Carbon Mitigation Cost of Waste Management Methods

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Global warming is associated with adverse effects in the biodiversity, human survival and development and the earth environment. The need to reduce the Greenhouse Gas (GHG) emissions has by now been accepted universally. Among other methods to slow down the greenhouse effect, waste management can play a key role, directly or indirectly. In addition, inadequate management of municipal solid waste (MSW) impacts on public health and the environment and may affect the development and improvement of future generations. The primary waste treatment options, recycling (including composting), waste to energy (WTE) and landfill are associated with different environmental burdens. In this study, five scenarios were investigated, i.e.: 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 to compare their respective carbon mitigation costs 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 were calculated. The carbon mitigation cost followed the same ranking as implied in the waste management hierarchy. Among the five target scenarios, MBT plus WTE indicated the lowest carbon mitigation cost. WTE ranked the second but had the highest GHG reductions. Also, two landfilling mitigation measures exhibited economic benefits for reducing GHG. The introduction of carbon credit schemes was beneficial for decreasing carbon mitigation cost.

Keywords: carbon mitigation, waste management, waste-to-energy, WTE, mechanical biological treatment, landfilling

1. Introduction

According to the hierarchy of sustainable waste management the most preferable option for municipal solid waste (MSW) treatment, after prevention, is recycling and composting. Recycling reduces energy-related greenhouse gases (GHG) emissions in the manufacturing process and also avoids emissions from landfill. However, there are limitations to the materials that can be recycled in a community, mainly associated with the strength of the secondary markets. For the management of the post recycled MSW that means the waste that does not any recovery potential or value in the market, there are two options. Landfilling or combustion for the production of energy or waste to energy (WTE). Landfilling is the most widely used waste management method because of its very low technology and cost. However, landfilling is a large anthropogenic source 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. Landfill gas collection and utilization or flaring has been applied to many sanitary landfills to reduce gas emissions and there is an increasing tendency to use landfill gas for electricity production. The other alternative for the management of the post recycled waste is the combustion for the production of energy. When waste is combusted, the amount of waste to landfills is reduced, 90v/v%, and waste is transformed to energy in the form of electricity and heat. The energy produced is provided for industry or household uses and thus conserves fossil fuels used in power plants.

Although GHG emission is an important factor when considering a new project, however, the ideal sustainability model implies that sustainable development should be 'decoupled' from the economics of the process; and therefore, economics is always a key concern. 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 [2]. 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 [1], 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 [3].

The carbon mitigation cost is an effective method to characterize both the technical and economic efficiency of processes. 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 [4].

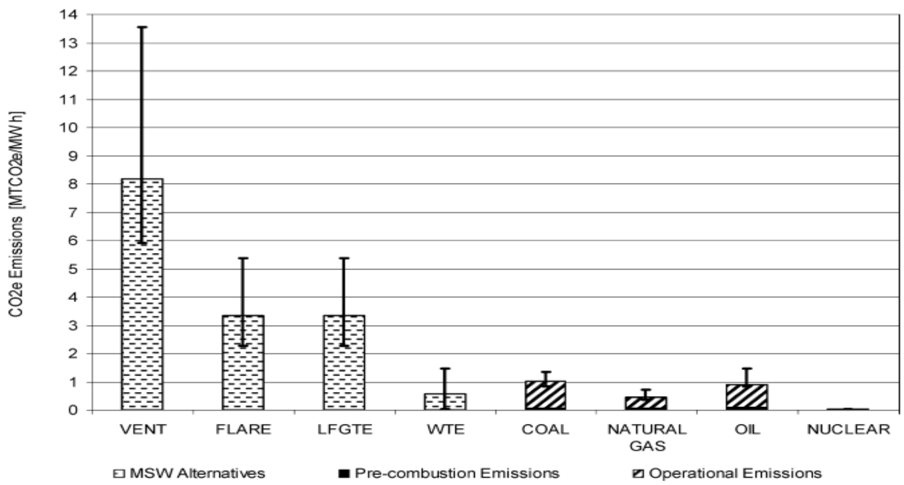

Figure 1 Comparison of carbon dioxide equivalents for LFGTE, WTE, and conventional electricity-generating technologies (reproduced from Kaplan et. Al., 2009)

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) [5]. The World Bank's Energy sector identified the low carbon path for six emerging economies (China, Brazil, India, Indonesia, Mexico, South Africa) [6]. In waste management, Beaumont and Tinch has used the abatement cost curves to enable copper abatement in waste technologies [7]. US EPA has derived MAC curve on Non-CO_2 reductions for top 5 Emitters (China, Mexico, Malaysia, Russia, US) [8]. 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.

This study aims to determine the carbon mitigation cost of different waste management methods. The authors investigated both environmental and economic performance of waste management systems. In addition, the study tries to establish the relationship for the contribution of the carbon credit to the revenue and its influence on the final carbon mitigation cost.

2. Methodology and Description of Research Scenarios

2.1 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 [9] for constructing marginal abatement cost curves for climate action and is revised by the author for application in waste management. The following equations were used:

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:

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

And the GHG emissions avoided (CE):

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

2.2 Description of Scenarios

In this study, five common waste management scenarios were used. 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:

<u>Scenario one (baseline): sanitary landfilling</u>

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 meets the requirements for soil and water pollution preventions.

<u>Scenario two (mitigation option): sanitary landfilling with landfill gas collection and flaring</u>

This scenario considers partially energy recovery in sanitary landfills. MSW is disposed in a sanitary landfill, where about half of the landfill gas is collected and flared.

<u>Scenario three (mitigation option): sanitary landfilling with electricity generation</u>

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

<u>Scenario four (mitigation option): Waste to Energy (WTE)</u>

MSW with the average U.S. composition is assumed to go directly to a WTE plant. After combustion of MSW, metals in the ash are recovered and the rest mineral ash fraction will be disposed to a sanitary landfill.

<u>Scenario five (mitigation option): Mechanical Biological Treatment (MBT) plus WTE</u>

MSW is processed in a MBT plant. Certain amount of materials will be recycled and the 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.

3. Assumptions and Data analysis

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.

3.1 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 the assumptions made.

The C-H-O molecular structure of the U.S. MSW was calculated by Themelis, Kim et. al [10] 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:

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

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 [11]. 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[12], 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 [13], 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 1,364,000 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.

- **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.

A summary of the capital and operation costs used in this study is provided in the Appendix and Table A1 [13].

(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 to be $45/ton.

3.2 Sanitary Landfilling with LFG Collection and Flaring

(1) GHG emissions:

According to the calculations presented in section 3.1, 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 $1,022,000, or $25,500 per acre for installed capital costs. These costs can vary depending on several design variables of the gas collection system [14]. Assuming the site has same capacity ranges as in section 3.1, 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 3.1, 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 [14], annual O&M cost for the LFG collection and flaring system of the same size ranges in section 3.1 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:

- **Gate fee**: 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.

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

3.3 Sanitary Landfilling with LFG for Electricity Generation

(1) GHG emissions:

If 50% of landfill gas is collected for electricity generation, the total CO_2eq emitted is 0.95 tons/ton MSW and the reduced CO_2eq emissions compared with the baseline scenario is around 0.78 CO_2eq tons/ton MSW, as presented in section 3.2.

(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 $5,306,874, include costs for energy generation equipment and also interconnection equipment [14]. Adding to the results presented in section 3.2, 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 $566,786 [14], adding to the numbers calculated 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]. The typical capital costs and O&M costs according to their electricity production capacity were obtained from [13,14].

(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 in this study.

- **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$16. As noted above, the CO_2eq reduced per ton MSW for sanitary landfilling with LFG electricity generation is about 0.78 CO_2eq tons/ton MSW. In this case, the conservative value of US$ 12.48 per ton of MSW was used.

3.4 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:

$$C_6H_{10}O_4 + 6.5O_2 = 6CO2 + 5H_2O \quad (5)$$

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

As noted above in section 3.1, 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 the baseline scenario 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, 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 [15], 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 the baseline scenario 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. [16]. 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, and considering the total site capacity for the whole life of the 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 [16].

(3) WTE Plant Revenues :

- **<u>Revenues from electricity</u>**: 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.

- **<u>Gate fee:</u>** 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.

- **<u>Carbon credits revenues</u>**: 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:** 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.

3.5 MBT plus WTE facilities

In this scenario, some facts and assumptions are based in the successful application of an MBT followed by a WTE facility in Barcelona, Spain, and an MBT plant near Valencia [17]. The assumptions 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 1.
- 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 plant in Valencia.

(1) GHG emissions

The percentage of various recyclables and compost in MSW in MBT plant are shown in Table 1. Also according to the avoided GHG emissions by recycling over landfill disposal calculated by Themelis, Krones et. al. [15], and also according to the avoided GHG emissions by composting over landfill by EPA WARM [18], the total avoided GHG for per ton MSW that was recycled and composted in MBT plant is 0.25 MTCE as shown in Table 1.

Table 1. 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 the GHG benefits, the total savings for this scenario would be **0.83 MTCE/ton MSW**.

(2) Costs

- **Capital Cost:** Consists of costs for facility construction, engineering and equipment. 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 will be reduced by 45-50%, compared to the single WTE option. 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, and 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.

- **O&M Cost**: 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 [19].

(3) Revenues:

- **Sales of recyclables and compostables from MBT**: 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.

- **Gate fee**: Typically, a MBT plant will have the gate fee from $50-55 per ton MSW [19]. 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**: Mataro 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 [17]**.** Also, assuming the electricity price is $0.032/kWh, the revenue should be 390 kWh/ton MSW * $0.032/kWh=$12.48/ton.

- **<u>Carbon credits</u>**: 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. In this case the conservative value of US$13.28 per ton of MSW was used.

5. Results and Discussion

5.1 GHG emissions of five scenarios

Figure 2 presents the GHG reductions for the five scenarios examined with sanitary landfilling as the baseline scenario, i.e. zero GHG reduction. For the other four mitigation options, WTE has the highest GHG reduction overall. The second highest GHG reductions is the MBT plus WTE scenario followed by two types of landfilling with energy recovery that indicate the least GHG reductions.

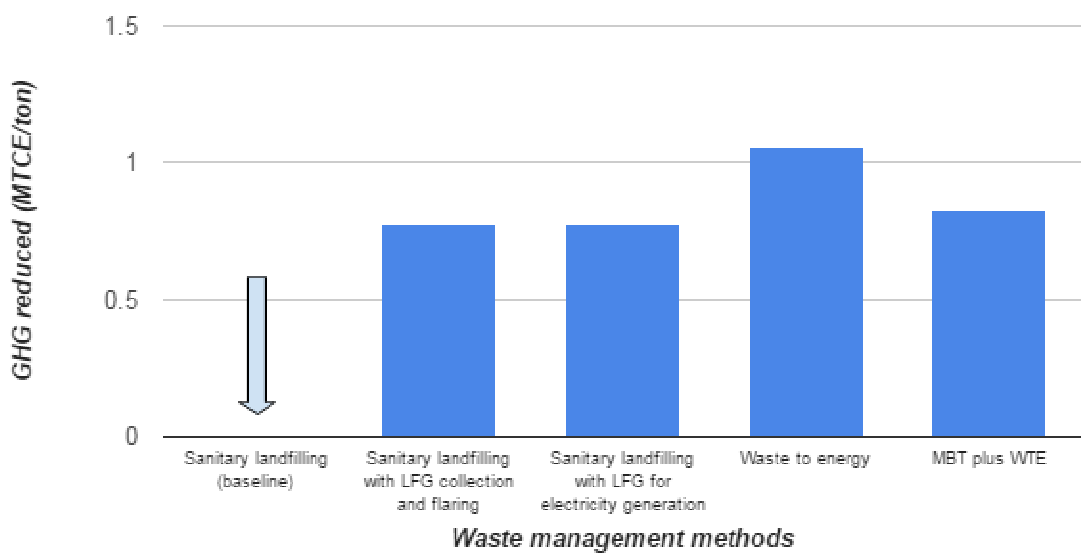

Figure 2 GHG Reductions for Five Scenarios

The GHG reduction of MBT plus WTE plants is lower than WTE plant, and maybe associated with the low recycling rate, of only 7.3% of MSW, 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 3, 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, 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 the three types of landfilling with relatively lower profits, as attenuated. WTE has the highest since it is assumed that metals are recovered from the WTE residues, which are typically the stream with the highest value and demand in the market.

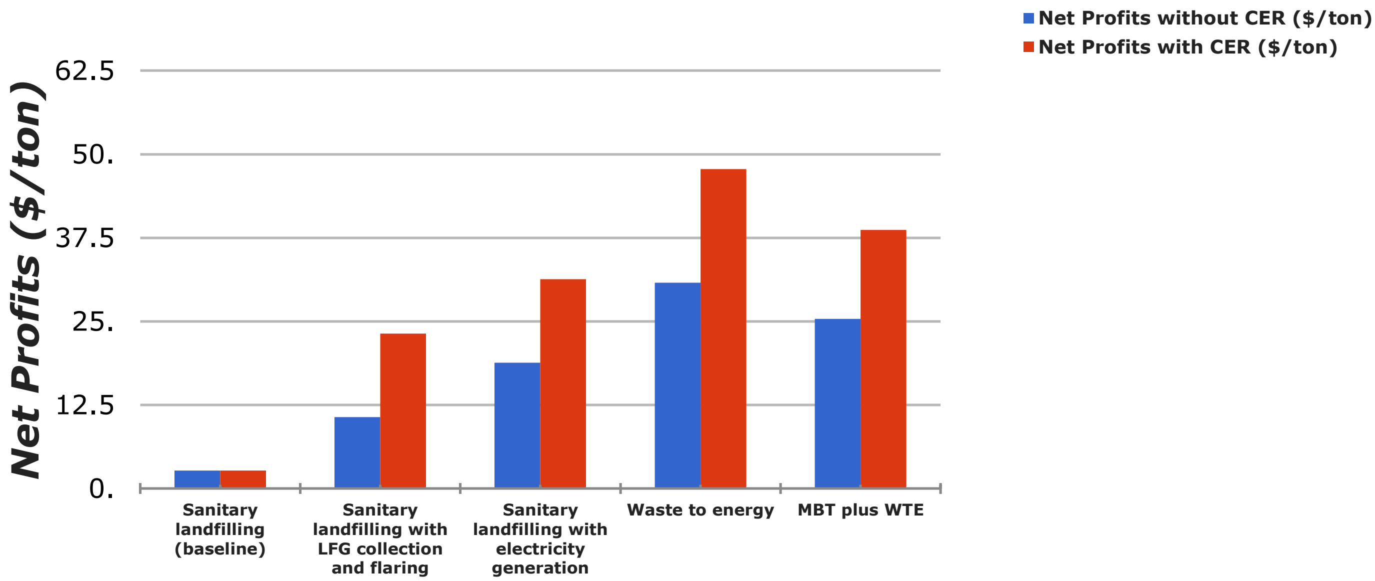

Figure 3. Net Profits Comparison Among Five Waste Management Scenarios

5.3 Carbon mitigation cost analysis

The GHG benefits and economics of waste mitigation options are presented in Figure 4. 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.

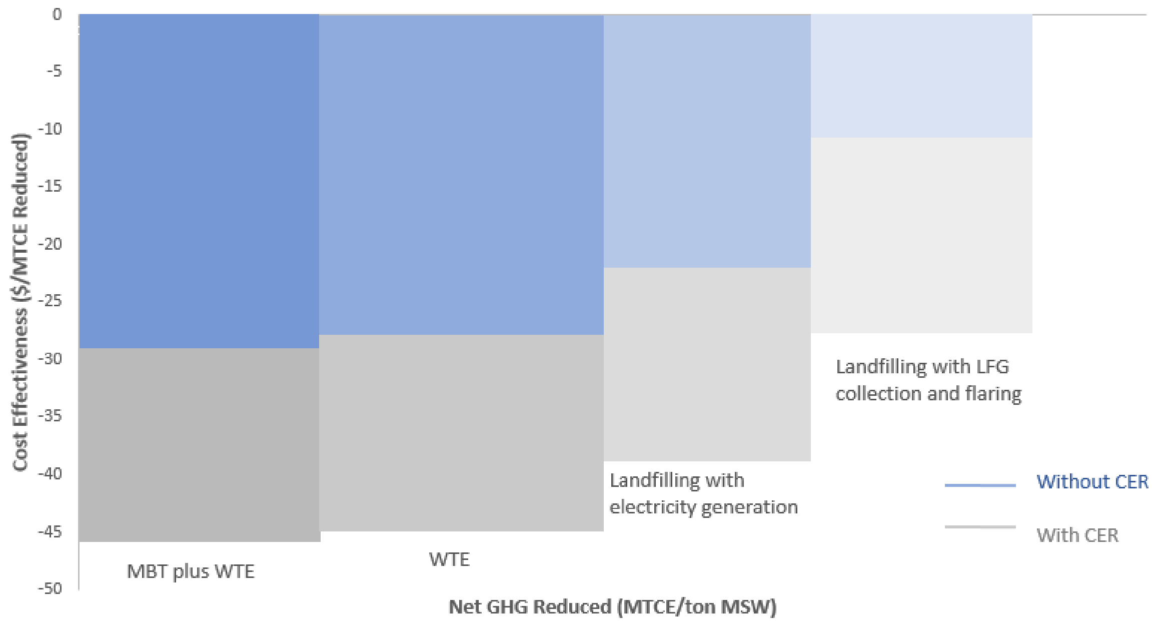

Figure 4. Carbon Mitigation Cost (with and without CER) of Four Waste Management Options Compared with the Baseline scenario

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 and there is a reduction in the emissions of carbon dioxide 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 economics for reducing GHG. The second lowest carbon mitigation cost is the single 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 higher carbon mitigation cost compared with WTE and WTE plus MBT; but improved performance as compared with the sanitary landfilling without any energy recovery. Between the 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.

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 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 reduces the most GHG and with relatively low carbon mitigation costs in the scenarios examined. 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 more profits than LFG collection and flaring and by reducing the same amount of GHG. Carbon credit reflects its big contribution to the total revenue and carbon mitigation cost. It can work as a big incentive for carbon mitigation.

The following suggestions are given:

1. From the perspective of carbon mitigation cost, the approach implied in waste hierarchy is verified again. Ideally MSW should be reduced, reused and recycled/composted first. MBT plus

WTE is an advanced method 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 sector;
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 studies should be used for improved data analysis.

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Appendix

Table A1. Detailed Costs Analysis for Two MSW Landfills in Rural Oklahoma (Eilrich, 2003)

	88 Tons per Day		220 Tons per Day	
Item	**Cost per**	**Total Cost**	**Cost per**	**Total Cost ($)**

	Ton ($)	($)	Ton ($)	
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**

Table A2. 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**