds is about \$100 billion per year [2], but the capital costs for achieving the goal to maintain global warming below 2℃ will require almost \$350 billion to \$1.1 trillion per year by 2030 [4]. The carbon mitigation cost is an effective method to characterize both the technical and economic aspects of the cost-effectiveness of such actions to reduce GHG with respect to policy maker, company leaders and climate experts.

A lot of existing researches have addressed the abilities to decrease GHG emissions for an integrated waste management system depending on different situations. For example, Kaplan et. al compared carbon dioxide equivalents emitted from landfilling, WTE and other electricity-generating technologies by conducting life-cycle analysis (Figure 1). Landfilling had significantly higher CO_2eq than other alternatives [5].

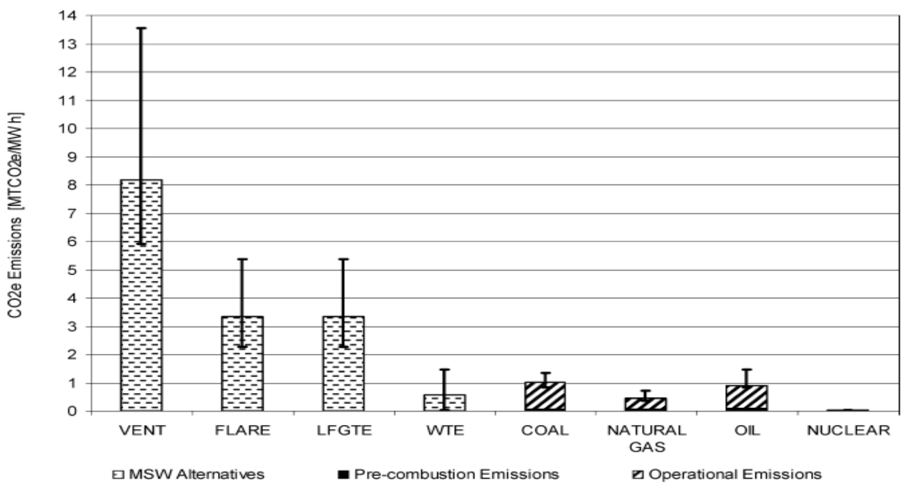
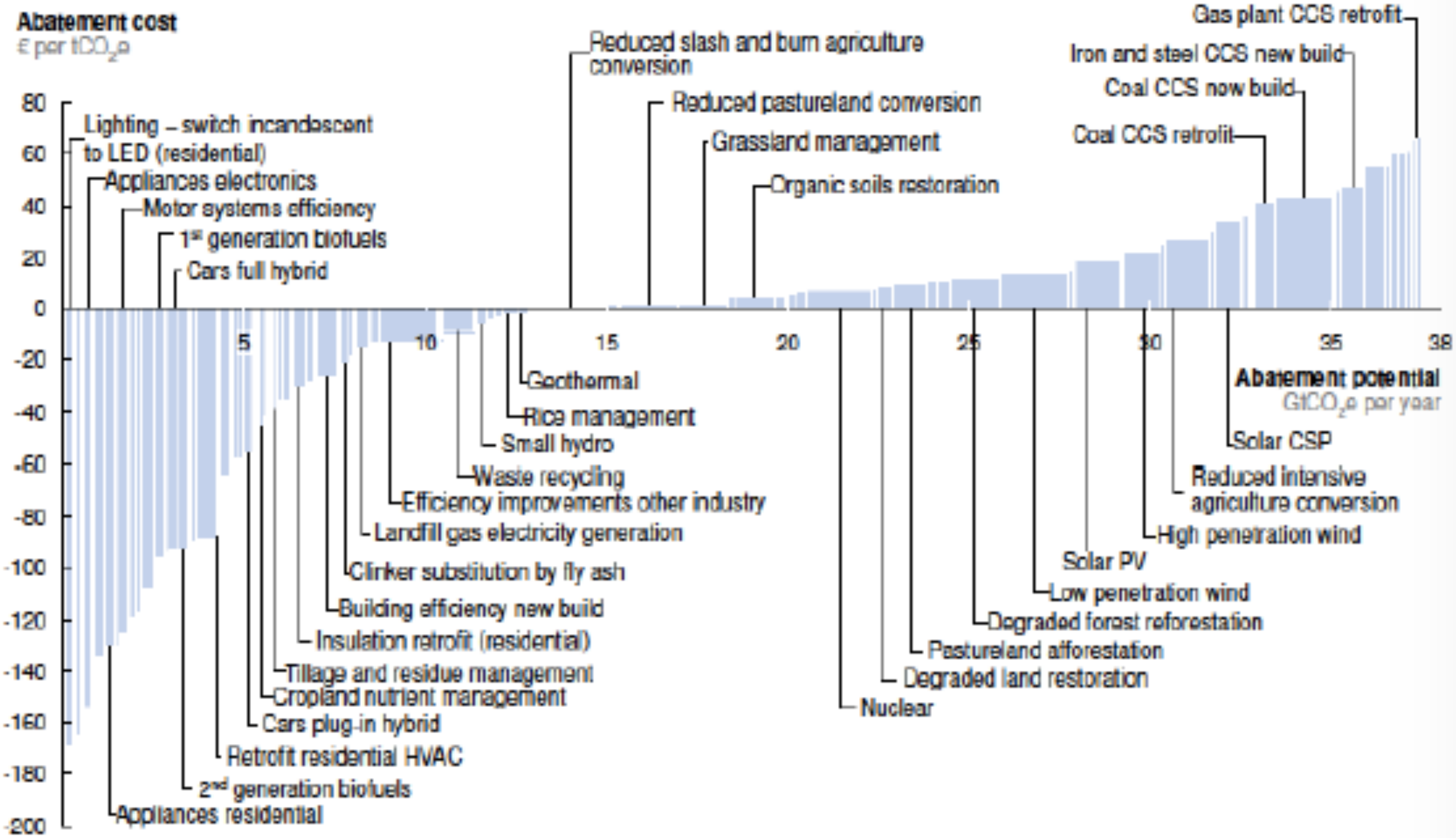


Figure 1 Comparison of carbon dioxide equivalents for LFGTE, WTE, and conventional electricity-generating technologies **(reproduced from Kaplan et. Al., 2009)**

From the economic perspective, carbon mitigation costs for the whole industry have attracted the attentions of many researchers and policy makers the recent years. Mckinsey & Company firstly developed and popularized the marginal abatement cost (MAC) curves for GHG mitigation in 15 countries (Greece, Poland, India, Russia, Brazil, China, Switzerland, Israel, Belgium, Czech Republic, Sweden, Australia, US, UK and Germany) [6]. After that, the World Bank's Energy sector showed identified low carbon path for six emerging economies (China, Brazil, India, Indonesia, Mexico, South Africa) [7]. Other MAC curves have also been developed for other countries and Unions. Besides, global MAC curves and MAC curves for some cities were also developed now. Figure 2 is the most recent version of Global MAC curve by McKinsey that shows the impact of financial crisis on carbon economics [8].



Note: The curve presents an estimate of the maximum potential of all technical GHG abatement measures below €80 per tCO_2e if each lever was pursued aggressively. It is not a forecast of what role different abatement measures and technologies will play.
Source: Global GHG Abatement Cost Curve v2.1

Figure 2 Global GHG Abatement Cost Curve Beyond BAU-2030 (McKinsey & Company, 2010)

In the waste management world, Beaumont and Tinch has used the abatement cost curves to enable copper abatement in waste technologies [9]. US EPA has derived MAC curve on Non-CO_2 reductions for top 5 Emitters (China, Mexico, Malaysia, Russia, US) [10]. While the above-mentioned studies have made great contributions in terms of the data developed for either environment or economic aspects, none of them reflects the relationship between these two factors. Thus there is still much space to discuss about it.

Ideally, the choice of final disposal methods requires a systematic comparison of GHG emissions, cost and benefits involved. This research is the first to present a comprehensive analysis of carbon mitigation cost of various waste management methods. The primary calculation in this research is to enable waste-related decision making to incorporate the economics together with the technical merits of GHG mitigation in waste management area. By quantifying the GHG emission reduction and costs/revenues, the results enable government, communities, companies and other waste management decision makers to measure the benefits of their actions.

This study aims to determine the carbon mitigation cost of different waste management methods. We would like to see both environmental and economical performance of these methods. Another specific objective is to identify the contribution of the carbon credit to the revenue and its influence to the final carbon mitigation cost. This study will firstly present a brief description of what is the sustainable hierarchy of waste management, since the five scenarios of this project is designed corresponding to the hierarchy. Section 3 presents the basic calculation methods and scenarios chosen for this study. Data gathered for each scenario is provided in Section 4. Section 5 compares and discusses the findings for the results. Finally, Section 6 contains some conclusions plus some ideas for further work.

2. Sustainable Waste Management Hierarchy

2.1 Definition of Solid Waste

To begin with we will provide a brief background on the solid waste. According to the definition by Resource Conservation and Recovery Act (PCRA), solid waste refers to any solid, semi solid, liquid, or contained gaseous materials discarded from industrial, commercial, mining, or agricultural operations, and from community activities. Solid waste includes garbage, construction and demolition debris, commercial refuse, hospital waste, sludge from water supply, waste treatment plants or air pollution control facilities, and other discarded materials.

Depending on the sources, solid waste can be classified into different types: Household and commercial waste: is generally defined as municipal solid waste; Industrial waste: is classified as hazardous waste; Biomedical/hospital waste: is classified as infectious waste.

In this study we are interested in municipal solid waste (MSW), as defined by EPA, MSW is "used and then thrown away, such as product packaging, grass clippings, furniture, clothing, bottles, food scraps, newspapers, appliances, paint, and batteries," which comes from "homes, schools, hospitals, and business". However, the compositions of solid waste various in different places and seasons. Figure 3 shows the average MSW generation percentage in the U.S. in 2014, which is done by the U.S. Environmental Protection Agency (EPA) [11].

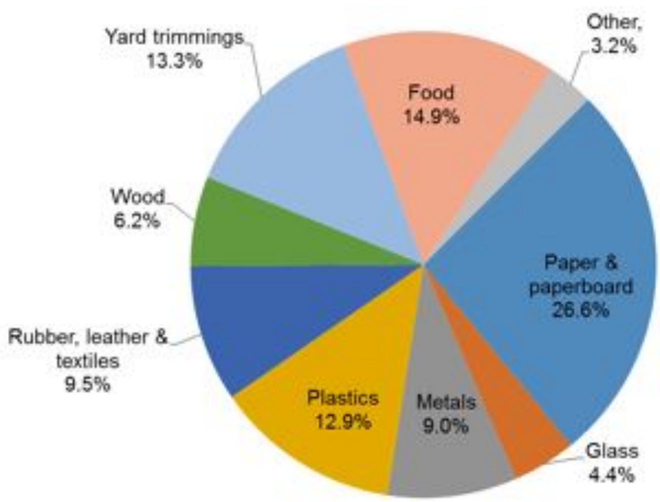


Figure 3 Average Composition of U.S. MSW (EPA, 2014)

2.2 Solid Waste Management Methods

As noted above, MSW includes many materials with different properties, which made them complex for handling. According to their properties, various materials should go to different destinations by sorting, processing and recycling. For example, metals and glasses are either not combustible or compostable, the best way for them would be recycling. Some non-recyclable plastics and fibers with high heating value should be combusted to generate electricity and heat. The only thing should be landfilled is inorganic compounds such as non-recyclable glasses and ashes from Waste to Energy plants.

For a sustainable waste management system, waste should be firstly reduced as it was placed at the very top of the waste management hierarchy. As shown in figure 4, Waste Reduction is followed by Reuse & Recycling, then followed by Composting, Waste to Energy (WTE) and landfilling, ranging from landfills with energy recovery to the non-regulated open dumps that are still used in many developing countries. Landfilling is considered as the worst option because it consumes a lot of space, run a high risk of leaking to the air, soil, groundwater and make less use of energy contents in the waste [12].

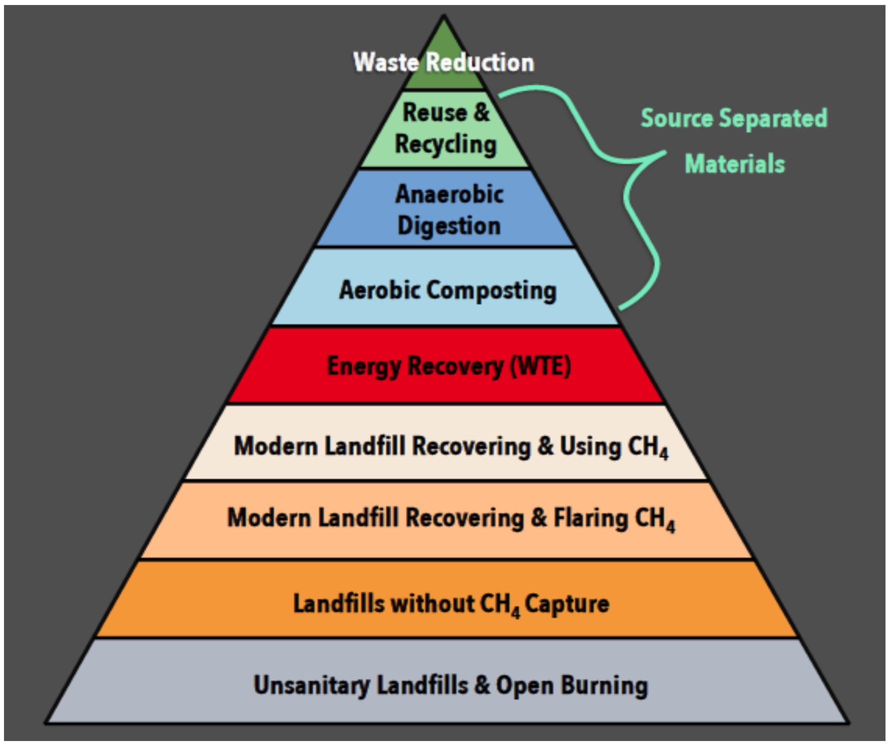


Figure 4 The EEC Hierarchy of Waste Management (Kaufman & Themelis, 2009)

A brief description of the major waste management methods is presented below:

Landfilling: The most basic and well established infrastructure for waste management is landfilling. It usually has hundreds of hectares, and the waste would be deposited into land. After depositing, a cover of soil or liner is applied in order to minimize environmental impact. Different from open dump in some developing countries, sanitary landfilling in developed countries is required to prevent contamination of ground and surface water. Besides, in the U.S. now, most basic sanitary landfilling have landfill gas collection and flaring systems in order to reduce gas emissions from landfilling. Some of them even have been applied to convert landfill gas to electricity. Even though landfilling is the least favorable option in the waste management hierarchy, most of the MSW is still landfilled.

Waste to Energy (WTE): Non-recyclable MSW is combusted in the boiler at high temperature. The produced steam can drive a turbine generator for electricity. Besides, some WTE plants have utilized the low pressure steam for district heating/cooling. An air pollution control system is used to remove gaseous or particulate pollutants before gas is released to the atmosphere. The air emissions should be tested and strictly meets standards of Environmental Protection Agency (EPA). Finally, the remaining 20%-25% residue can be disposed in landfills. Till now, there are 77 WTE plants in the US. Figure 5 and Table 1 show the evolution of WTE plants in the U.S in recent 30 years [13][14][15]. Modern WTE facilities under the MACT (Maximum Achievable Control Technology) standards for Large Municipal Waste Combustors (MWC), issued by the U.S. EPA are strictly protective for human health and the environment. While source reduction is always the best, there are inevitably a great portion of wastes are disposed in landfill, which takes up a lot of space and produces more GHG. Thus WTE is the only proven alternative to landfilling for post recycling waste.

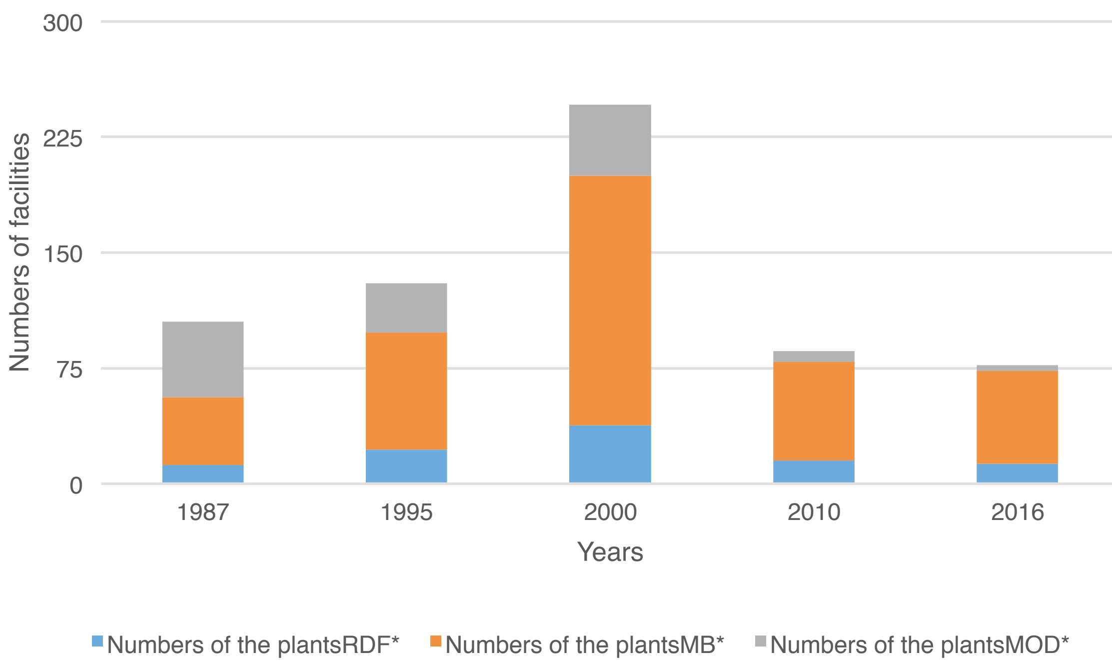


Figure 5 WTE Evolution in the U.S. [13][14][15]

Table 1 Numbers of WTE Plants in the U.S., 1987-2016

Year	Numbers of the plants				Reference
	RDF*	MB*	MOD*	Total	
1987	12	44	49	105	[13]
1995	22	76	32	130	
2000	38	162	46	246	
2010	15	64	7	86	[14]
2016	13	60	4	77	[15]

*RDF: Refuse Derived Fuel; MB: Mass Burn; MOD: Two stage MSW combustion.

Composting: Wastes that mainly consist of organics such as yard wastes, food scraps and manure can be composted by microorganisms. Organic materials are separated firstly in composting facilities, then can be composted in different ways. Major composting methods include window composting, static-pile composting, anaerobic digestion and in-vessel composting.

Recycling: In the U.S., recyclables are mainly collected by curbside collection, drop-off, buy-back, and deposit/refund programs. Typically, the collected recyclables include paper fibers (office paper, newsprint, cardboard), glass, metals (ferrous metals and non-ferrous metals), plastic, consumer electronics and tires. Then the collected recyclables are sent to material recovery facilities (MRF) or to a transfer station first. The incoming recyclables are sorted, may be shredded for further processing. The residues are landfilled or sent to WTE plants. There is also another relatively new method, which is the Mechanical and Biological treatment (MBT) plant, that can be used to recycle materials from waste and reduce the amount of waste going to landfills by mechanical treatment technologies (screens, sieves, magnets, etc) in combination with biological technologies (composting, anaerobic digestion).

3. Methodology and Description of Research Scenarios

3.1 Methodology

The carbon mitigation cost of each scenario is based on the cost of abatement measures taken to ensure GHG emission reductions, operating costs and potential benefits and combining all these numbers to compute the cost effectiveness for each method. The methodology used to calculate the overall cost of carbon mitigation is based on that proposed by Ibrahim and Kennedy [16] for constructing marginal abatement cost curves for climate action and is revised by the author for application in waste management. The following equations show the major calculation path:

Cost effectiveness of mitigation measure = Net present cost / GHG emissions avoided (1)

(\$/MTCE reduction) = (\$/ton MSW) / (MTCE/ton MSW)

where MTCE: metric tons of carbon dioxide equivalent and MSW: municipal solid waste

The net present cost (NPC) is defined as follows:

$$\text{NPC (\$/ton MSW)} = (\text{Capital cost} + \text{Operating cost} - \text{Revenue})_{\text{mitigation measure - baseline}} \quad (2)$$

And the GHG emissions avoided (CE):

$$\text{CE (MTCE/ton MSW)} = \text{CE}_{\text{mitigation measure}} - \text{CE}_{\text{baseline}} \quad (3)$$

3.2 Description of Scenarios

This study chose five common waste management scenarios following the order of the waste management hierarchy (Figure 4). Scenario 1 is the baseline and the other four are carbon mitigation options. All of them are assumed to be based in the U.S and are described briefly below:

Scenario one (baseline): sanitary landfilling

This is the baseline scenario since sanitary landfilling without any energy recovery is the most basic waste management method. In this case, MSW would be disposed in a standard sanitary landfilling which arrives the requirements for soil and water pollution preventions.

Scenario two (mitigation option): sanitary landfilling with landfill gas collection and flaring

This scenario considers part of energy recovery after sanitary landfilling. MSW would be disposed in a sanitary landfilling, then about half of the landfill gas would be collected and flared in order to reduce the direct GHG emissions.

Scenario three (mitigation option): sanitary landfilling with electricity generation

This scenario assumes the most advanced sanitary landfilling is applied. After disposing MSW into the sanitary landfilling, half of the landfill gas would be collected and used for electricity generation. Direct GHG emissions can be reduced and there are extra cost savings from sales of electricity.

Scenario four (mitigation option): Waste to Energy (WTE)

MSW with the average U.S. composition in the figure 1 would directly go to a WTE plant with assumed moving grate combustion chamber and air pollution control system. After combusting, metals in the ash are recovered and the rest ash go to the sanitary landfilling.

Scenario five (mitigation option): Mechanical Biological Treatment (MBT) plus WTE

MSW would be firstly sent to the MBT plant. Certain amount of materials will be recycled and amount of waste will be reduced by mechanical treatment technologies in combination with biological technologies. Then the residues will go to a WTE plant for the same treatment process as scenario four.

4. Assumptions made in Cost Benefits Analysis and Data Availability

This section discusses the assumptions and data collected including emission factors, capital costs, operation costs, potential benefits and system design assumptions used in the cost effectiveness analysis for five scenarios above. It is notable that all the following calculations are based on the input of one ton MSW.

4.1 Sanitary Landfilling

(1) GHG emissions

In this section, the actual amount of carbon dioxide equivalent emitted is calculated per ton of MSW landfilled, on the basis of assumptions made.

The C-H-O molecular structure of the U.S. MSW was calculated by Themelis, Kim et. al [17] on the basis of chemical analysis. The average composition of combustible materials in MSW can be expressed by the formula $C_6H_{10}O_4$ (kmol wt=146kg). This C-H-O compound reacts as follows in landfills and anaerobic digestion as follows:

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2 \qquad (4)$$

Landfill gas is a product of biodegradation of refuse in landfills, and it contains mostly methane (CH_4) and carbon dioxide (CO_2), with a small amount of non-methane organic compounds that include air pollutants and volatile organic compounds. Assuming that MSW contains 60% of dry organics results in 417 kg (2.86kmol) of $C_6H_{10}O_4$ /ton of MSW as derived from Themelis and Ulloa [18]. A simple material balance based on equation (4) shows that complete reaction of one ton MSW would generate 0.149 tons of methane plus 0.346 tons of CO_2. The CO_2 equivalent of the 0.149 CH_4/ton MSW can be obtained by multiplying this number by its GHG potential, generally assumed to be 21[19], which results in 3.129 tons CO_2eq per ton MSW. If it is assumed that only 50% of the landfilled biomass in MSW is actually reacted to methane, the generation of landfill gas from methane is 1.56 tons CO_2eq/ton MSW. So the total CO_2eq emitted is 1.56 (from CH_4) plus 50% of 0.346 (from CO_2), i.e. **1.73 tons CO_2eq per ton MSW**.

(2) Cost of sanitary landfilling:

- **Capital cost**: Capital costs include site development and construction costs. Derived from the study by Eilrich [20], a 31.5-acre landfill site with a total capacity of 543,884 tons would cost over 7 million dollars for site development and construction compared with a 78.9-acre landfill site with a total capacity of 1364000 tons that cost about 12 million dollars. Transferring all the dollars to 2016$, the capital cost per ton ranges from 11.5 to 17.1 dollars.

- **Operation and maintenance cost**: Includes operation and monitoring cost, closure cost, post-closure care cost. From the study of Eilrich, on a per ton base, O&M cost also increases with decreasing of the landfilling site size, from US $15.1/ton MSW to $27.56/ton MSW, for the smaller landfill. Transferring all the dollars to 2016$, the O&M cost per ton ranges from 19.8 to 36.2 dollars.

Table 2 summarizes the capital and operation costs used in this study [20].

Table 2 Detailed Costs Analysis for Two MSW Landfills in Rural Oklahoma (Eilrich, 2003)

	88 Tons per Day		220 Tons per Day	
Item	**Cost per Ton ($)**	**Total Cost ($)**	**Cost per Ton ($)**	**Total Cost ($)**
Site Development Costs	2.38	1,296,233	1.00	1,367,400
Contingency (15%)	0.36	194,435	0.15	205,110
Construction Costs-Through Phase 1	3.18	1,731,704	1.03	1,408,461
Construction Costs-Remaining Phases	5.93	3,225,767	5.70	7,769,866
Contingency(10%)	0.91	495,747	0.67	917,833
Site Development & Construction Financing Costs	0.28	153,006	0.19	2556,922
Total Site Development and Construction Costs	**13.04**	**7,096,892**	**8.74**	**11,925,591**
Net Interest on Revenue Bonds	5.94	3,233,157	3.96	5,402,863
Total Site Development, Construction, and Financing		**10,330,049**		**17,328,454**
Operation and Monitoring Costs	23.21	12,622,754	12.21	16,647,632
Closure Costs (Annuity payments)	0.71	385,127	0.30	415,341
Post-Closure Care Costs (annuity payments)	3.65	1,983,405	2.59	3,529,983
Total Operation, Closure, and Post-Closure Costs	**27.56**	**14,991,285**	**15.10**	**20,592,957**
Total Estimated Costs	**46.56**	**25,321,334**	**27.80**	**37,921,412**

Number of Acres Developed	31.5	78.9
Development, Construction, and Financing Per Acre	**327,938**	**219,626**
Average Total Cost Per Acre	**804,762**	**480,571**
Site Capacity (tons)	543,884	1,364,000
Average Cost Per Ton	**46.56**	**27.80**

(3) Benefits:

For sanitary landfilling without energy recovery, the only revenue is derived from the gate fee. The landfill gate fee in the U.S. ranges from $24/ton in Utah to $91/ton in Main. For this case, we assume the gate fee is $45/ton.

The table below summarizes the data used for calculating carbon mitigation cost of sanitary landfilling:

Table 3 Sanitary Landfilling Data Summarization

Avoided GHG per ton of material (MTCE)	0			
Cost	highest	lowest	Mean value	Standard deviation
Capital cost ($/ton)	17.1	11.5	14.3	3.0
O & M cost ($/ton)	36.2	19.8	28.0	8.2
Revenue ($/ton)	45.0			

4.2 Sanitary Landfilling with LFG Collection and Flaring

(1) GHG emissions:

According to the calculations of section 4.1, the CO_2eq of methane emitted from per ton MSW is about 1.56 tons. Assuming 50% of the LFG is captured and either flared or used (not all LFG is collected due to delays and leaks), the loss of methane is 0.78 tons CO_2eq per ton MSW landfilled. Adding with the direct CO_2 emissions 0.17 tons/ton MSW, the total CO_2eq emitted would be 0.95 tons/ton MSW. Compared with sanitary landfilling (baseline), the reduced CO_2eq emissions is around 0.78 CO_2eq tons/ton MSW.

(2) Cost:

- **Capital cost**: Capital costs includes the fee for design and engineering, permits, site preparation and installation of utilities, equipment, startup costs and working capital, and administration. It is more expensive than a sanitary landfilling without gas collection and flaring system. According to USEPA Landfill Methane Outreach Program, a mid-sized LFG collection and flare system for a 40-acre wellfield designed to collect 600 cfm is approximately \$1022,000, or \$25,500 per acre for installed capital costs. These costs can vary depending on several design variables of the gas collection system [21]. Assuming the site has same capacity ranges as in section 4.1, the total capital cost for the LFG collection and flare system would be over 10 million. For a per ton base, it is about \$1.48 per ton MSW. Adding to the capital cost in section 4.1, the total capital cost is about \$13 to \$18.6 per ton MSW.

- **Operation and maintenance cost**: Includes parts and material, labor, utilities, financing costs and taxes. Also derived from EPA [21], annual O&M cost for the LFG collection and flaring system of the same size ranges in section 4.1 is around \$4,500 per acre. For a per ton base, it is \$0.26 per ton MSW. Adding to the numbers in 3.1, the total O&M cost is about \$20.1 to \$36.8 per ton MSW.

(3) Benefits:

- **<u>Gate fee</u>**: The landfill gate fee in the U.S. ranges from \$24/ton in Utah to \$91/ton in Main. In this scenario, we assume the gate fee is \$55/ton.

- **<u>Carbon credits</u>**: According to the WTE guidebook, the value of credits per ton of avoided carbon emissions (CER) is estimated at US\$16. As noted above, the CO_2 eq reduced per ton MSW for sanitary landfilling with LFG collection and flaring is about 0.78 CO_2 eq tons/ton MSW. So in this case the conservative value of US\$ 12.48 per ton of MSW was used.

The table below summarizes the data used for calculating carbon mitigation cost of sanitary landfilling with LFG collection and flaring.

Table 4 Sanitary Landfilling with Gas Collection and Flaring Data Summarization

Avoided GHG per ton of material (MTCE)	0.78			
Cost	highest	lowest	Mean value	Standard deviation
Capital cost (\$/ton)	18.6	13.0	15.8	3.0
O & M cost (\$/ton)	36.8	20.1	28.5	8.2
Revenue without CER(\$/ton)	55.0			
Revenue with CER (\$/ton)	67.5			

4.3 Sanitary Landfilling with LFG for Electricity Generation

This is also one of the carbon abatement options considered in the analysis. Using LFG collected for electricity generation can not only save GHG emissions but also make LF more cost-effective.

(1) GHG emissions:

Also assuming 50% landfilling gas would be collected for electricity generation, the total CO_2eq emitted is 0.95 tons/ton MSW and the reduced CO_2eq emissions compared with baseline is around 0.78 CO_2eq tons/ton MSW as illustrated in section 4.2.

(2) Cost

- **Capital Cost**: According to USEPA Landfill Methane Outreach Program, capital costs for a 3-MW engine project without LFG collection and flaring system is $5306874, include costs for energy generation equipment and also interconnection equipment [21]. Adding to numbers in section 4.2, the capital cost is about $16.9 to $22.5 per ton MSW.
- **O & M cost**: According to USEPA Landfill Methane Outreach Program, O&M costs for a 3-MW engine project without LFG collection and flaring system is $566786 [21], adding to numbers in section 4.2, the O&M cost is about $20.5 to $37.2 per ton MSW.

Typically, LF electricity generation technology can be divided into five types: Internal combustion engine (>0.8 MW), Small IC engine (<1MW), Gas turbine (>3MW), Micro-turbine (<1WM) and CHP with IC engine (<1 MW) [10]. Table 5 also shows the typical capital costs and O&M costs according to their electricity production capacity [21].

Table 5 LFG Electricity Project Technologies — Cost Summary

Technology	Optical Project Size Range	Typical Capital Costs ($/kW)*	Typical Annual O&M Costs ($/kW)*
Microturbine	1 MW or less	2,800	230
Small internal combustion engine	799 kW or less	2,400	220

Large internal combustion engine	800 kW or greater	1,800	180
Gas turbine	3 MW or greater	1,400	130

*2013 dollars for typical project sizes

(3) Benefits:

- **Sales of electricity**: According to the total tonnages of MSW landfilled and the total output of electricity produced by LFG [18], the LF gas to energy value is about 0.05 to 0.1 MWh for per ton MSW. Assuming the market electricity price is $0.032 per kWh[1], the revenue from selling electricity is about 1.6 to 3.2 dollars per ton MSW. The average number of $2.4/ton is used here.
- **Gate fee**: The landfill gate fee in the U.S. ranges from $24/ton in Utah to $91/ton in Main. For this case, we assume the gate fee is $65/ton.
- **Carbon credit**: According to the WTE guidebook, the value of credits per ton of avoided carbon emissions (CER) is estimated at US$16. As noted above, the CO_2eq reduced per ton MSW for sanitary landfilling with LFG electricity generation is about 0.78 CO_2eq tons/ton MSW. So in this case the conservative value of US$ 12.48 per ton of MSW was used.

The table below summarizes the data used for calculating carbon mitigation cost of sanitary landfilling with electricity generation.

Table 6 Sanitary Landfilling with electricity generation data Summarization

Avoided GHG per ton of material (MTCE)	0.78

[1] According to EIA, the average wholesale electricity price is $32/MWh .https://www.eia.gov/electricity/wholesale/#history.

Cost	highest	lowest	Mean value	Standard deviation
Capital cost ($/ton)	22.5	16.9	19.7	3.0
O & M cost ($/ton)	37.2	20.5	28.9	8.2
Revenue without CER($/ton)	67.4			
Revenue with CER ($/ton)	79.9			

4.4 Waste to Energy

There are two main WTE technologies: moving grate and circulating fluid bed combustion with energy recovery. This study is based on moving grate combustion since it is the most common WTE technology.

(1) GHG Emissions:

According to Themelis and Kim, The $C_6H_{10}O_4$ (kmol wt=146kg) compound reacts as follows in WTE combustion chambers:

$$C_6H_{10}O_4 + 6.5O_2 = 6CO2 + 5H_2O \tag{5}$$

As noted above in section 4.1, assuming dry organics in amount to 60% of biomass results in the 417 kg (2.86kmol) of $C_6H_{10}O_4$ /ton of MSW. The amount of CO_2 emitted would be 17.16 kmol and 0.755 tons/ton MSW. Thus the directly reduced CO_2eq compared with baseline is **0.98 tons/ton MSW.**

The recovery of metals from WTE ashes contributes to the environment also, since it is associated with the avoidance of the extraction of raw materials. If we also consider this part of GHG benefits, it is usually estimated that at least 50% of the metals contained in MSW can be recovered from the WTE bottom ash. Since the MSW in the U.S. contains 9.0% metals (Figure 3), then from every ton of MSW combusted approximately 45 kilograms of metal could be recovered. Citing from the avoided GHG emissions by recycling over landfill disposal calculated by Themelis, Krones et. al [22], the total avoided

GHG for per ton mixed metal is 1.741 MTCE compared with sanitary landfilling. So the GHG benefits from metal recovery is 0.045tons/ton MSW * 1.741 MTCE/ton=0.078 MTCE/ton MSW.

Adding them together, the total reduced CO_2eq compared with baseline is **1.06 tons/ton MSW.**

(2) Cost:

- **Capital Cost**: Includes facility design and construction fee, also the cost of land, incinerators, ash handling system, turbine, air pollution control and monitoring devices. According to a study from Themelis, construction and operation of a WTE facility of 235,000 tons per year capacity may cost over US$96 million ($600 per ton of annual capacity) in the U.S. [23]. From WTE Guidebook, a mid-range plant of 160,000 tons annual capacity may cost from US$80 million ($500 per ton of annual capacity) to US$120 million ($750 per ton of annual capacity). Assuming WTE plant has a lifetime of twenty years, consider the total site capacity for the whole life of WTE plant, then the estimated cost for per ton MSW processed would be $25 to $37.5 dollars.
- **O&M Cost**: Includes disposal of bottom and fly ash, cost of chemicals, cost of labor and electricity fee, on a per ton base, O&M cost usually increased with decreasing of the WTE plant size, which is from US $32/ton MSW for the one million tons plant of Buenos Aires to $47/ton MSW for 160,000 tons plant in Toluca [18].

(3) WTE Plant Revenues:

- **Revenues from electricity**: Assuming that 0.55MWh of electricity is produced per ton of MSW, amounting to about $17.6 per ton MSW at the market electricity price of $32/MWh.
- **Gate fee:** The WTE gate fee for the U.S. ranges from $25/ton in Alabama to $98/ton in Washington. The average number of $61.5 was used here.
- **Carbon credits revenues**: According to the calculation before in this section, the projected reduction in greenhouse gas emissions due to the WTE operation would be 1.06 tons of carbon dioxide per ton MSW, in comparison to sanitary landfilling. According to the WTE Guidebook, the value of credits per ton of avoided carbon emissions (CER) is estimated at US$16. So in this case the conservative value of US$ 17.0 per ton of MSW was used.

- **Sales of metals recovered from bottom ash:** It is usually estimated that at least 50% of the metals contained in MSW can be recovered from the WTE bottom ash. Since the MSW in the U.S. contains 9.0% metals (Figure 3), then from every ton of MSW combusted approximately 45 kilograms of metal could be recovered. Using an estimated price of US$500 per ton scrap metals, the WTE facility would have a revenue of US$22.5 per ton of MSW combusted.

The table below summarizes the data used for calculating carbon mitigation cost of WTE plant.

Table 7 Waste to Energy Data Summarization

Avoided GHG per ton of material (MTCE)	1.06			
Cost	highest	lowest	Mean value	Standard deviation
Capital cost ($/ton)	37.5	25.0	31.3	6.3
O & M cost ($/ton)	47.0	32.0	39.5	7.5
Revenue without CER($/ton)	101.6			
Revenue with CER ($/ton)	118.6			

4.5 MBT plus WTE facilities

In this scenario, some facts and assumptions are based in the successful applied MBT plus WTE cases in Mataro facility near Barcelona and the Hornillos plant near Valencia applied by SACYR Group of Spain. Earth Engineering Center (EEC) of Columbia University has recently examined this technology for its material flows, composition and heating value, system design and the economic perspective [24]. The assumptions referred from the EEC SACYR report that used in this study are as follows:

- The MBT plant will have a capacity of 235,000 tons per year, plus a WTE facility of 168,000 tons per year.

- There are 7.3% of the total MSW recycled in MBT plant, as shown in Table 8.
- In general, 20% of the total MSW is composted in MBT plant.
- MBT plant can reduce the feedstock to the subsequent WTE stage by 45-50%.
- The WTE would have a CAPEX of $600/annual ton and the MBT $400/ annual ton according to the Hornillos plant in Valencia.
- Matero facilities typically provide 0.39 MWh/ton electricity to the grid.

(1) GHG emissions

Referring to an analysis of the MBT-WTE Technology applied at the Mataro Plant in 2015, the percentage of various recyclables and compost in MSW in MBT plant are shown in Table 8 [24]. Also according to the avoided GHG emissions by recycling over landfill disposal calculated by Themelis, Krones et. al. [22], and also according to the avoided GHG emissions by composting over landfill by EPA WARM [27], the total avoided GHG for per ton MSW that was recycled and composted in MBT plant is 0.25 MTCE as shown in Table 8.

Table 8 Percentage and GHG Emissions Avoided in MBT Plant

Recyclable materials	Reduction in GHG emissions (MTCE per ton of material) [22]	Tons recovered per ton of MSW to MBT plant [24]	Avoided GHG per ton of MSW (MTCE)
Ferrous (incl. bulky and secondary)	0.5	0.016	0.008
Non-Ferrous (Al, Cu)	4.0	0.007	0.028
Paper/Cardboard	0.8	0.017	0.0136
Plastics	0.4	0.025	0.01
Glass	0.1	0.008	0.0008
Compost	0.95	0.2	0.19

TOTAL (recyclables and compostable)		0.273	0.25

When one ton of MSW goes to the MBT, there are 0.55 tons residues go to WTE. Since one ton MSW in WTE will save 1.06 MTCE compared with sanitary landfilling, the GHG from WTE part would be 0.55tons*1.06 MTCE/ton MSW = 0.58 tons MTCE.

Adding up two parts GHG benefits, the total savings would be **0.83 MTCE/ton MSW** in MBT plus WTE facility.

(2) Costs

- **<u>Capital Cost</u>:** Consists of costs for facility construction, engineering and equipments. Since the Mechanical Biological Treatment (MBT) plant can reduce the feedstock to the subsequent WTE stage by 45-50% by means of mechanical recycling and biochemical processing. Therefore, the size and capital cost of the Mataro WTE plant was reduced by 45-50%, compared to the single WTE option. So the capital cost for the MBT ($400 per ton of MSW) plus WTE ($600) option should be around $400+$600*55%=$730 per annual ton. Assuming 20 years lifetime, consider the total site capacity for the whole life of MBT plus WTE plant, the cost for each ton MSW processed is about 36.5 dollars.
- **<u>O&M Cost</u>**: Includes maintenance fee of facility and equipment, wages, landfilling of MBT process. Adding the landfilling fee of MBT process ($30/ton) to the WTE O&M costs, the average O&M cost of this facility is about $36.66 to $51.66 per ton MSW. The table below also shows the typical MBT cost in EU [25], which has an even wider cost range.

Table 9 Typical MBT Cost in EU

Aerobic process	AD processes

Capacity (TPY)	CapEx ($/T/year)	OpEx ($/t)	CapEx ($/T/year)	OpEx ($/t)
<50,000	120-250	<235	270=700	>38
>50,000	50-380	33-115	180-470	26-115

(3) Revenues:

- **<u>Sales of recyclables and compostables from MBT</u>**: Recyclables and compostables constitute 27.3% of the total MSW in MBT plant. According to the percentage of different recyclables and the secondary market price in the U.S., for per ton MSW goes to the integrated system, the revenue is $96.42/ton MSW. Table 10 shows a more detailed data of this revenue.

Table 10 Breakdown of the price for recyclable products to the secondary markets

Recyclables and compostables	% of total MSW in MBT plant [24]	Price ($/ton)	revenue ($)
Ferrous (incl. bulky and secondary)	1.6	165.0	0.26
Non-Ferrous (Al, Cu)	0.3	770.0	2.31
Paper/Cardboard	1.7	77.0	1.31
Mixed plastics	0.8	17.4	0.14
PET	0.8	198.0	1.58
Glass	0.8	23.1	0.18
Film	0.7	N/A	0

Tetra pack	0.4	-10.1	-0.04
HDPE	0.2	341.6	0.68
Compost	20	4.5	0.9
TOTAL (recyclables and compostable)			**7.32**

- **Gate fee**: Typically a MBT plant will have the gate fee from $50-55 per ton MSW [26]. Also using 61.5 dollars per ton MSW as the gate fee for WTE, according to the percentage (55% MSW go to WTE after MBT), for one ton MSW goes to the combined facility, the estimated gate fee would be about $86.3 per ton MSW.
- **Electricity**: Matero facilities typically provide 0.39 MWh/ton electricity although WTE plant of this capacity (500 metric tons/day) typically provides to the grid 0. 55 MWh per metric ton [24]. Also assuming the electricity price is $0.032/kWh, the revenue should be 390 kWh/ton MSW * $0.032/kWh=$12.48/ton.
- **Carbon credits**: According to the calculation before in this section, the projected reduction in greenhouse gas emissions for this integrated facility is 0.83 tons of carbon dioxide per ton MSW, in comparison to sanitary landfilling. According to the WTE guidebook, the value of credits per ton of avoided carbon emissions (CER) is estimated at US$16. So in this case the conservative value of US$13.28 per ton of MSW was used.

The table below summarizes the data used for calculating carbon mitigation cost of MBT plus WTE plant.

Table 11 MBT plus WTE data Summarization

Avoided GHG per ton of material (MTCE)	0.83

Cost	highest	lowest	Mean value	Standard deviation
Capital cost ($/ton)	36.5	36.5	36.5	0
O & M cost ($/ton)	51.7	36.7	44.2	7.5
Revenue without CER($/ton)	106.1			
Revenue with CER ($/ton)	119.4			

4.6 Data Summary

In this study, we consider two kinds of total revenue: with and without Certified Emissions Reductions (CER). As illustrated in the above sections, all of the last four scenarios have corresponding carbon reductions compared with the baseline. However, the U.S. have not yet agreed to the Kyoto Protocol so the continuation of the carbon market is still uncertain while E.U. has declared the long term commitment to the Clean Development Mechanism. So the revenue without CER can represent more common situations in reality, however we also would like to see what happens for carbon mitigation cost if CER is included.

The overall summarization of the key numbers used for calculation for five scenarios are shown in Table 12 below. For the numbers with a range, average numbers are used for the final calculations.

Table 12 Summary of cost and price assumptions for different waste management technologies

Waste management methods	Capital Cost ($/ ton)	O&M Cost ($/ton)	Revenue Without CER ($/ton)	Revenue With CER ($/ton)	GHG reduced (MTCE/ton)
Sanitary landfilling (baseline)	14.3	28	45	45	0

Sanitary landfilling with LFG collection and flaring	15.8	28.5	55	67.5	0.78
Sanitary landfilling with electricity generation	19.7	28.9	67.4	79.9	0.78
Waste to energy	31.3	39.5	101.6	118.6	1.06
MBT plus WTE	36.5	44.2	106.1	119.4	0.83

5. Results and Discussion

5.1 GHG emissions of five scenarios

In summary, Figure 6 is the visualization of GHG reductions for five scenarios. Sanitary landfilling has no reduction since it is the baseline. For the other four mitigation options, WTE has the highest GHG reduction overall. The second highest GHG reductions derives from MBT plus WTE, two kinds of landfilling with energy recovery have the least GHG reductions.

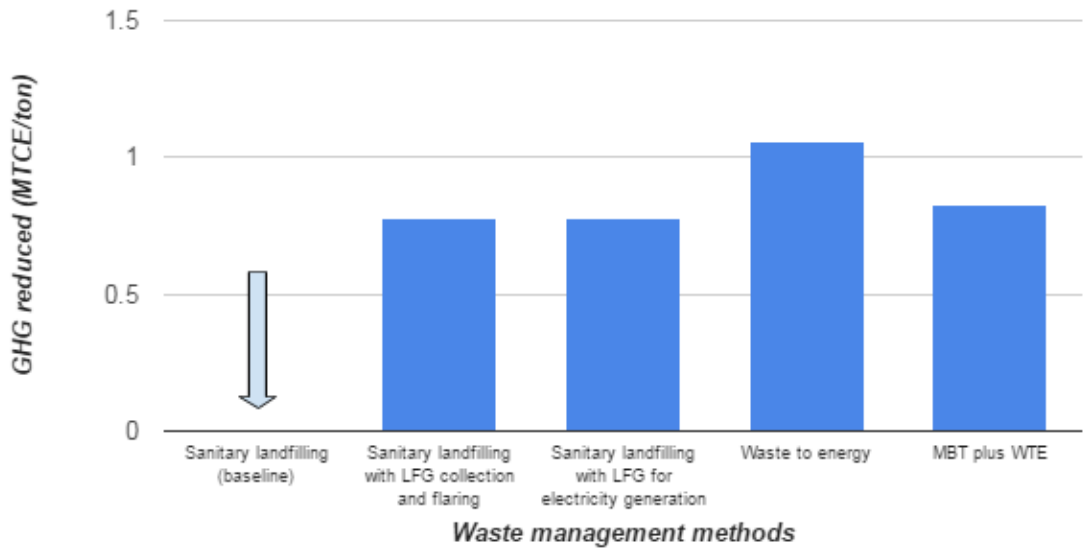


Figure 6 GHG Reductions for Five Scenarios

Surprisingly, the GHG reduction of MBT plus WTE plants is lower than WTE plant, reasons may come from that there are only 7.3% of MSW recycled in MBT, and there are certain parts of MSW being composted that would also emit methane to the atmosphere.

5.2 A cost-benefit comparison among different waste management options

Considering the net profits of each scenario, as shown in Figure 7, all of them have a positive net profit, which means their revenues exceed the costs. Although their costs are increasing from scenario one to five according to Table 12, their net profits also have an increasing tendency due to their different energy output and gate fee. WTE has the highest profits, MBT plus WTE ranks the second highest, then three kinds of landfilling have relatively lower profits.

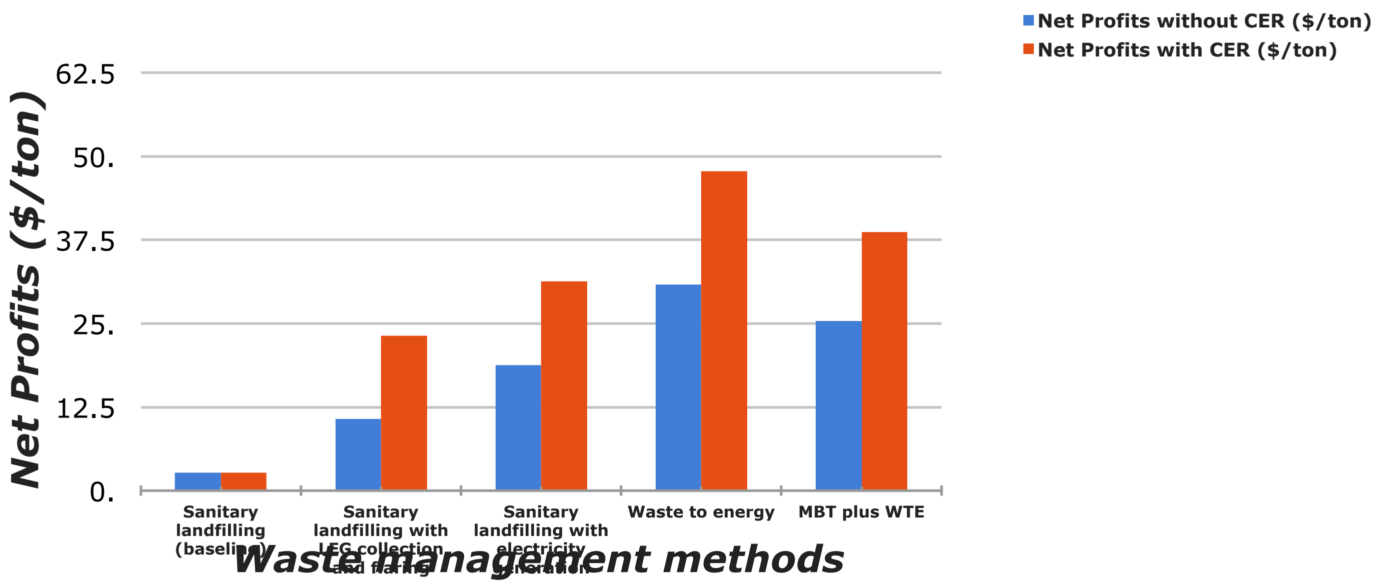


Figure 7 Net Profits Comparison Among Five Waste Management Scenarios

5.3 Carbon mitigation cost analysis

When considering both GHG benefits and economics of waste mitigation options, Figure 8 is the visualization of comparable mitigation measures that demonstrate the economics as well as the technical merits of reducing GHG emissions. This graph is constructed by showing the GHG abatement cost of waste division options (vertical line) as a function of their GHG reduced (horizontal line), and placing mitigation measures in ascending order of cost-effectiveness. It's worth noting that these numbers do not mean that whether these waste management methods are necessary or not. This graph is a reflection of economic position when their environmental benefits are considered at the same time. It is more of a reference for decision makers.

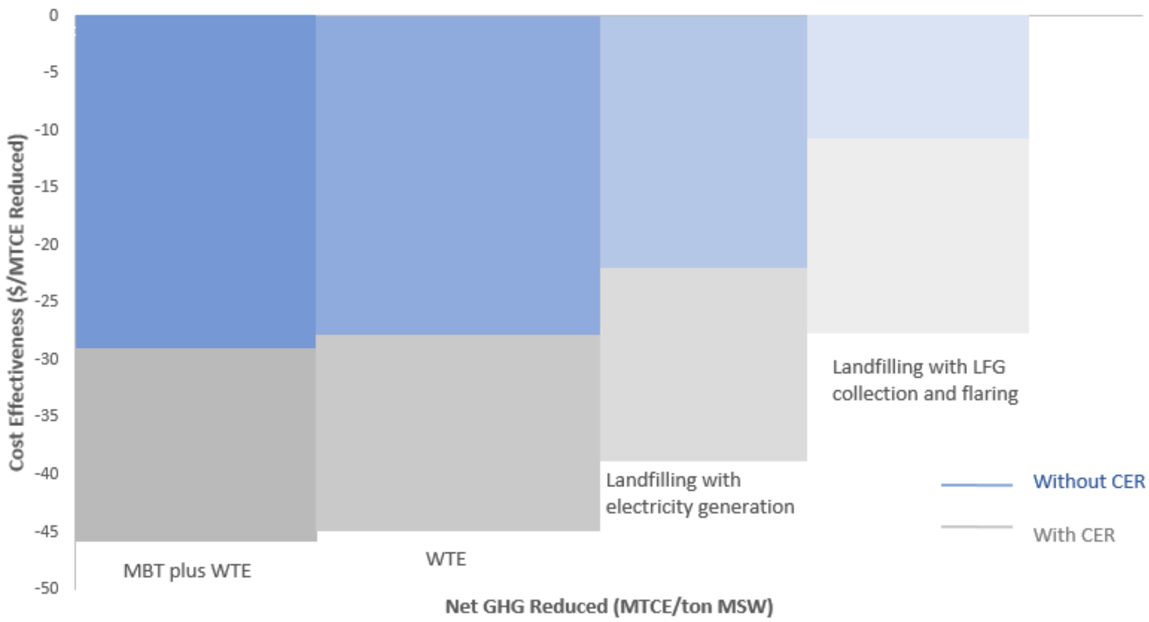


Figure 8 Carbon Mitigation Cost (with and without CER) of Four Waste Management Options Compared with Baseline

This graph reflects dual effects from economical and environmental perspectives for different mitigation options. The result is not only just a reflection of cost but also influenced by the GHG benefits. Different technologies are ranked by the value of their carbon mitigation costs, and all of them are negative, which means that their revenue has passed the cost when reduce per ton carbon dioxide equivalent. For different carbon mitigation measures, the more rely on the left, the more economical advantages they have for decreasing the impact on GHG effect.

When reducing same amount of carbon dioxide equivalent (here use the unit of reducing one million tons carbon equivalent), MBT plus WTE has the highest profits, which is 27.34 dollars for reducing one metric ton of carbon dioxide equivalent without considering CER. This scenario appears to be the best option if considering the economic costs for reducing GHG.

The second lowest carbon mitigation cost derives from WTE. It not only eliminates the environmental impacts of landfill waste and helps mitigate global warming, but also has the highest profits from the energy recovery. Since not 100% waste can be reduced or recycled, WTE is the best choice to decrease waste that will be landfilled.

Two kinds of landfilling with energy recovery have relatively higher carbon mitigation cost compared with WTE and WTE plus MBT. But both of them showed the better performance compared with the sanitary landfilling without any energy recovery. Between this two landfilling mitigation methods, LFG for electricity generation has obviously more profits than LFG collection and flaring. Despite the efforts for reducing waste from source and increasing recycling rates, U.S. population growth ensures the portion of MSW discarded in the landfills will remain significant and growing. In this situation, equipping sanitary landfill with gas collection and electricity generation system is more environmental friendly and economical profitably.

If considering carbon credits, all of the costs become lower since they have more revenue than before. In certain scenario such as landfilling with gas collection and flaring, carbon mitigation cost with CER is even two times lower than it without CER. Although their CER revenues are different, their total carbon mitigation cost remains the same ranking as when they without CER. From this figure, it is obvious that CER can be an effective economic incentive for carbon mitigation. By including CER, waste management can be more cost effective while reaching GHG reduction targets.

The prioritization of cost-effectiveness can stimulate climate policy discussion focused on investment opportunities. From environmental perspective, abatement options can guide the adoption of newer technologies when considering updating an integrated waste management system; from economic perspective, the cost-effectiveness supports the financial measures of different projects; and from social perspective, the impact of climate and waste management policies can be quantitatively calculated and demonstrated in this graph.

Overall, the performance of carbon mitigation costs for waste management options discussed in this study obeys the waste management hierarchy sequence. From scenario one to five, they reflect higher level in the hierarchy and are more cost effective to reduce the GHG.

5.4 Uncertainties and Limitations

- The percentages for recycling and composting in MBT plant are derived from only one plant in Spain, they may differ in different places and plants according to local waste characteristics and waste management systems. For MBT plus WTE mode, further researches on its GHG reductions are required.
- All the prices for electricity and recyclables are based in the 2016 U.S market. However, fluctuations in prices exist with the time and place change.

- Regional/local situations differ across states, specific costs and GHG emissions for different place are rely on many factors, like annual waste in place, plant capacity, local labor price, certain technology applied, which further complicates the GHG emission factors and economic data collections.
- This study has considered the most common revenue sources. However, other possible revenues may also be existed in some situations. For example, German has imposed landfilling tax (up to $130/ton) to decrease landfilling rate. This kind of extra revenue may also influence the cost effectiveness to reduce the GHG emissions.
- Carbon mitigation cost curve has a clear economic focus based on a least-cost approach. However, policy makers should consider not only cost effectiveness of carbon mitigation, but also some wider effects of climate change on society, like labour market, competitiveness and capital markets.

6. Conclusions and Suggestions

The objective of this study was to determine the carbon mitigation cost of various waste management methods. Five scenarios demonstrate that MBT plus WTE appears to be the best option, although single WTE actually has the most GHG reduction and profits. If the goal is GHG reduction, the WTE is the one reduces the most GHG and with the relatively low carbon mitigation costs in the researched scenarios. Landfilling with energy recovery has better environment and economic performance than landfilling without any energy recovery. Also, although LFG for electricity generation has more CAPEX, it has obviously more profits than LFG collection and flaring to reduce the same amount of GHG. All in all, carbon mitigation cost ranks the same level as their positions in the waste management hierarchy no matter considers CER or not. Furthermore, carbon credit reflects its big contribution to the total revenue and carbon mitigation cost. It can work as a big incentive for carbon mitigation.

Having analyzed the five scenarios and reviewed the literature, the following suggestions are given:

1. From the perspective of carbon mitigation cost, the scientific of waste hierarchy is verified again. We would like to suggest again that waste should be reduced, reused and recycled first. Then

MBT plus WTE is a worthy way for GHG reduction. WTE is highly recommended to replace the direct landfilling;

2. For the sanitary landfilling, installing energy recovery system is highly suggested;
3. Although there are still many controversies about Clean Development Mechanism internationally, from this research, CER is a big benefit incentive for GHG emissions in the waste management world;
4. Due to the limitations and data availability in this study, further research is required to develop a more comprehensive carbon mitigation cost data for waste management. More scenarios should be selected, and certain case study should be used for better rectifying the numbers.

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