Impact of management alternatives on GHG emissions from waste

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ABSTRACT

This paper presents the greenhouse gas (GHG) emissions accounting of the integrated solid waste management system for the municipal waste generated primarily in the City of Beirut and its surroundings. Several scenarios were tested to assess the influence of policy management alternatives in terms of variation in waste diverted to composting, anaerobic digestion, incineration, landfilling or recycling, while still economically viable. The results indicate that direct GHG emissions constitute the major contributor to the overall emissions inventory (96%), while the contribution of indirect upstream emissions were relatively less significant (4%). Landfilling remains the major contributor to GHG emissions from the waste sector with diversion of materials through recycling and composting coupled with energy recovery having the greatest effect on reducing GHG emissions. The scenario analysis demonstrated that optimizing composting and recycling coupled with landfilling or incineration reduced net emissions by 31% to 96%, respectively at a corresponding cost saving of 7% or increased cost of 43% including carbon credit. This study can assist policy makers to meet future emissions mitigation measures/reduction targets or influence investments in carbon credit to meet countries' Nationally Determined Contributions under the Paris Agreement.

Keywords: *solid waste; emission reduction, life cycle assessment, carbon credit*

1. INTRODUCTION

The waste sector is considered as a small contributor to the overall greenhouse gas (GHG) emissions whereby it accounted for ~3% (1446×10^6 $MTCO_2E$) of worldwide GHG emissions in 2010 (Blanco et al., 2014). However, it can be a major contributor to reduce GHG emissions at a country level, particularly, in developing economies whereby emissions from the waste sector can reach up to 11% of GHG emissions, which are equivalent to emissions from industrial processes (~10%), for the case of Lebanon for instance (MoE/UNDP/GEF, 2016). Note that globally, the contribution of landfills to methane (CH_4) is up to 45% of total emissions from the waste sector (IPCC, 2014), representing the third largest anthropogenic source of CH_4 (GMI, 2011; EPA, 2010). In Lebanon, this contribution reached ~80% of total emissions from the waste sector (MoE/UNDP/GEF, 2015) stressing the significance of potential carbon credit from this sector.

The growth of voluntary mechanisms for GHG emissions estimation and reduction can thus stimulate actions for mitigating climate change and enabling new openings for initiatives and public administrations (Gentil et al., 2009; Friedrich and Trois, 2010). Despite many voluntary and carbon market driven initiatives in developed economies, developing countries did not have mandatory obligations for reducing emissions under the Kyoto Protocol. The situation has changed following the Paris agreement (United Nation, 2015) whereby it became mandatory for all parties to report regularly on their emissions and implementation efforts through nationally determined contributions (NDCs) that incorporate attempts by each country to decrease national emissions and adapt to climate change impacts. In this respect, municipal solid waste (MSW) management has emerged as a potential to reduce GHGs in developing economies in particular.

While several studies (e.g. Marchi et al., 2017; Bogner et al., 2008; Mohareb et al., 2008; Gugliano et al., 2011) have estimated GHG emissions from various waste management processes in the context of developed economies whether by applying the life cycle assessment (LCA) modeling or the 2006 IPCC Guidelines at a regional scale; limited studies have been reported for developing economies (Maalouf and El-Fadel, 2019, 2018). In this context, Premakumara et al. (2018) stress the need for more efforts aiming at quantifying and assessing emissions from the waste sector in developing economies.

In Lebanon, MSW disposal has been a chronic challenge particularly in areas with high population density, high generation of refuse, and scarce land resources for landfills. Slow burning and uncontrolled dumping on hillsides and sea shores have been commonly practiced resulting in serious land, sea, and air pollution. In this study, we evaluate the integrated solid waste management (ISWM) system following a life cycle inventory approach to identify economically viable waste management alternatives with minimal environmental externalities including best strategies for GHG emission reduction taking the Beirut and surroundings as a pilot test area. The ultimate objective is to assess emissions reporting targets under the United Nations Framework Convention on Climate

Change (UNFCCC) commitments or guide decision making and reduction targets using carbon credit to meet NDCs under the Paris Agreement.

2. MATERIALS AND METHODS

2.1. Study area

The study area is the City of Beirut and its surroundings in Lebanon consisting of 297 municipalities for which data were collected from the year 1994 to 2013 with the latter selected as the inventory year. The pilot region encompasses more than two Million inhabitants generating 2,800-3,000 tonnes of MSW per day with an average waste composition presented in Table 1.

Table 1. MSW composition (Laceco/Ramboll 2012)

Waste category	(%)
Food	53.4
Glass	3.4
Metals	2
Nappies	3.6
Papers	15.6
Plastics	13.8
Textiles	2.8
Wood	0.8
Others	4.6
Total	*100*

The management system in the pilot region consists of commingled MSW collection, sorting and recycling, composting, and sanitary landfilling. Waste is collected daily by a fleet of 332 collection vehicles that consume an average of 6.2 L/tonne of waste generated (Laceco/Ramboll, 2012). The waste is then transferred into two materials recovery facilities (MRFs)[1] where it is sorted into bulky items, inert material, biodegradable organics, and recyclables. The biodegradable fraction is sent for windrow composting[2] with relatively low-quality compost often rejected by consumers and hence mostly transferred along with other rejects to be used as intermediate cover in a sanitary landfill[2] (Table 2). The latter is equipped with a gas collection and flaring system with LFG collection since 2001 at 3 Gg of CH_4/year that reached 14 Gg of CH_4/year in 2013. While direct GHG emissions are related to the decomposition of MSW through various processes and other activities[2] at the management facilities, indirect emissions are related to activities outside these facilities mostly through electricity and fuel provision that were quantified for each process with associated emission factors[3].

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[1] Locally referred to by Amrousieh and Quarantina sorting facilities, Coral Composting plant, and Naameh landfill

[2] Average annual diesel fuel consumption (Laceco/Ramboll, 2012): 16,563,700 Liters at landfill sites that encompasses 9,358,600 Liters to operate 170 specialized equipment, 7,205,100 Liters to operate 28 electrical generators, and 365,000 Liters to operate onsite equipment (e.g. bulldozers, rotator disks, etc.) at composting site with corresponding Emission Factors from fuel combustion $EF_{fuel_{CO_2}} = 0.003$; $EF_{fuel_{CH_4}} = 7.7 * 10^{-5}$; $EF_{fuel_{N_2O}} = 3.1 * 10^{-8}$ $MTCO_2E$/Liter (McDouall et al. 2001)

[3] Average electricity consumption: 32 kWh/ton of waste composted (Manfredi *et al.*, 2009); 8 kWh/ton of waste landfilled (Boldrin et al., 2009) with corresponding emission factor $EF_{elec} = 6.87$ $MTCO_2E$ / kWh consumed (IEA, 2014) based on electricity provision from diesel and heavy fuel oil at thermal operating power plants. Emissions from fuel provision (extraction, processing, storage, and transportation of the fuel): $EF_{fuelpro_{CO_2}} = 0.00045$ $MTCO_2E$/Liter (Fruergaard et al., 2009)

Table 2. MSW management in the pilot test area

Year	Waste generated (tonnes/yr)[a]	Waste disposal sites: Naameh landfill (tonnes/yr)[b]	Burj Hammoud (tonnes/yr)[c]	Dumpsites (tonnes/yr)[d]	Recycling (tonnes/yr)[e]	Composting (tonnes/yr)
1994	463,823	-	355,875	89,395	18,553	-
1995	471,476	-	383,250	69,367	18,859	-
1996	479,255	-	410,625	49,460	19,170	-
1997	587,722	115,410	438,000	10,803	22,157	1,352
1998	689,802	603,456	-	-	32,507	53,839
1999	742,828	596,108	-	-	35,006	111,715
2000	746,436	584,754	-	-	40,199	121,483
2001	760,215	587,877	-	-	48,203	124,136
2002	794,423	617,832	-	-	66,244	110,348
2003	823,516	636,571	-	-	68,212	118,733
2004	837,105	658,857	-	-	70,058	108,190
2005	831,973	677,732	-	-	65,592	88,649
2006	801,281	682,559	-	-	51,522	67,200
2007	819,408	651,672	-	-	60,723	107,013
2008	827,973	724,790	-	-	59,981	43,202
2009	934,715	821,570	-	-	59,625	53,520
2010	1,005,985	873,214	-	-	62,730	70,042
2011	1,034,431	904,133	-	-	65,032	65,266
2012	1,051,499	926,529	-	-	59,462	65,508
2013	1,068,849	887,145	-	-	70,517	111,187

(a) As weighted at sorting plants receiving areas (Laceco/Ramboll, 2012)
(b) As weighted at Naameh landfill (Laceco/Ramboll, 2012)
(c) As reported for the Burj Hammoud, deep unmanaged dumpsite (SWECO International, 2000)
(d) MoE/UNDP, 2010.
(e) As weighted at sorting plants (Laceco/Ramboll, 2012).

2.2. Scenario Definition: Policy Management and Economic Analysis

Several scenarios were tested to assess the influence of policy management alternatives (Table 3) in terms of variation in waste diverted to composting, anaerobic digestion, incineration, landfilling or recycling, and find waste management systems that contribute least while still economically viable. Waste collection is assumed the same for all scenarios and simulations were conducted for the year 2013. The financial cost of MSW management under each scenario is calculated by multiplying the tonnes of waste managed under each process by conventional costs (Maalouf and El-Fadel, 2017) and summed to estimate the total financial cost of MSW management under each scenario for comparison. Note that costs under the existing baseline scenario (S0) reflect actual prices in the pilot test area, while alternative scenarios were evaluated based on additional gas and leachate management costs, as well as costs/savings from energy recovery.

Table 3. Alternative policy management scenarios tested

Scenario	Description	Recycling (%)	Composting (%)	Anaerobic Digestion (%)	Incineration (%)	Landfilling (%)
S0	Existing baseline scenario	7	10	0	0	83[(a)]
S1	S0 + LFG energy recovery	7	10	0	0	83
S2	Upgrade LFG capture system	7	10	0	0	83[(b)]
S3	S2 + LFG energy recovery	7	10	0	0	83
S4	Max recycling & composting + landfilling	12	18	0	0	70
S5	S4 + LFG energy recovery	12	18	0	0	70
S6	S4+ Upgrade LFG capture system	12	18	0	0	70[(b)]
S7	S6+ LFG energy recovery	12	18	0	0	70
S8	Landfilling all waste	0	0	0	0	100
S9	S8 + LFG energy recovery	0	0	0	0	100
S10	Substitute composting in S0 by anaerobic digestion + energy recovery	7	0	10	0	83
S11	Substitute landfilling in S0 by incineration	7	10	0	83	0
S12	Incinerate all waste	0	0	0	100	0
S13	S12 + energy recovery	0	0	0	100	0
S14	Max recycling and composting + incineration	12	18	0	70	0
S15	S14 + energy recovery	12	18	0	70	0

[(a)] With LFG collection and flaring;

[(b)] Collection efficiency of (60 %) for a typical operating landfill with wet waste (EPA/ICF, 2016).

3. RESULTS AND DISCUSSION

3.1. Emissions from baseline conditions

Direct emissions from waste management constituted the major contributor (96%) to GHG emissions (Figure 1), while indirect emissions from electricity and fuel provision during collection and operations were less significant (4%). Landfilling remains associated with the highest contribution followed by collection and composting, with recycling contributing to savings. Emissions from collection contributed 2% of total emissions and were considered as part of the overall indirect GHG emissions. The global warming factor (GWF) of collection weighted on the basis of mass of wet waste generated includes direct and indirect emissions from fuel consumption (0.019 and 0.003 $MTCO_2E$/tonne of wet waste collected, respectively) which are consistent with internationally reported values (see Table 2) for developing economies (Friedrich and Trois, 2013a) and falls within the upper range reported for developed economies (Larsen et al., 2009a).

The total net GWF of recycling (-2.655 $MTCO_2E$/tonne of wet waste recycled) includes direct (remanufacturing of recyclable materials) and indirect downstream processes (manufacturing of virgin material) that contribute to GHG savings. The latter depends on the waste management and the energy systems for the production and reprocessing of materials (Smith et al., 2001; Merrild et al., 2009; Astrup et al., 2009; Damgaard et al., 2009; EPA, 2006; Larsen et al., 2009b). Similarly, the results are within the range of internationally reported values (-19.3 to -0.06 $MTCO_2E$/tonne of wet waste recycled – see Table 2) because most reprocessing and production activities take place outside the country and recycling emission factors of various components relied on default factors reported by the EPA/ICF (2016). Note that, materials are modeled in an open-loop or a closed-loop (mostly) recycling process, based on how these materials are often recycled, while also accounting for material losses.

Direct GHG emissions from composting due to waste degradation and fuel consumption by operating equipment are nearly five-fold the indirect emissions from electricity consumption. The indirect downstream carbon storage is insignificant because the quality of the produced compost is low and hence, is mostly used in landfill operation and not for land application. The total GWF from composting (1.3% of total emissions or 0.123 $MTCO_2E$/tonne of wet waste composted,) is in line with values reported in other studies (Kim & Kim, 2010; Friedrich & Trois 2013b). Improving compost quality reduces emissions and increases revenues associated with land application (carbon storage) and substitution for mineral fertilizers. Note that percentages of emissions were calculated using total emissions excluding avoided emissions from recycling.

Finally, landfilling where much of the waste is ending (83%), without energy recovery, was responsible for the maximum share of net emissions (97% of total emissions or 1.172 $MTCO_2E$/ $MTCO_2E$/tonne of wet waste landfilled,) after accounting for indirect savings from carbon storage (-16% of total emissions or -0.198 $MTCO_2E$/tonne of wet waste landfilled) with a minor contribution associated with upstream indirect emissions from electricity and fuel provision (25% of total emissions 0.014 M $MTCO_2E$/tonne of wet waste landfilled), which are comparable with reported values (Kim & Kim, 2010; Friedrich and Trois, 2013).

Table 4. Baseline GWF and total GHG emissions in 2013

Category	Collection	Recycling	Composting	Anaerobic Digestion	Incineration	Landfilling	Open Dumping	Total[(b)]
Waste (tonnes x 10^6)	**1.069**	**0.071**	**0.111**	**0**	**0**	**0.887**	**0**	**1.069**
Overall Direct emissions	0.019		0.100	0	0	1.356	0	0.851
Waste degradation	…		*0.090*	*0*	*0*	*1.299*	*0*	
Fuel consumption	*0.019*		*0.010*	*0*	*0*	*0.057*	*0*	
Overall Indirect emissions	0.003		0.023	0	0		0	0.038
Upstream emissions	0.003		0.023	0	0	0.014	0	
Electricity consumption	-		*0.022*	*0*	*0*	*0.006*	*0*	
Fuel provision	*0.003*		*0.001*	*0*	*0*	*0.008*	*0*	
Downstream emissions	…		0	0	0	-0.198	0	
Electricity production	…	…	…	*0*	*0*	*0*	*0*	
Carbon storage	…	…	*0*[(d)]	…	…	*-0.198*	…	
Total GWF [(a)]	0.022	-2.655[(c)]	0.123	0	0	1.172	0	
Total GHG emissions S0[(b)]	**0.023**	**-0.187**	**0.014**	**0**	**0**	**1.040**	**0**	**0.890**

(a) GWF expressed in MTCO2E/tonne of waste in 2013 (GWP_{100}, IPCC 1995); (b) Total GHG emissions expressed in $MTCO_2E$ x10^6/Year
(c) Total GWF from direct and indirect downstream recycling processes; (d) Compost produced

While the temporal variation of the overall GHG emissions from 1994 to 2013 is expected to show an increasing trend with increasing population and waste generation rate, the decreasing trend between 1998 and 2007 (Figure 1) reflects changes in the adopted MSW management strategy, which differed with time. Prior to 1997, a small fraction (~4%) of MSW was recovered for recycling and the majority of the waste (~96%) was disposed of at uncontrolled dumpsites (see Table 2). In 1997-1998, a new integrated plan was adopted whereby the waste was diverted from dumpsites into a managed landfill reflected by an upward trend in emissions up to 1998 when material recovery and composting were introduced resulting in a decrease in emissions between 1998 and 2002 with an increasing percentage of recycled waste reaching 8%. Emissions remained stable between 2002 and 2005 with improved performance on composting and recycling at 8% with a drop in 2006-2007 due to a decrease in the percentage of waste landfilled (drop of 5%) and an increase in material recovery. The period between 2007 and 2012 witnessed again an increase in emissions with increasing rates of waste generated, although the percentages of waste recycled, composted and landfilled remained relatively stable at 6, 6, and 88%, respectively (see Table 2). In 2013, waste recovery was upgraded and landfilling decreased (5%) explaining the drop in total GHG emissions.

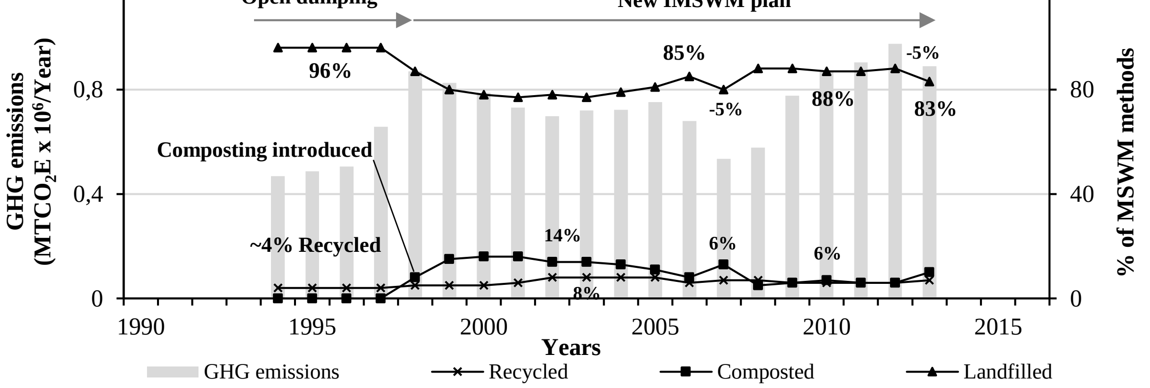

Figure 1. Temporal variation in GHG emissions under baseline scenario (S0)
MSWM: Municipal solid waste management **methods**

3.2. Scenario Analysis: Policy Management and Economic Implications

The results of the baseline scenario were used to test the impacts of policy options on decreasing GHG emissions under the Paris Agreement (Table 4). Scenarios with landfilling (S0 to S10) resulted in greater emissions in comparison with scenarios involving incineration (S11 to S15) (Figure 2). Maximizing waste recycling and composting in scenario S4 minimizes the overall emissions from complete landfilling (S8) by 50 % (Table 4). Maximizing waste recycling and composting coupled with energy recovery from landfilling (S5) minimizes the overall emissions by 34% with respect to S0 (Table 4). While incineration (S14) coupled with maximum recycling and composting minimizes the overall emissions by 96% with respect to S0, coupling energy recovery to incineration in scenario (S15) reduces emissions further by 32% (Table 4).

Note that additional energy recovery from landfilling (S1, S5, and S9 in comparison to S0, S4, and S8 in Table 4) did not contribute significantly to emissions reduction (<4%). However, upgrading the LFG collection system to 60% efficiency reduced emissions by 55% (S2 coupled with flaring of LFG collected) with additional emissions savings from energy recovery (S3) (65% less with respect to S0) (Table 4). Substituting the composting process by anaerobic digestion with energy recovery (S10) contributed to insignificant reduction in GHG emissions (3%) with respect to S0 (Figure 2 and Table 4). However, considering that the produced compost is of good quality, this translates to significant savings in GHG emissions by substituting mineral fertilizers and carbon storage associated with the application of compost on land.

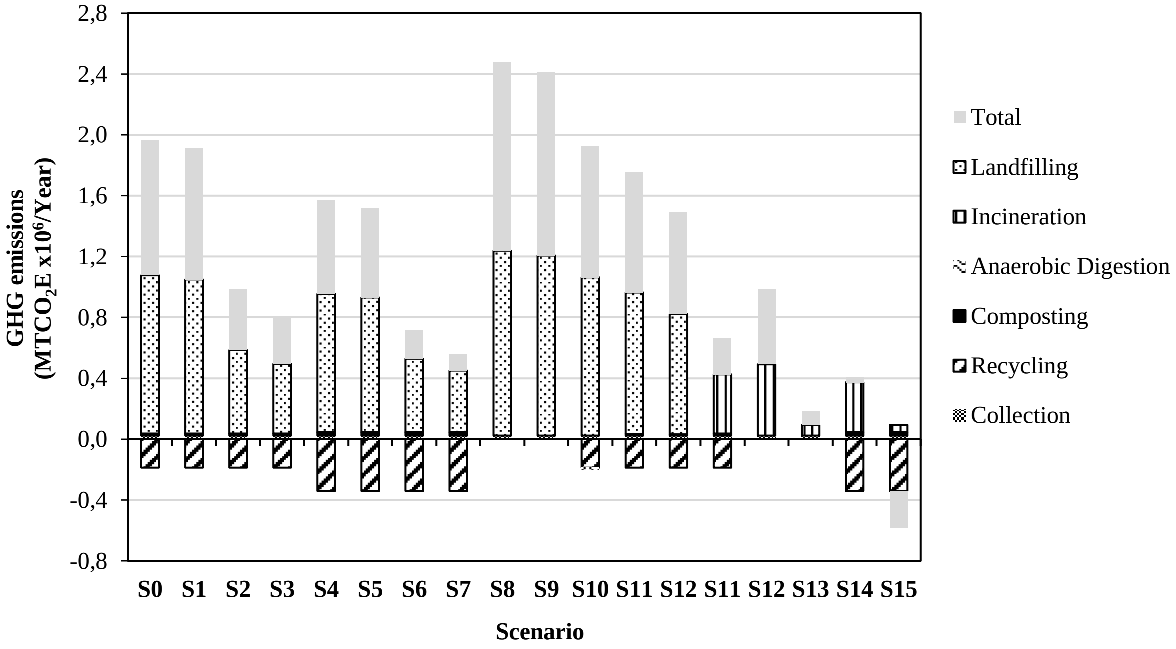

Figure 2. Impact of policy options on GHG emissions in 2013

S0	*Existing baseline scenario*
S1	*S0 + LFG energy recovery*
S2	*Upgrade LFG capture system*
S3	*S2 + LFG energy recovery*
S4	*Max recycling & composting + landfilling*
S5	*S4 + LFG energy recovery*
S6	*S4+ Upgrade LFG capture system*
S7	*S6+ LFG energy recovery*
S8	*Landfilling all waste*
S9	*S8 + LFG energy recovery*
S10	*Substitute composting in S0 by anaerobic digestion + energy recovery*
S11	*Substitute landfilling in S0 by incineration*
S12	*Incinerate all waste*
S13	*S12 + energy recovery*
S14	*Max recycling and composting + incineration*
S15	*S14 + energy recovery*

The potential of emissions reduction from alternative scenarios can be subject to economic constraints depending on the technology adopted and whether reductions are considered in the economic valuation (Table 4). In the context of the existing waste management system, the results show that maximizing waste recycling and composting coupled with upgrading LFG collection for energy recovery from landfilling decreases the overall cost of MSW management most (-26% with carbon credit). Incineration with any variation (S11 to S15) increases the cost significantly in the absence of carbon credit (up to 98%). Optimizing emissions reduction through incineration (S14) reduces emissions most (-96%) at the expense of an overall net cost increase by ~43% if carbon credit is considered (Table 4). Note however that other externalities (real estate depreciation, air and groundwater pollution with potential health impacts) may affect the economic valuation of various scenarios significantly. Similarly, possible changes in costs due to the dynamics of economy of scale can play a role that was not considered in this analysis. Another limitation is time factor considerations that affects both costs and emissions. For instance, the models do not account for the time required for the construction of various waste facilities. Moreover, the offset of electricity was assumed the same as the current case for future years.

Table 5. Policy scenario analysis: Economic implications

Scenario	Description	Cost variation [(a)] (%)	Avoided emissions (%)	Adjusted cost variation [(b)] (%)
S0	Existing baseline scenario	0	0	0
S1	S0 + LFG energy recovery	-6	-3	-7
S2	Upgrade LFG capture system	3	-55	-7
S3	S2 + LFG energy recovery	-6	-65	-19
S4	Max recycling & composting + landfilling	-1	-31	-7
S5	S4 + LFG energy recovery	-9	-34	-15
S6	S4+ Upgrade LFG capture system	-1	-79	-16
S7	S6+ LFG energy recovery	-9	-88	-26
S8	Landfilling all waste	9	39	16
S9	S8 + LFG energy recovery	-2	36	4
S10	Substitute composting in S0 by anaerobic digestion + energy recovery	11	-3	10
S11	Substitute landfilling in S0 by incineration	77	-73	63
S12	Incinerate all waste	98	-45	89
S13	S12 + energy recovery	56	-90	39
S14	Max recycling and composting + incineration	61	-96	43
S15	S14 + energy recovery	32	-128	7

[(a)] Cost variation with respect to current MSW management cost (S0) without carbon credit
[(b)] Cost variation with respect to current MSW management cost (S0) with carbon credit
Note that the emission reduction is calculated with respect to reference baseline scenario (S0) and the carbon credit is based on 17.4 USD/MTCO$_2$E

4. CONCLUSION

This study showed that landfilling constitutes the major contributor to GHG emissions from the waste sector with diversion of materials through recycling and composting coupled with energy recovery from incineration having the greatest effect on reducing emissions assuming that emissions associated with the construction phase for all treatment systems are similar. Hence, optimizing composting and recycling coupled with upgrading LFG collected for energy recovery from landfilling reduced equivalent emissions by 88% at a corresponding savings of 9 and 26% without or with carbon credit, respectively. Optimizing composting and recycling coupled with incineration without energy recovery reduced equivalent emissions by 96% at a corresponding increased cost of 43 and 61% with or without carbon credit, respectively. The results provide guidelines for policy and decision makers on the economic viability of investment in carbon credit to meet NDCs under the Paris Agreement.

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