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Environmental and economic modelling for municipal solid waste management strategies: a case study in OH, USA

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Abstract: Management strategies for municipal solid waste (MSW) have been conducted concerning greenhouse gas (GHG) emissions for cities and large geographical regions, but few have been conducted related to GHG emissions from a single facility. This study fills that gap by evaluating economic cost, and social cost of CO₂e for the treatment of MSW streams for a single large facility in Ohio, USA moving towards a zero waste to landfill strategy. A total of eight scenarios related to varying IWM strategies at the facility were studied. Life cycle assessment (LCA) was conducted using the Integrated Waste Management Model (IWM) to find the best potential integrated MSW management strategy. The results indicated that the economic cost and social cost of CO₂e decreased by 49.05% and 2.25 times respectively compared with the current scenario by increasing the recycling rate for the facility by 50%, diverting 30% of food waste to AD processing (from 0%), incinerating the rest of the waste for energy, and sending little to zero waste to landfills.

Keywords: zero waste to landfill; GHG emissions; CO₂e social cost; municipal solid waste; life cycle assessment; LCA; integrated waste management.

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1 Introduction

1.1 Literature review

Human induced climate change generated by the increased GHG emissions to the atmosphere is a serious global concern, and it is currently threatening and will continue to threaten the environment. A recent study by US EPA indicated that nearly 42% of the GHGs emissions are caused by in the entire life circle – ‘procure, produce, deliver and dispose of goods and service’ (US EPA, 2007). The economic policy of many countries considers both economic and environmental factors into the decision-making process as the importance of environmental protection has increased (Kulczycka and Smol, 2016). Solid waste generation is a result of human daily activities. Solid waste management deals with the way resources are being used as well as with end-of-life deposition of materials in the waste streams. The world’s cities generate about 1.3 billion tons of solid waste per year and the volume is expected to be increased to 2.2 billion tons by 2025 (Hoorweg and Bhada-Tata, 2012). The waste sector is a significant contributor to greenhouse gas (GHG) emissions accountable for approximately 5% of the global greenhouse budget (IPCC, 2006) and improper management of MSW through open burning, open dumping and unsanitary landfilling contributes other environmental problems besides global warming, such as ozone depletion, human health hazards, abiotic resource depletion, etc. (Laurent et al., 2014). Management options for MSW can affect the GHG emissions released into the atmosphere, various ways can be used to dispose solid waste: landfill, waste to energy, recycling, organic waste composting, and each method cannot avoid GHG emissions. Landfilling is the most common waste management strategy and a major contributor to the greenhouse gas emissions from the waste (Lou and Nair, 2009). Due to the increased quantity of waste and environmental awareness, the concept of ‘zero waste’ was developed as a solution for waste. ‘Zero waste’ is one of the most visionary concepts to reduce the harm from waste disposal. Many cities have declared their zero-waste vision, such as Adelaide, San Francisco, and Stockholm (Zaman and Lehmann, 2013). Strategies based on tools, systems and technologies in related to waste management can assist cities in their transformation into ‘zero waste cities’ (Zaman and Lehmann, 2011). Zero waste to landfill facilities represent a philosophy that encourages to redesign the life cycles of resources, so that all products are reused, recycled, recovered, and little to zero waste was sent to landfills. El-Haggag and Samaha (2019) explored the sustainable practices on MSW and proposed a holistic zero waste strategy. Common methods utilised at zero landfill facilities include material reuse, recycling, composting, AD, and energy conversion from solid waste that would normally be disposed at landfills. Also, zero waste design principles go beyond recycling

and it focuses firstly on avoidance and reduction of waste by innovative product design and then recycling or resource recovery (City of Austin, 2008).

A waste hierarchy is often suggested and used in waste policy making, hierarchy might be different in different scenarios, but in most cases the following is the suggested order: Reduce the amount of waste-reuse-recycle materials-waste to energy-landfilling (Finnveden et al., 2005). Many researches have been done to assess the impact of different MSW management strategies on climate change based on different cases using LCA tools. Khandelwal et al. (2019) had a comprehensive worldwide review in the application of Life cycle assessment (LCA) in MSW management. LCA has been acknowledged as a tool to enable the researchers to consider the full life cycle of MSW management system and offer potential information that can be used for decision making, and it has been used recently only to the MSW management. Most of the cases are city/region based, in the cases, LCA of MSW management were conducted related to GHG emissions or energy consumption using different modelling tools (Özeler et al., 2006; Mohareb et al., 2008; Zhao et al., 2009; Batool and Chuadhry, 2009; Mahar et al., 2016; Balogun-adeleye et al., 2019), but few have been conducted related to GHG emissions from a single facility's waste treatment management strategy, specifically as it relates to a zero waste to landfill management policy. The study related to the waste in the facilities generally focus on the impact of one waste treatment to the facilities, such as recycling (Franchetti and Kilaru, 2012), food waste treatment (Franchetti, 2013). Life cycle cost (LCC) are often used to evaluates the financial costs during the LCA, Reich (2005) did economic assessment of municipal waste management systems – case studies using a combination of LCA and LCC, Kulczycka and Smol (2016) developed algorithms to link the LCA model associated with environmental issues and the life cycle cost analysis (LCCA) model associated with economic factors to evaluate the investment projects. Not many studies are related to the monetary number of social costs of carbon in life cycle assessments, therefore, various research has tried to integrate the LCA with economic valuation (EV) methods to include the social cost estimation. Kara et al. (2007) presents a methodology to estimate the environmental costs of products during the concept design phase by integrating a simplified life cycle assessment (SLCA) methodology with EV methods. Alkhayyal (2019) designed an optimisation carbon cost network in a reverse supply chain, CO₂ emissions were considered to the maximisation of the profitability to prevent substantial environmental damage.

The social cost of carbon (SCC) is the monetise damage from emitting one unit of CO₂ to the atmosphere, often obtained from computational integrated assessment models (IAMs). Research related to SCC has been conducted in a wide area, Kotchen (2018) illustrated the importance of the SCC. Ricke et al. (2018) studied the county-level social cost of carbon, van den Bijgaart et al. (2014) and Zhen et al. (2018) both developed a closed-form, relatively simple formula for the social cost of carbon, which offered a clear, intuitive understanding of the core relationships in determining SCC. In terms of social cost of MSW management in the literature review, Rathore and Sarmah (2020) studied the economic, environmental and social optimisation of solid waste management in the context of circular economy, Haraguchi et al. (2019) did stochastic cost -benefits analysis of urban waste-to-energy systems, Paes et al. (2020) conducted integrated analysis of environmental and economic indicators on MSW management. None or few have been studied in the economic and social cost of MSW management from a single facility. This study fills that gap by evaluating the environmental and economic modelling for MSW Management for a single large facility in Ohio, USA, moving

towards a zero waste to landfill strategy. The annual operation cost of the MSW management in the facility is applied in the economic modelling, and the GHG emissions from annual MSW generated in the facility is applied in the environmental modelling.

1.2 Background of the facility

The facility is a large automotive assembling facility located in Northwest, Ohio. The top solid waste generated in the facility are paint sludge, trash, baled cardboard, ferrous scrap, adhesive sealer waste, metal, and mixed plastic containers. In this study, only the MSW generated in the facility was studied. The recyclables that are studied in this paper are mainly cardboard, aluminium cans and plastic bottles. All the recycled materials were sent to a local recycling company in Northwest, OH. The office paper is sent to a shredding company for confidentiality issues. The facility was used as an example facility to evaluate different strategies for treatment of MSW in a facility toward zero waste to landfill.

The waste generated in the facility was compacted before collected by the waste removal company and sent to the local landfill in Ohio. There are approximately four to six trash pick-ups in one month. The distance between the facility and landfill/material recovery facility (MRF) is around 6 miles. The distance between the facility and the waste to energy facility is around 67 miles.

2 Methodology

2.1 Economic cost of MSW management system

The economic operation cost in this study is considered to be the yearly operation cost, including the MSW collection and disposing, including truck direct stock (C_1), direct fuel (C_2), direct labour (C_3), equipment depreciation (C_4), and applied overhead cost (C_5), total revenue from the recyclables (C_6), and the process fee of the waste sent to landfill facility, EFW facility, AD facility and composting facility and MRF facility: $C_{(Landfill)}$, $C_{(EFM)}$, $C_{(AD)}$, $C_{(Composting)}$ and $C_{(MRF)}$. Recyclable materials mainly include PET, HDPE, aluminium cans, and cardboard, mixed office paper.

The equation for the economic cost of each MSW strategy is:

$$C_{Economic} = C_1 + C_2 + C_3 + C_4 + C_5 - C_6 + C_{Process\ fee} \quad (1)$$

The data for economic cost C_1 to C_5 in equation (1) is refereed from 2018 Equipment Standard Rates published by Ohio Department of Transportation (ODOT) (2018), For 'DUMP TRUCK, 25,000–35,000 GVW', which is used in this article, the cost per mile is \$2.57. The per mile rate is calculated: miles driven divided by FY total cost. Miles driven: average of last five years total mileage driven. FY total cost: last fiscal year total operational cost (direct stock + direct fuel + direct labour + equipment depreciation + applied overhead cost).

The yearly travelling miles of the waste from the facility to different waste disposal facilities was estimated from the truck average pick-up quantity, the pick-up frequency, and the distance between the facility and the disposal facilities, which will stated in Section 2.3.4.

The material processing fee is shown in Table 1. The current landfilling is for the facility around \$52 per tons, the facility does not have to pay for the MRF process fee, the revenues is estimated to be \$15 per tons for all recycles, the AD process fee is estimated to be \$50 per tons (Correa, 2018), the Composting process fee is estimated to be \$50 per ton which is given by a local composting facility, the EFM processing fee is around \$15 per ton, the data is obtained from a local facility.

Table 1 Waste processing fee

<i>Process</i>	<i>C_{Landfill}</i>	<i>C_{EFM}</i>	<i>C_{MRF}</i>	<i>C_{Composting}</i>	<i>C_{AD}</i>
<i>C_{Process fee} (\$/ton)</i>	52	15	−15	50	50

2.2 CO_{2e} social cost of MSW management system

EPA and other federal agencies use estimates of the social cost of carbon (SC-CO₂) to value the climate impacts of rulemakings. The social cost of CO_{2e} is a measure, in dollars, of the long-term damage. Various ranges of federal CO₂ prices for rulemakings, by discount rate are shown in Table 2 (US EPA, 2017). Zhen et al. (2018) estimated that SCC concentrated between \$35/tCO₂ and \$55/tCO₂. Based on the data above, in this research, the carbon cost (the parameter of θ) was set to CCO_{2e} = \$36/ton CO_{2e}. Assuming that Q_{CO_2e} is the weight of the CO_{2e} generated in the MSW system in the facility, the social cost of CO_{2e} can be calculated as below:

$$C_{CO_2e} = 36 * Q_{CO_2e} \quad (2)$$

Table 2 Range of federal CO₂ prices for rulemakings, by discount rate

<i>Discount rate and statistic (in 2007 dollars per metric ton CO₂)</i>				
<i>Year</i>	<i>5% average</i>	<i>3% average</i>	<i>2.5% average</i>	<i>3% 95th percentile</i>
2015	\$11	\$36	\$56	\$105
2020	\$12	\$42	\$62	\$123
2025	\$14	\$46	\$68	\$138
2030	\$16	\$50	\$73	\$152
2035	\$18	\$55	\$78	\$168
2040	\$21	\$60	\$84	\$183
2045	\$23	\$64	\$89	\$197
2050	\$26	\$69	\$95	\$212

The quantity of CO_{2e} emissions in equation (2) is calculated using MSW LCA model, which is stated in the next section. LCA process is governed under ISO 14000, the series of international standards addressing environmental management. The conventional LCA accounts for all resource use and all emissions from the whole system accumulated from a ‘cradle-to-grave’ process (Xu et al., 2016). The LCA system is generally modelled from the inputs and output data that are followed from raw material manufacturing to product disposal.

2.3 Life cycle assessment

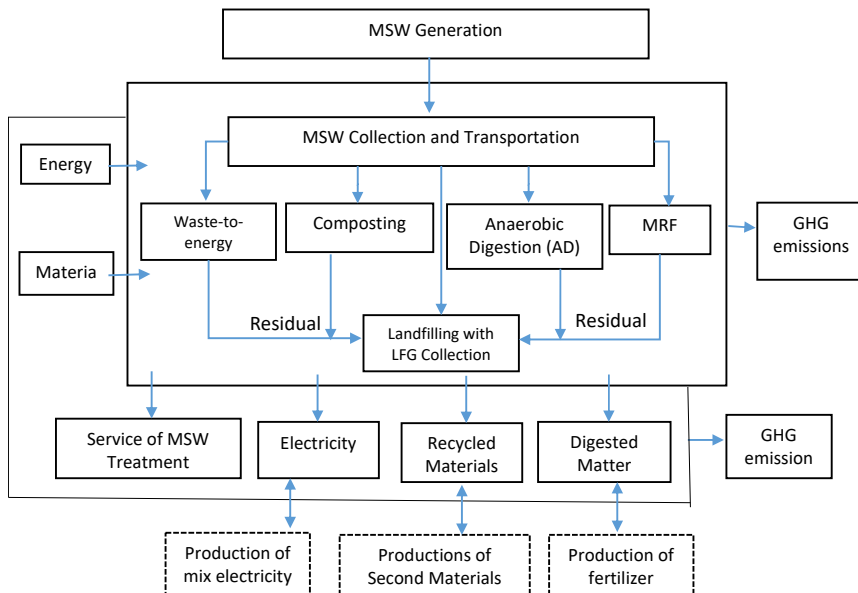
2.3.1 Goal of the LCA study, function unit

The goal of this LCA study is to evaluate and compare different scenarios for MSW management in the facility related to GHG emissions and social cost of CO₂e, toward zero waste to landfill facility, and to investigate the potentials of social cost of CO₂e mitigation and trade-offs under different scenarios in the facility. The functional unit for this study was the annual MSW generated in the facility, in OH, USA of 2015, the waste streams, categories and weight are specified in Section 2.2.

2.3.2 System boundary

LCA of MSW is different from a conventional ‘cradle-to-grave’ LCA analysis. In general, LCA systems are modelled to assess environmental impacts from raw material extraction through materials processing, manufacture, distribution, use, repair and maintenance, and disposal or recycling. However, the LCA of waste management does not consider the process before waste generation, it often starts when the solid waste is generated to the disposal and processing of the waste, such as landfilling, material recovery facility, waste to energy and so on, and emissions are counted from the point that the discarded material reaches the curb or waste collection bin (Finnveden, 1999). This difference does not have an effect given the general premises of a LCA but does require modifications for different aspects of the analysis. These aspects include system boundaries, recycling, multi-input processes, and time-frame considerations. Abeliotis (2011) illustrates the complete life cycle of MSW, from waste generation, waste collection, transportation, and landfilling. The relevant processes in this study are included within the boundary of MSW management system, as shown in Figure 1. MSW is the input of the MSW management system.

Figure 1 Life cycle of MSW and system boundary (see online version for colours)



2.3.3 *Choice of integrated waste management LCA model*

Several models can be applied to help with decision on waste management to reduce the GHG emissions (Khandelwal et al., 2019; Den Boer et al., 2007). Environmental assessment of solid waste systems and technology (EASEWASTE) (Kirkeby et al., 2006; Riber et al., 2008; Chen and Christensen, 2010), integrated waste management-2 (IWM-2) (McDougall et al., 2008), the Waste and Resources Assessment Tool for the Environment (WRATE) (Lazarevic et al., 2012) and the US EPA (2006) all have been developed under the LCA framework. The study in this paper used integrated waste management model (IWM) for municipalities, produced by Corporations Supporting Recycling (CSR) and the Environment and Plastics Industry Council (EPIC), which is offered through the University of Waterloo (The University of Waterloo, n.d.). Life cycle inventory (LCI), Life cycle impact assessment (LCIA) were carried out based on IWM, the model focuses on the major components of residential waste: paper, glass, plastic, aluminium, ferrous metals, food and yard waste. It reviews each waste in terms of the available waste management options, including recycling, anaerobic digestion, composting, land application, energy recovery and landfill.

2.3.4 *Scenarios*

There are nine scenarios proposed for the facility in terms of MSW treatment, the results of the scenarios were evaluated and compared to in terms of GHG emissions and energy consumption. The following scenarios were modelled, and after the analysis of the proposed nine scenarios, the integrated strategy was modelled too.

- the baseline scenario, all waste was sent to landfill, no recycling, with LFG collection (scenario 1)
- the current scenario for the facility, the waste was sent to landfill, and recycling materials were sent to MRF at a certain rate which was obtained in the audit in the facility (scenario 2).
- based on scenario 2, current wastes that were sent to landfill were all sent to EFW for waste to energy (scenario 3)
- all waste was sent for waste to energy (scenario 4)
- diversion of food waste, 30% of food waste sent for composting (scenario 5)
- diversion of food waste, 30% of food waste sent for AD (scenario 6)
- under current scenario, source reduction on all waste by 10% (scenario 7)
- under current scenario, 50% of the glass were sent to MRF (scenario 8)
- improved diversion rates of materials currently being recycled, 50% of the recyclables that were sent to landfill were sent to MRF (Scenario 9).

The recycle rate was chosen to be 50%, the figure was from the recycling goal of the district (Franchetti, 2009), and the glass generated in the facility was not recycled as the local MRF does not recycle glass. In scenario 1, all waste was assumed to be sent to the local landfill, currently the local landfill has LFG capture system, no energy conversion system. The gas recovery efficiency is 59%, which is calculated 850/1,442 standard cubic

feet per minute (SCTM). Energy used in the facility includes mainly diesel fuel, electricity and small quantities of natural gas. The energy consumed by landfill operation showed in table 6, which was the value of total annual energy (diesel/gas/electricity) consumed/total annual waste, which is 0.29 litre/ton for diesel, 0.000097 m³/tons for natural gas, and 2.73 Kwh/ton for electricity. The leachate collection efficiency was 77%. In scenario 5 and 6, the organic diversion rate was assumed to be 30%, this figure is assumed based on literature review (Mohareb et al., 2008). In scenario 3, wastes sent for landfilling were assumed to be sent for waste to energy. In scenario 4, all waste was sent for waste to energy to investigate the impact of waste to energy on waste treatment. In scenario 7, source reduction rate of all waste was both assumed to be 10%, which will help to see how the environmental impact can be alleviated due to source reduction. The glass is not recycled in current scenario, in scenario 8, the glass was assumed to be recycled at 50% to see how this could change the modelling results. In the IWM model, the composition of leaf and yard waste need to be input, which is not considered in this study, as the quantity of yard waste found in the facility was too small. Then an integrated strategy can be suggested based on the modelling results in terms of net GHG emissions and net energy consumption, which will be discussed in the following section.

2.3.5 IWM model LCA input and output

The life cycle inventory (LCI) aims at identifying and quantifying the environmental interventions related to the LCA system, resulting in a list of environmental input and outputs.

IWM LCA model is a Microsoft Excel spreadsheet with macros designed for data input related to waste management, where each screen of the spreadsheet covers different aspects of the waste management, such as landfill, transportation/collection, recycling (The University of Waterloo, n.d.). The model's outputs are in the form of Excel spreadsheets named module outputs, including environmental modules output and environmental inventory of waste management system.

IWM model input tables are a summary of the input data, a summary of the outputs for each waste management process, including recycling, composting, energy from waste (EFW), landfill, and anaerobic digestion. Each waste management process includes the total life-cycle emissions of GHGs and criteria pollutants, an output table that breaks down the burdens from each waste management process, for example, the emissions from the landfilling process includes emissions from collection/transportation, landfilling and net energy/emissions.

To model the GHG emissions from the MSW sector generated in the facility using the IWM model, several inputs are required for different scenarios, including (EPIC, 2002):

- Quantity and composition of the waste (the quantity of the waste generated that are currently sent to landfill, waste quantity of each category of the waste, such as paper, glass, ferrous metals, aluminum, plastic, organics).
- Waste flow, the destination of the waste generated, that is, how much of each component of the waste stream goes into recycling, anaerobic digestion, composting, waste to energy, or landfilling.

- Data related to waste collection to different destinations, distance driven by collection trucks, including garbage, recycling, and yard waste and so on. For recyclables, the distance from materials recovery facilities to markets is also required.
- Energy consumed in facility operation and transportation is required, for example, diesel/natural gas/electricity efficiency.
- For a landfill, the extent of landfill gas (LFG) capture and ultimate use of LFG (flaring, conversion to energy) is required.
- For AD process, the percentage of residue from process, additional process water, and efficiency of energy production, moisture in percentage and so on is needed.
- For energy from waste (EFW), data input: energy recovery efficiency, energy consumption, distance fly ash transported, and so on.

The emissions from the transport of waste to the landfills, MRFs, waste to energy facility, composting facilities are required in the model, the MSW generated in the facility were sent to a local landfill located in North West of OH. The recyclables are sent to a local recycling facility located in OH. Total travelling miles of the waste collection trucks to landfill was estimated from the truck average pick-up quantity, the pick-up frequency, and the distance between the facility and the landfill. The wastes were picked up 4–6 times a month. The recycles were picked up twice a week by the local recycling company, the truck travelling miles were estimated to be 1,500 miles. The distance from the facility to the waste to energy is estimated to be 67 miles, which is in Michigan. The distance from the facility to the local landfill, the composting facility and AD facility is assumed to be the same.

The distance that recycled materials travel from MRFs to markets is also a required input for the model in recycling section, including paper, glass, ferrous, aluminium, and plastics. Since the local recycling company does not deal with glass, the glass was trashed. The distance that the residuals generated in the MRF travel to the local landfill is also needed. The location of the MRFs and location that the recycles are marketed must be known parameters. The distance was estimated based on the information provided by the local MRF showed that the papers were sent to Ohio and Michigan areas, an estimation of 100 miles will be travelled. Ferrous and aluminium were sent to Toledo, an estimation of 20 miles of travelling. Plastics were sent to Ohio, India or Vietnam, an estimate of 500 miles travelled for recyclable plastics to markets was estimated. According to the audit of the local MRF, the residue rate is around 10–15%.

The MSW GHG emissions from the IWM model mainly includes CO₂, NO_x and CH₄, NO_x is one of the categories of GHG emissions, In IWM model, in the calculations of GHG emissions and global warming potentials of the gases, all NO_x emissions are N₂O emissions. This is not accurate, NO_x is defined to be a combination of all nitrogen oxides with different percentage of O and N elements (Huselstein et al., 2002). It has been estimated that the N₂O emissions are about 10% of total NO_x emissions (EIOLCA, n.d.). Thus, the N₂O emission data shown in Tables are 10% of the results given by the IWM model. In this model, the global warming potential (GWP) of N₂O is assumed to be 331, it is higher than the data from EPA, from EPA (US EPA, 2017), N₂O has a GWP of 265–298 times that of CO₂ for a 100-year timescale. Based on the IPCC's assessment, N₂O has a GWP of 310 in the Second Assessment Report (SAR) in 1995, 298 in the

Fourth Assessment Report (AR4) in 2007, and 265 in the Fifth Assessment Report in 2014. The GWP of CH₄ is estimated to be 21 in IWM model, which is lower than the data from EPA (US EPA, 2017): CH₄ is estimated to have a GWP of 28–36 over 100 years. And the second, fourth and fifth assessment of IPCC, the GWP of CH₄ is 21, 25, 28. The use of the latest (AR5) values is recommended from IPCC (2013).

2.3.6 Identification of waste streams in the facility

As it is described above, the model begins with the identification of the MSW streams at the facility, several methods can be applied to collect the data in the facility. The most useful and accurate method to gain information from the facility is waste hauling and historical records such as invoices and receipts, tipping slips, other records, or forms, and assessing waste in each waste container in the facility. Invoices and receipts typically contain little or no information on waste composition. Tipping slips also provide information on the amount of waste that is disposed at landfills, but from the emissions point, these slips do not provide enough data as needed for the model (Franchetti and Kilaru, 2012). And a waste audit can be helpful and necessary to determine annual MSW generation in terms of volume and composition. A waste assessment was conducted in the facility, a walking through audit was carried out in the facility to estimate the MSW streams in the plant involved an audit of waste containers in different areas, such as subway dining areas in the workshop, resting area, offices, and conference rooms. The waste containers were inspected to record their size (volume), the total volumes of waste (percentage of container filled), types of materials, and relative quantity (percentage) of each material. The MSW in the facility is estimated in cubic yards and then the volume was converted into respective weight based on the density of the waste materials. These density conversion factors of different wastes were determined experimentally based on MSW analysis by the research team in the University of Toledo funded by Lucas County Business Waste Reduction Assistance Program (BWRAP), a list of common materials and volume to conversion is provided in Table 3. This volume to weight conversion is completed assuming that the MSW in each container is uncompact, unbaled and loose. The conversion from volume to weight is done using the data in table 3.

Table 3 Volume to weight conversion of materials recycled in Lucas County

<i>Material</i>	<i>Volume in cubic metre</i>	<i>Kg</i>
Mixed office paper	1.00	129
OCC	1.00	34
Newspaper	1.00	141
Magazines	1.00	71
PET	1.00	12
HDPE	1.00	8

From the data collected from the audit, estimated volumes of each material in the facility were calculated for each waste container. Then the weight of each component in the waste stream of all containers was calculated. The percentage of each waste component of total waste were calculated too, and from the waste shipments invoice provided by the facility, the total waste was 941 tons for 2015, and then the annual weight of the waste components were calculated in Table 4.

Table 4 Annual weight of solid waste from audit

<i>Annual waste of solid waste audit</i>		
<i>Component</i>	<i>Percent of total</i>	<i>Tons per year</i>
Mixed office paper	7.33%	69
Newspaper	9.67%	91
Magazines	2.55%	24
Cardboard	8.29%	78
Aluminium cans	5.53%	52
PET (1)	6.80%	64
HDPE (2)	1.17%	11
Other plastics	1.59%	15
Glass	4.99%	47
Plastic wrap	0.11%	1
Organics/food	46.01%	433
Others/non-recyclables	5.95%	56
Total	100.00%	941

The data related to the recycles, mainly cardboard, aluminium cans and plastic bottles were gained from the company's waste shipment invoice, and the data was stated in Table 5, all were sent to a local MRF facility.

Table 5 Recycling stream in the facility

<i>Waste category</i>	<i>Baled cardboard</i>	<i>Baled white paper</i>	<i>Aluminium cans</i>	<i>PET plastic</i>	<i>Baled film (PVC)</i>	<i>HDPE plastic</i>
Amount (tons)	288.6	79.99	21.75	17.29	24.66	3.25

The total MSW generated in the facility was 1,377 tons, summed up from the above tables. The liquid and sludge waste generated in the facility is not studied here, they are sent to special facilities to be treated. Some other waste, such as the auto scrap plastic and ferrous scrap generated in the production line is not studied in the paper.

Inputs for IWM model for the current scenario in the facility in OH is shown in Table 6, the current scenario, the waste collected in the facility were sent to a local landfill in OH. Table 6 displays the inputs for IWM model modelling the current scenario: the waste sent to landfill, and recycling materials were sent to MRF at a certain rate which was obtained in the audit in the facility. These data were collected on site at the facility and discussed in the previous sections. In this scenario, there is no AD, composting or EFW waste flow analysis in current scenario. Land application, transfer station is not applied in this study. Input data related to yard waste was not discussed in this study either.

Table 6 Current scenario inputs for IWM model for the facility

<i>QUANTITY AND COMPOSITION OF WASTE</i>			
Quantity of waste	1,377 tons	MATERIALS RECOVERY FACILITY	
Composition of waste		Energy consumption	
Paper		Electricity	25 kwh/ton
Newspaper	115 tons	Natural gas	0.264 m ³ /ton
OCC	367 tons	Residue	5%
Telephone directories	0 tons	Residue management	landfilled
Boxboard	0 tons	Distance to markets:	
Mixed Paper	149 tons	Paper	160 km
Glass	47 tons	Glass	0 km
Ferrous metals	0 tons	Ferrous	0 km
Aluminium	74 tons	Aluminium	32 km
Plastics		Plastics	500 km
PET	81 tons	Distance from MRF to landfill/waste to energy facility	15 km
HDPE	14 tons	LANDFILLING	
LLDPE	5 tons	Carbon sequestration	Yes
PP	5 tons	Gas recovery	Yes
PS	5 tons	Gas recovery efficiency	59%
PVC	26 tons	Energy recovery	No
Organics		Energy recovery efficiency	0
Food waste	433 tons	Annual precipitation	852.17 mm
Yard waste	0 tons	Landfill lined, with leachate collection	Yes
Other waste	56 tons	Landfill not lined, with leachate collection	No
WASTE FLOW		Landfill not lined, leachate not collected	No
Recycling	436 tons	Leachate collection efficiency	77%
Composting	0 tons	Energy consumed by landfilling	
Land application	0 tons	Diesel	0.29 litres/ton
Energy from waste	0 tons	Natural gas	0.000097 m ³ /ton
Landfill	941 tons	Electricity	2.73 kwh/ton
AD	0 tons	Waste sent for recycling	436 tons

Table 6 Current scenario inputs for IWM model for the facility (continued)

<i>QUANTITY AND COMPOSITION OF WASTE</i>			
WASTE COLLECTION		Recovery rates	
Distance driven by collection trucks annually		Paper	
Garbage trucks	2,400 km	Newspaper	0 tons
Recycling trucks	936 km	OCC	289 tons
Yard waste trucks	0 km	Telephone directories	0 tons
Source separated	0 km	Boxboard	0 tons
Co-mingled	0 km	Mixed paper	80 tons
Type of fuel	Diesel	Ferrous metals	0 tons
Fuel efficiency		Aluminium	22 tons
Collection trucks	1.25 km/litre	Glass	0 tons
Transport trucks	2.5 km/litre	Plastics	
Transfer station	No	PET	17 tons
ELECTRICITY – PROVINCIAL GRID SELECTED	US national	HDPE	3 tons
ELECTRICITY – CUSTOM GRID SELECTED		LLDPE	0 tons
Coal	55%	PP	0 tons
Natural gas	14%	PS	0 tons
Diesel and light fuel oil	0	PVC	25 tons
Heavy fuel oil	4%	Forest sequestration	No
Hydro	8%		
Nuclear	19%		

3 Results and discussion

3.1 Results from IWM modelling scenarios

The results from the nine scenarios for the facility related to the MSW treatments were displayed and discussed in this section, including GHG emissions and energy consumption analysed from the IWM models. Due to the assumptions in the models, such as bias from transportation distance estimation, waste component estimation, the results cannot be exact as the scenarios. The output for each model includes three sheets, summary output, burden equivalents, and detailed breakdown. Only energy consumption and GHG emissions were studied in this paper. Acid gas emissions, Smog precursors, toxic emissions that displayed in the output from the modelling process were not studied in this paper.

Tables 7–8 show the current scenario modelling results. The summary output displayed the environmental inventory of the MSW management system, Table 7 shows

the tons managed, energy consumed, GHG emissions for different waste process. The current scenario only has data for recycling and landfill. Table 8 displays the breakdown information about the current scenario waste process. The recycling process was broken down into collection, MRF, reprocessing and total recycling, virgin material displacement credit and net energy/emissions. The landfill process was broken down into collection, landfilling and net energy/emission. The other waste process including composting, EFW and AD have no data in this scenario.

Table 7 Current scenario environmental inventory summary

	<i>Recycling</i>	<i>Landfill</i>	<i>Total waste management system</i>	<i>Virgin material displacement credit</i>	<i>Reprocessing of recycled materials</i>	<i>Net life cycle inventory</i>
Tons managed (tons)	436.00	941.00	1,377.00			
Energy consumed (GJ)	265.62	227.00	492.61	-17,908.13	6,603.57	-10,811.94
GHG						
CO ₂ (tons)	14.70	-296.97	-282.28	-454.16	24.12	-712.32
CH ₄ + NO _x (tons)	0.11	38.53	38.64	-4.21	1.60	36.03
CO ₂ e (tons)	39.33	540.68	580.01	-1,473.57	519.18	-374.38

Table 8 Current scenario detailed breakdown environmental inventory output

<i>RECYCLING</i>					
	<i>Collection and transp.</i>	<i>MRF</i>	<i>Reprocessing</i>	<i>Total recycling</i>	<i>Virgin material displacement credit</i>
Energy consumed (GJ)	94.63	170.9	6,603.57	6,869.19	-17,908.13
GHG					
CO ₂ (tons)	6.64	8.05	24.12	38.82	-454.16
CH ₄ + NO _x (tons)	0.07	0.05	1.60	1.71	-4.21
CO ₂ e (tons)*	24.83	14.50	519.18	558.51	-1,473.57
<i>LANDFILL</i>					
	<i>Net energy/emissions</i>	<i>Collection</i>	<i>Landfilling</i>	<i>Net energy/emissions</i>	
Energy consumed (GJ)	11,038.94	86.79	140.21	227.00	
GHG					
CO ₂ (tons)	-415.34	6.09	-303.06	-296.97	
CH ₄ + NO _x (tons)	-2.50	0.06	38.47	38.53	
CO ₂ e (tons)*	-915.06	22.77	517.91	540.68	

Table 9 Gross and Net GHG emissions from the nine scenarios in the facility in IWM model

Scenario	tCO ₂ e				Gross GHG emissions (tCO ₂ e)	Virgin material displacement credit	Reprocessing of recycled materials	Net life cycle inventory
	Recycling	Composting	EFW	AD				
1 Landfill all waste	0.00	0.00	0.00	0.00	867.3	0.0	0.0	867.3
2 Current scenario	39.33	0.00	0.00	0.00	580	-1,473.6	519.2	-374.38
3 Waste to landfill was sent for EFW	39.33	0.00	390.60	0.00	444.15	-1,473.57	519.2	-510.23
4 All EFW	0.00	0.00	695.18	0.00	698.79	0.0	0.0	698.8
5 Composting 30% food waste	39.33	6.31	0.00	0.00	433.22	-1,473.57	519.2	-521.16
6 AD 30% of food waste	39.33	0.00	0.00	1.21	428.02	-1,473.57	519.2	-526.36
7 Waste source reduction by 10%	35.38	0.00	0.00	0.00	521.50	-1,394.77	467.1	-406.14
8 Glass recycled by 50%	40.63	0.00	0.00	0.00	580.40	-1,506.95	537.01	-389.53
9 Improved recycling rate	60.03	0.00	0.00	0.00	590.06	-2,308.79	762.41	-956.32

A summary of the emissions calculated from IWM is demonstrated in Table 9. The emissions have been categorised as collection (or transport) emissions, landfilling emissions, recycling emissions (this category includes emissions from reprocessing recycled materials in Table 8 for total recycling), composting or anaerobic digestion emissions and energy from waste emissions. In Table 9, the GHG emissions for recycling exclude the emissions from reprocessing the materials, and all process includes the energy for waste collection and transportation. The virgin material displacement credit presented in the table refers to emissions reduced, and energy saved by reprocessing the recycling materials instead of virgin materials. The net GHG emissions were calculated through subtracting the credit from the gross GHG emissions.

Figure 2 summarised the gross and net emissions from the nine scenarios in terms of equivalents of CO₂. Scenario 1 (all waste to landfill) and scenario 4 (all waste for EFW) has the highest level of gross GHG emissions: 867.3 tons and 698.79 tons respectively. GHG emissions generated in landfill are more than that in FEM. Scenarios 6 (30% of food waste sent for AD) generated the lowest volume of gross GHG emissions, 428.02 tons. Scenario 5 (30% of the food waste sent for composting) and scenario 3 (waste to landfill sent for waste to energy) generated the second and third least gross GHG emissions. Scenario 9 has the lowest net GHG emission when diversion rates of materials currently being trashed was recycled by 50%, as it has the most Virgin material displacement credit, -2,308.79 t CO₂e. Scenario 6 and scenario 5 generated the second and third least net GHG emissions: -526.36 t and -521.16 t CO₂e, respectively. As it is shown in Table 8, it can be estimated that the GHG emissions rate of virgin material displacement credit is -3.38 t CO₂e per ton of recycling waste for scenario 2, 3, 5, 6. Scenario 8 has a very slight different rate. For scenario 8 (glass was assumed to be recycled by 50%) and scenario 9 (improved recycling rate of recycles in the waste stream by 50%), it is -3.28 t CO₂e/t and -3.62 t CO₂e/t, respectively. This is due to different GHG emissions from producing different virgin material categories.

Figure 2 Gross and net GHG emissions in the facility (CO₂e) (see online version for colours)

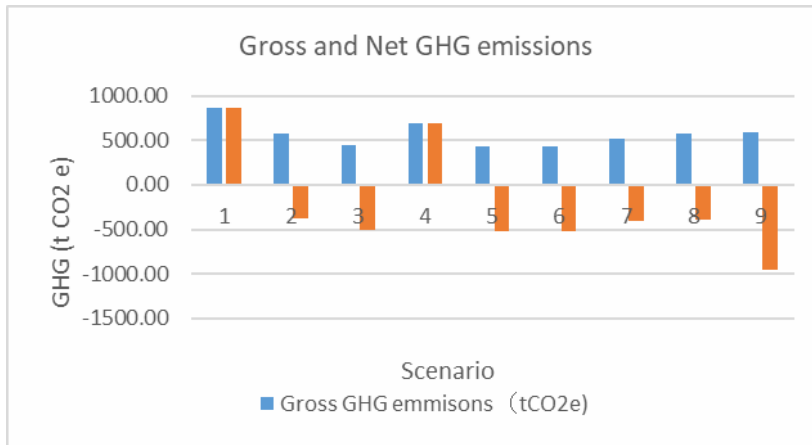


Figure 3 Gross GHG emissions from MSW disposal for different scenarios proposed in the facility, by GHG category (see online version for colours)

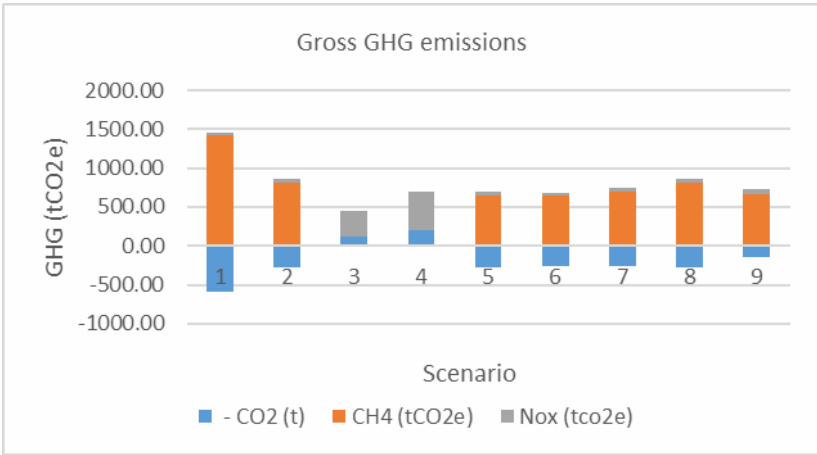


Figure 4 and 5 displays gross and net GHG emissions in different scenarios by GHG category: CH₂, CH₄ and NO_x. For gross emissions, scenario 3 and 4 almost have no CH₄ emissions, it is because that CH₄ is generated mostly in landfilling process. In all other scenarios, CH₄ is the main GHG emissions. For net emissions, scenarios 1 and 4 have no change due to no recycling. Figure 4 displays gross emissions from the nine scenarios by emission source (recycling, composting, EFW, AD and landfill), it can be seen that the majority of GHG emissions are from landfill process except scenario 3 and 4, so controlling the GHG emissions from landfill is very important, especially the CH₄ emissions. The GHG emissions from AD and composting are small. In scenario 3 and 4, the GHG emissions are mainly from waste to energy. The fossil fuel emissions that are displaced by the generation of power associated waste handling treatment, such as waste to energy, composting and AD, are not incorporated in the figures.

Figure 4 Net GHG emissions from MSW disposal for different scenarios proposed in the facility, by GHG category (see online version for colours)

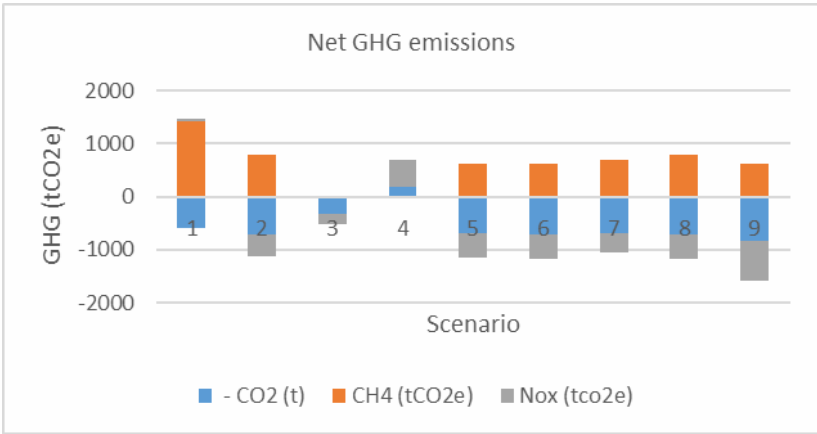
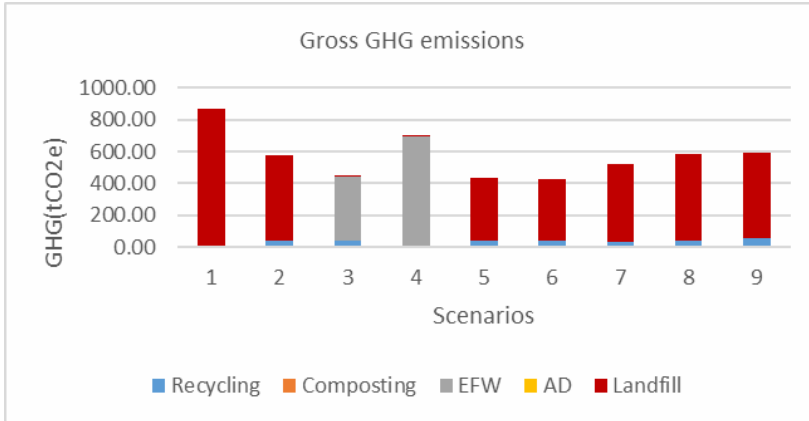


Figure 5 Gross GHG emissions from MSW disposal for different scenarios proposed in the facility, by emission source (see online version for colours)



It is also important to demonstrate the energy consumption in each scenario, as it is linked to GHG emissions. In this Model, except LFG emissions, most of the GHG emission calculated is based on energy consumption. Figure 6 displays the gross and net energy consumption for the facility from the nine scenarios proposed. It is not surprising that scenario 3, 4 and 6 have the lowest level of gross energy consumption. In scenario 3, all MSW in the facility (1,377 t) sent for waste to energy generates around 2,800 GJ energy excluding energy consumed in collection from the facility to waste to energy. In scenario 3, wastes sent to landfill in current scenario were sent for waste to energy generates around 1,696 GJ energy. Scenario 2, 8 and 9 has the highest level of gross energy consumption, as the energy consumed in recycling is larger than other process. Scenarios 9, 3 and 6 have the lowest level of net energy consumption (net life cycle inventory) due to improved recycling rate, energy generated from waste to energy and AD, respectively.

Figure 6 Gross and net energy consumption for the facility from the nine scenarios proposed (see online version for colours)

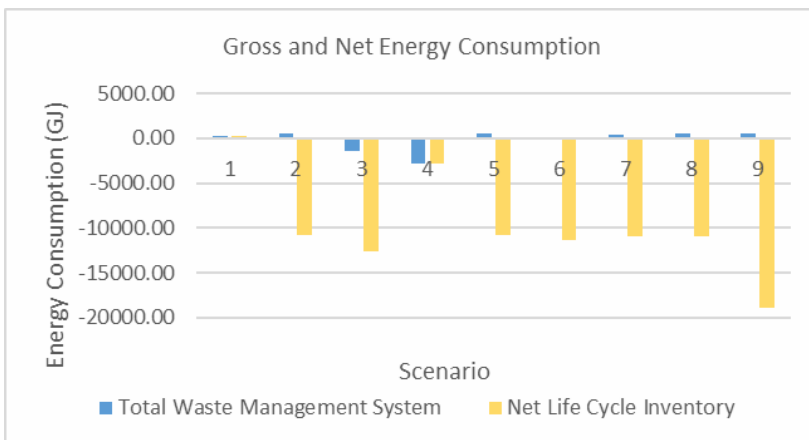


Table 10 Integrated strategy for waste treatment in the facility

<i>Integrated strategy</i>	<i>Recycling</i>	<i>EFW</i>	<i>AD</i>	<i>Landfill</i>	<i>Total waste management system</i>	<i>Virgin material displacement credit</i>	<i>Reprocessing of recycled materials</i>	<i>Net life cycle inventory</i>
Energy consumed (GJ)	398,1181	-708.17	-496.57	20.34	-777.28	-28,793.26	9,314.55	-20,255.99
t CO ₂ e	70,02538	228.61	1.21	29.85	329.69	-2,308.79	762.41	-1,216.69

From the nine scenarios proposed in the facility, the main options for the facility to go zero waste to landfill facilities and contribute less GHG emissions are through source reduction, recycling, AD, composting, and waste to energy. Minimum recycled contents legislation will further promote material recycling to reduce GHG emissions. 10% source reduction reduced net emissions by only 0.20 t CO₂e/tons waste reduced, this is partially because that most of the LFG emissions come from the degradation of the food and other compostable waste, in BB facility, food waste only took 20%. Anaerobic digestion (AD) and composting has potential in GHG emissions, and it has better potential in energy consumption reduction. An integrated waste strategy was proposed and suggested for the facility: increasing the recycling rate for the facility by 50%, diverting 30% of food waste to AD processing (from 0%), incinerating the rest of the waste for energy, and sending little to zero waste to landfills. The integrated strategy was running in the IWM model and the results related to GHG emissions and energy consumption was displayed in table 10 below. It has the lowest GHG emissions and energy consumption compared with all scenarios above, and with zero waste to landfill facility.

Table 11 Economic cost and social cost of CO₂e for all scenarios in the facility

<i>Scenario</i>	<i>Total economic cost (\$)</i>	<i>Social cost of total CO₂e(\$)</i>
1	76,134	31,224
2	46,911	-13,478
3	29,651	-18,368
4	50,877	25,156
5	46,647	-18,762
6	46,647	-18,949
7	42,285	-12,137
8	45,302	-14,023
9	33,371	-34,427
Integrated strategy (IS)	23,900	-43,801

3.2 Results of the economic and CO₂e social cost of MSW management system

The results displayed in this section are indicative of the economic cost of the MSW management system and the CO₂e social cost statistics that may be possible through the scenarios analysed in BB facility. Due to the assumptions made in this study, the statistics should not be assumed the same. For the economic operation cost, the extra labour for waste separation for recycles to be recycled, organic waste sent for AD and composting is not considered to be collected voluntarily in BB facility. The economic cost of the MSW annual in the facility for the ten scenarios and the integrated scenario is calculated based on equation (1), the social cost of CO₂e emissions is calculated on equation (2). The economic cost and social cost CO₂e of MSW management system in the facility is shown in Table 11. From the results, the integrated strategy has the lowest social cost of CO₂e for the MSW in B facility, as it has the lowest CO₂e emissions. Minimum recycled content legislation, training staffs for recycling, and visualised recycling signage will further promote material recycling, encouraging greater GHG emissions reductions and social CO₂e cost. Incineration offers significant emissions reductions, but the political

cost of this option may be too great. Source reduction reduced net emissions by only about 0.11 t CO₂e/T waste reduced in BB facility.

The integrated strategy also has the lowest economic cost dealing with the waste, as it has the highest revenue from the recycles and the waste to the incinerator has much lower disposal cost than the waste to landfill, AD and composting has lower cost than Waste to energy mainly due to the shorter transportation distance.

4 Conclusions and recommendations

The annual cost in disposing the MSW of the facility was approximately \$47,000, the social cost of the CO₂e was -\$13,478 in 2018. The integrated waste strategy for the facility (few to zero waste to landfill): recycling rate of trash improved by 50%, 30% of food waste sent for anaerobic digestion, incinerate the rest of the waste, had the lowest social cost of CO₂e and economic cost, compared with the current scenario, it reduced the economic cost and social cost of CO₂e by 49.05% and 2.24 times respectively.

The economic cost of MSW management in the facility was estimated through the equation (1), based on the scenarios' results, reducing the waste to landfill has the most potential to reduce the cost as it has the highest disposal fee, and improving the recycling rate to gain revenues from the recyclables can highly reduce the cost too. The equation can be applied in other MSW management system to determine the estimated economic cost.

The key to reduce social CO₂e cost is to reduce the CO₂e emissions. The IWM model was used to analyse the GHG emissions from the MSW in BB facility, the facility generated 580 t CO₂e from disposing 1,377 tons of MSW in 2018, of which 90% was generated by landfilling, mostly was from CH₄ emissions. The net GHG emissions were estimated to be -374.4 tons due to the virgin material displacement credit from current recycling. From the scenarios proposed and analysed in IWM model, it is indicated that increasing the recycling rate has the greatest effect on reducing GHG emissions, mostly through reducing production emissions through feeding recycled materials instead of virgin material to production processes. AD follows with the next highest levels of GHG emissions reductions, followed by composting and waste to energy then source reduction. And waste to energy directly reduces the GHG emissions for their lower emission generation rather than landfilling. Recycling and source reduction indirectly reduce the GHG emissions, recycling reducing emissions by virgin material displacement credit. Compared with the current scenario, the gross and net GHG emissions of the integrated waste strategy for the facility (few to zero waste to landfill), were reduced by 43.16% and 2.25 times, respectively. The anaerobic digestion and composting for food waste will have high potential in GHG emission reduction if the food waste diversion rate can be increased. Further efforts to divert recyclables materials in the waste sector of the facility will have the biggest potential to reduce the GHG emissions.

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