AMERICAN UNIVERSITY OF BEIRUT

A UOD APPROACH FOR ASSESSING EMISSIONS FROM MSW MANAGEMENT: DEVELOPMENT, VALIDATION, AND POLICY ANALYSIS

by
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AN ABSTRACT OF THE THESIS OF

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This study presents an Upstream-Operating-Downstream (UOD) model developed to quantify direct and indirect emissions from the integrated management of municipal solid waste (MSW) using a life-cycle inventory approach. The model was validated and applied at a pilot regional level with a policy scenario analysis to define economically attractive management systems taking into consideration the footprint of related processes to optimize carbon credit. Direct greenhouse gas (GHG) emissions constituted the major contributor to the overall GHG emissions inventory (96%), while the contribution of indirect upstream GHG emissions was 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 energy recovery from landfilling or incineration reduced equivalent emissions by 89 to 127%, respectively at a corresponding cost saving of 45% or increased cost of 21% including carbon credit.

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ABREVIATIONS

AR4	Fourth Assessment Report
AR5	Fifth Assessment Report
CAS	Central Administration for Statistics
CDM	Clean Development Mechanism
CH_4	Methane
CO_2 eq.	CO_2 equivalents
CO_2	Carbon dioxide
EDL	Electricité de Liban
EEA	European Environment Agency
EFs	Emission Factors
EPA	U.S. Environmental Protection Agency
EPE	Entreprises pour l’Environnement
GBA	Greater Beirut Area
GHG	Greenhouse Gas
GHGs	Greenhouse Gases
GW	Global Warming
GWFs	Global Warming Factors
GWP	Global Warming Potential
IMSWM	Integrated Municipal Solid Waste Management
IPCC	Intergovernmental Panel on Climate Change
ISO	International Standard Organization
IWM	Integrated Waste Management model for municipalities
IWM-2	Integrated Waste Management model-2
KP	Kyoto Protocol
LC	Life Cycle
LCA	Life Cycle Assessment
LCI	Life cycle inventory analysis

MoE	Ministry of Environment
MSW	Municipal Solid Waste
MSWM	Municipal Solid Waste Management
$MTCO_2E$	Metric tons of carbon dioxide equivalents
N_2O	Nitrous oxide
OECD	Organization for Economic Co-operation and Development
SAR	Second Assessment Report
SWDS	Solid Waste Disposal Sites
TAR	Third Assessment Report
UNFCCC	United Nations Framework Convention on Climate Change
UOD	Upstream Operating Downstream
WARM	Waste Reduction Model

This thesis is dedicated to my family for their love and support.

INTRODUCTION

With increased concerns about climate change and its impacts, research on greenhouse gas (GHG) emissions from the solid waste sector gained attention in recent years because the sector contributes appreciably to the total global GHG emissions that can be minimized with management alternatives.

The solid waste sector contributes to greenhouse gas (GHG) emissions primarily in the form of carbon dioxide (CO_2), methane (CH_4) and nitrous oxide (N_2O), and a few other gases that have a minor impact (Gentil *et al.*, 2009). These gases are emitted through various processes and components of the waste management system (from collection and transport to reuse, recycling, composting, incineration, land application, and landfilling) and accounted for ~3% (1446×10^6 $MTCO_2E$) of worldwide GHG emissions in 2010 (Blanco et al., 2014). While relatively a smaller contributor to total GHG emissions, the waste sector is considered to present an appreciable potential towards emissions reduction through selected technologies (Bogner et al., 2007; Friedrich and Trois, 2011; IFEU and Ökoinstitut, 2010) particularly in developing countries where waste emissions can account for a greater percentage reaching 15% due to the greater content of highly biodegradable organics. The extent to which GHGs contribute to global warming is usually reported in CO_2 equivalents (CO_2E) using 1) the global warming potential (GWP) of various gases for a 100-year time horizon that have evolved with time (Table 1), and 2) global warming factors (GWFs) for various management processes (Table 2).

Table 1. GWP for 100-year time horizon

GHGs	Symbol	First assessment report (FAR) IPCC (1990)[1]	Second assessment report (SAR) IPCC (1995)[2]	Third assessment report (TAR) IPCC (2001)[3]	Fourth assessment report (AR4) IPCC (2007)[4]	Fifth assessment report (AR5) IPCC (2013)[5]
Carbon dioxide	CO_2	1	1	1	1	1
Methane	CH_4	21	21	23	25	34
Nitrous oxide	N_2O	290	310	296	298	298

[1] IPCC, 1990; [2] IPCC, 1995; [3] IPCC, 2001; [4] Forster *et al.*, 2007; [5] Myhre *et al.*, 2013

Table 2. GWFs per MSWM methods

	MTCO$_2$E / 1 Ton of MSW managed				
Reference	Collection	Recycling	Composting	Incineration	Landfilling
Astrup *et al.* 2009a	-	Pl: -0.06 to -1.6	-	-	-
Astrup *et al.* 2009b	-	-	-	0.35 to 0.53	-
Boldrin *et al.* 2009	-	-	0.30	-	-
Cadena *et al.* 2009	-	-	0.06	-	-
Chen & Lin 2008	0.016	-2.49	0.03	-0.22	0.02
Daamgaard *et al.* 2009	-	Al: -5 to -19.3 St: -0.6 to -2.4	-	-	-
Eisted *et al.* 2009	0.005 – 0.03	-	-	-	-
Friedrisch & trois 2013a,b	0.015	-0.29 to -19.11	0.186	-	0.44 to 2.53
Hermann *et al.* 2011	-	-	1.10 – 1.70	-	-
ISWA,2009	-	-0.19 to -0.50	-	-	-
Kim & Kim 2010	-	-	0.12	-	1.10
Larsen *et al.* 2009a	0.004 to 0.03	-	-	-	-
Larsen *et al.* 2009b	-	G: -0.5 to -1.5	-	-	-
Manfredi *et al.* 2009	-	-	-	-	0.30
Merrild & Christensen 2009b	-	P: -0.4 to -4.4	-	-	-
Merrild & Christensen 2009a	-	W: -0.07 to -1.4	-	-	-
Nguyen & Wilson 2009	0.008 to 0.04	-	-	-	-
Smith *et al.* 2001	0.007	-	-	-	-
Range	*0.004 to 0.04*	*-0.06 to -19.3*	*0.03 to 1.7*	*-0.22 to 0.53*	*0.02 to 0.53*

Note: GWFs are expressed in MTCO$_2$E / 1 Ton of MSW managed for collection, recycling, composting, incineration or landfilling.
Pl: Plastics, Al: Aluminum, St: Steel, G: Glass, W: Wood

Using GWP and GWFs, various models have been developed to estimate emissions from the waste sector. Amongst these, the life cycle assessment (LCA) based-models proved to be most effective in identifying and assessing environmental burdens associated with waste management alternatives (EEA, 2003; Pires et al., 2011; Cherubini et al., 2008; Gentil et al., 2009; Friedrich and Trois, 2010). In this context, a waste management scheme involves *upstream* emissions arising from inputs of energy and material (electricity and fuel), direct *operational* emissions from systems' operations such as waste degradation and onsite equipment, and *downstream* emissions (or savings) related to energy and material substitution and carbon storage such as energy/electricity generation (Gentil *et al.,* 2009). In this study, we examined the waste management system within a wide context involving all components of the integrated waste management process (collection, recycling, composting, incineration, and landfilling) to account for direct and indirect upstream and downstream emissions along with energy produced and consumed across all stages. For this purpose, an *Upstream-Operating-Downstream (UOD)* model was developed and applied at a pilot regional level with a scenario analysis that defines economically attractive policies targeting minimal GHG emissions taking into consideration the carbon credit of related policies.

MATERIALS AND METHODS

1. Theoretical Framework

The system's boundaries (Figure 1) consist of MSW categories (*c*) with corresponding management processes including collection (*C*), recycling (*R*), composting (*Co*), incineration (*I*), landfilling (L_f) and associated GHG emissions (*E*), materials recovered (recyclables r), by-products such as compost (*Comp*), and electricity produced (*Elecpro*). The total amount of MSW (M_T) is extrapolated from the population (*P*) based on per capita generation rates (*GR*) for a general study area and inventory year (Equation 1), whereby each fraction (f_c) for waste category (*c*), and the corresponding mass (M_c) can be expressed by Equation 2. Similarly, the fraction (f_k) collected, recycled, composted, incinerated, or landfilled is multiplied by the total waste generated (M_T) to estimate the amount of waste (M_k) sent to waste management method k (Equation 3).

$$M_T = P * G_R \tag{1}$$

$$M_c = f_c * M_T \qquad \sum_{c=F}^{W} f_c = 1 \ ; \ \text{c} \in \{F; G; G_A; M; N; O; P; P_L; T; W\} \tag{2}$$

$$M_k = f_k * M_T \qquad \sum_{K=R}^{Lf} f_k = 1\, ; \ k \in \{R; C_o; I; L_f\} \tag{3}$$

Where

M_T Total mass of MSW generated in inventory year *t* (Tons/yr)

M_c Mass of MSW category *c* generated in year *t* (Tons/yr)

c Category of MSW: *F*= Food waste; *G*= Glass; G_A= Garden waste; *M*= Metals; *N*= Nappies; *O*= others; *P*= Mixed Paper; P_L= Plastics; *T*= Textiles; *W*= Wood

f_c Fraction of MSW category *c*

f_k Fraction of MSW under management method *k*

M_k Mass of MSW under management method*k* [collection (*C*), recycling (*R*), composting (*Co*), incineration (*I*), and landfilling (L_f)] in inventory year *t* (Tons/yr)

P Population in inventory year *t*

G_R Generation rate (Tons/cap/yr)

Greenhouse gas emissions from direct and indirect (upstream, operational and downstream) processes were estimated in Metric Tons of CO2 equivalent (MTCO2E) per characteristic unit where emission factors (EFs) were converted to CO2E using GWP (Table 3) for a time horizon of 100 years1. Estimation of GHG emissions from individual MSW management processes k are elaborated in Annex A.

The total GHG emissions, ET, during an inventory year t, is the summation of GHG emissions from all MSW management processes from waste collection to final disposal with each including total direct and indirect upstream and downstream GHG emissions (Equations 4 and 7). The net GHG emissions from each MSW management method, Ek, include: 1) Direct (D) operating emissions from waste processing and fuel combustion due to on-site

[1] CO_2 having a GWP of 1 as a reference, CO_2 biogenic, CH_4 and N_2O have 0, 21, and 310 GWP, respectively (GWP_{100}, IPCC 1995)

activities (e.g. mobile equipment at the treatment facility); and 2) indirect (ID) emissions from upstream processes (e.g. electricity consumption, combustion of fuel) as well as emissions from downstream processes or avoided emissions (e.g. offset of energy and material production substituted by the energy and material recovered) (Equation 5).

Emissions from direct or indirect (upstream and downstream) processes during a MSW management method k in inventory year t, Ek i, include all GHGs (e.g. CO2, CH4, and N2O) emitted and avoided with corresponding GWP (Equation 6). Therefore, the net Direct (Ek D g) or indirect (Ek ID g) emissions of GHG (g) during MSW management method (K) in inventory year (T) is represented by Equations 7a and 7b, respectively.

Then, GWFs are calculated by the sum of products of EF (Table 3) for each GHG and the corresponding GWP divided by the total tons of wet waste managed. When the aggregated GWFs are added together, they represent the overall potential contribution to global warming (GW) from upstream, operational and downstream processes expressed in (MTCO2E) per ton of wet waste (ww) managed: collected, recycled, composted, incinerated, or landfilled. A GWF is positive when there is a contribution to GW and negative when constituting offsets or savings.

$$E_T = \sum_{K=C}^{Lf} E_k ; \quad k \in \{\mathrm{C}; \mathrm{R}; \mathrm{C}_o; \mathrm{I}; L_f\} \tag{4}$$

$$E_k = \sum_{i=D}^{ID} E_{k\,i} ; \quad i \in \{\mathrm{D}; \mathrm{ID}\} \tag{5}$$

$$E_{k\,i} = \sum_{g=CH_4}^{N_2O} E_{k\,i\,g} * GWP_g ; \; g \in \{CH_4; \mathrm{CO}_2; \; N_2 0\} \tag{6}$$

$$\sum_{k=C}^{L_f} \sum_{i=D}^{ID} \sum_{g=CH_4}^{N_2O} E_{k\,i\,g} =$$

$$\begin{cases} \sum_{k=C}^{L_f} \sum_{g=CH_4}^{N_2O} E_{kDg} = \sum_{k=C}^{L_f} \sum_{g=CH_4}^{N_2O} \left\{ f_k * \left[\sum_{c=F}^{W} M_c * EF_{kcg}\right] + \left(M_k * V_{fuek} * EF_{fuel_g}\right)\right\} * GWP_g & \text{for i = D } (7a) \\ \sum_{k=C}^{L_f} \sum_{g=CH_4}^{N_2O} E_{kIDg} = \sum_{k=C}^{L_f} \sum_{g=CH_4}^{N_2O} \left\{\left(M_k * Elec_k * EF_{elec_g} * GWP_g\right) - \left(Elecprod_k\right) * a * b * EF_{elec_g} * GWP_g\right) + \left(M_k * V_{fuek} * EF_{fuelpro_{CO_2}}\right)\right\} & \text{for i = ID } (7b) \end{cases}$$

$\mathrm{k} \in \{\mathrm{C}; \mathrm{R}; \mathrm{C_o}; \mathrm{I}; \mathrm{L_f}\}, \mathrm{i} \in \{\mathrm{D}; \mathrm{ID}\}, \mathrm{c} \in \{\mathrm{F}; \mathrm{G}; \mathrm{G_A}; \mathrm{M}; \mathrm{N}; \mathrm{O}; \mathrm{P}; \mathrm{P_L}; \mathrm{T}; \mathrm{W}\}; g \in \{CH_4; \mathrm{CO}_2; \; N_2 0\}$

for k = Lf, b = fraction of CH_4 recovered * Metric tons of CH_4 generated;

for k = I : $\mathrm{b} = (M_c * f_I) \; for \; every \; M_c = f_c * M_T$

Where

E_T Total GHG emissions from MSW in inventory year *t* ($MTCO_2E$/yr)

E_K GHG emissions for MSW management method K in inventory year *t* ($MTCO_2E$/yr)

$E_{K\ i}$ GHGs emissions *i* (Direct *D* or indirect *ID*) for MSW management method *K* in inventory year *t* ($MTCO_2E$/yr)

$E_{K\ i\ g}$ GHG *g* (CH_4, CO_2, and N_2O) emissions *i* in Metric Tons *MT* of *g* emitted and avoided for MSW management method *K* in inventory year *t* (MT/yr)

GWP_g Global warming potential of GHG *g* for a 100-year time horizon ($MTCO_2E$ of gas g /MT of gas *g*)

$EF_{K\ c\ g}$ Emission factor for GHG *g* from each ton of waste category *c* under a MSW management method *K* (Metric Tons of *g*/ ton treated)

V_{fuel_K} Volume of fuel consumed during MSW management method *K* by onsite mobile equipment and combustion facilities in inventory year *t* (Liters/ton treated/ yr)

EF_{fuel_g} Emission factor for fuel combustion for GHG *g* (Metric tons of g/Liter of fuel)

$EF_{fuelpro_{CO_2}}$ Emission factor for provision of fuel for CO_2 ($MTCO_2$/Liter of fuel)

$Elec_K$ Electricity consumed during a MSW management method *K* in inventory year *t* (kWh/ton treated)

$Elec_{prod_K}$ Power potential during MSW management method *k* in inventory year *t* it is equal to Electricity produced from mass incinerated for Mass category c (kWh/ton of ww incinerated) or from CH_4 recovered from landfills and combusted (kWh/Metric Tons of CH_4 recovered)

EF_{elec_g} Emission factor of electricity consumed or recovered for GHG *g* emitted or avoided based on national electricity grid (Metric tons of g /kWh)

a Capacity factor for electricity generation or mass burn combustion system efficiency (fraction) (For k= I, a =0.2; For K= L_f, a= 0.85 adapted from USEPA, 2010-USEPA/ICF,2012)

b Amount of recovered methane $(fraction\ of\ CH_4\ recovered * Metric\ Tons\ of\ CH_4\ generated)$ (Metric Tons of CH_4/yr), or Mass of waste category *c* incinerated $(M_c * f_I)$ (Tons/yr)

Table 3. Aggregated EFs from various contributions in $MTCO_2E$ per characteristic unit
(Data sources: IEA, 2013; Fruergaard, 2009; USEPA, 2006; USEPA/ICF, 2012; EpE, 2013; McDouall et al. 2001)

Collection	Recycling	Composting		Incineration	Landfilling	
Direct and indirect	Direct and indirect[(a)]	Direct	Indirect[(b)]	Direct and indirect	Direct[(c)]	Indirect
$\boldsymbol{g=\{CH_4;CO_2;N_2O\}}$ $\boldsymbol{EF_{fuel_{CO_2}}=0.003}$ $\boldsymbol{EF_{fuel_{CH_4}}=7.7*10^{-5}}$ $\boldsymbol{EF_{fuel_{N2O}}=3.1*10^{-8}}$ $\boldsymbol{EF_{fuelpro_{CO_2}}=0.00045}$	c = {G; M; P; Pl; T; W} $EF_{R\ P}$ = -3.52 $EF_{R\ Pl}$ = -0.98 $EF_{R\ G}$ = -0.28 $EF_{R\ T}$ = -2.37 $EF_{R\ W}$ = -2.46 $EF_{R\ M}$ = -3.97	c=F; $g=\{CH_4;N_2O\}$ $EF_{Co\ F\ CH4}=$ 0.02604 $EF_{Co\ F\ N2O}=$ 0.06510 $g=\{CH_4;CO_2;N_2O\}$ $EF_{fuel_{CO_2}}=0.003$ $EF_{fuel_{CH_4}}=7.7*10^{-5}$ $EF_{fuel_{N2O}}=3.1*10^{-8}$	$EF_{fuelpro_{CO_2}}=$ 0.00045 $EF_{ele_{CO_2}}=6.87*10^{-4}$ c = F; $g=CO_2$ $EF_{Co\ F\ CO2}=$ -0.24	c = {F; G; M; O; P; PL; T; W} $g=\{CO_2;N_2O\}$ $EF_{I\ P\ CO2}=0.03$ $EF_{I\ T\ CO2}=1.67$ $EF_{I\ O\ CO2}=0.34$ $EF_{I\ F\ N2O}=0.04$ $EF_{I\ PL\ N2O}=0.04$ $EF_{I\ O\ N2O}=0.04$ a=0.178 $EF_{ele_{CO_2}}=6.87*10^{-4}$	c = {G; M; P; Pl; T; W} $EF_{Lf\ P\ CH4}=1.29$ $EF_{Lf\ F\ CH4}=1.55$ $EF_{Lf\ W\ CH4}=0.16$ $EF_{Lf\ O\ CH4}=3.42$ $EF_{Lf\ N2O}=0.0133$ $g=\{CH_4;CO_2;N_2O\}$ $EF_{fuel_{CO_2}}=0.003$ $EF_{fuel_{CH_4}}=7.7*10^{-5}$ $EF_{fuel_{N2O}}=3.1*10^{-8}$	$EFelec_{CO2}=6.87*10^{-4}$ a=0.85 $EF_{fuelpro_{CO_2}}=0.00045$

[(a)] Emission factors (EFs) for recycling are expressed in $MTCO_2E$/Ton ww recycled of category c ; [(b)] From soil carbon storage considered as avoided emissions; [(c)] Adjusted to account for: carbon storage, methane correction factor (MCF), and N_2O emissions from flaring; EF are expressed in $MTCO_2E$/Ton of MSW managed; $MTCO_2E$/KWh; $MTCO_2E$/Liter of Diesel fuel;
C=Collection; R= Recycling; C= Composting; I=Incineration; L_f=Landfilling; F = Food waste; G = Glass; M = Metals; O = others; P = Paper; P_L = Plastics; T = Textiles; W = Wood; *g* = gas

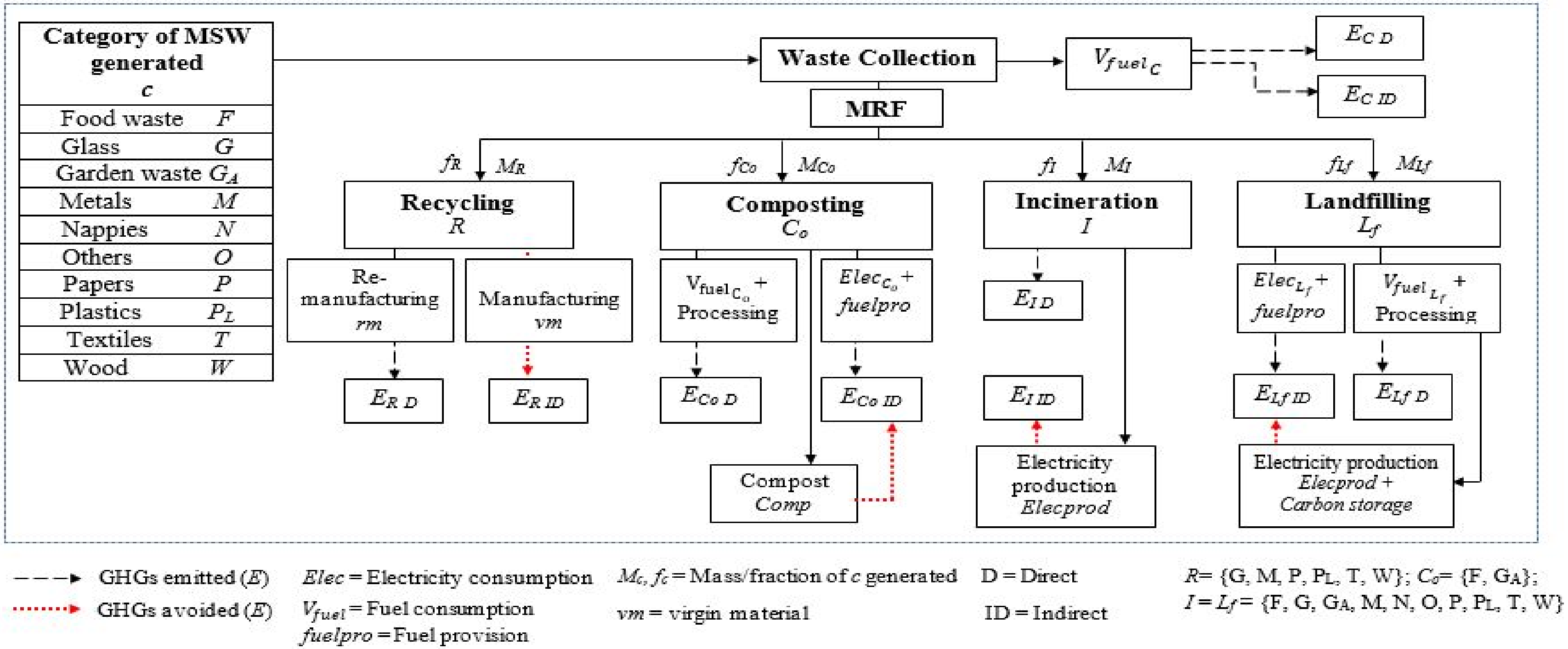

Figure 1. Model framework

2. Model application

The model was applied at a regional pilot level (Beirut and surroundings, Lebanon) (Figure 2), encompassing 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 Tons of MSW per day with an average waste composition presented in Table 4.

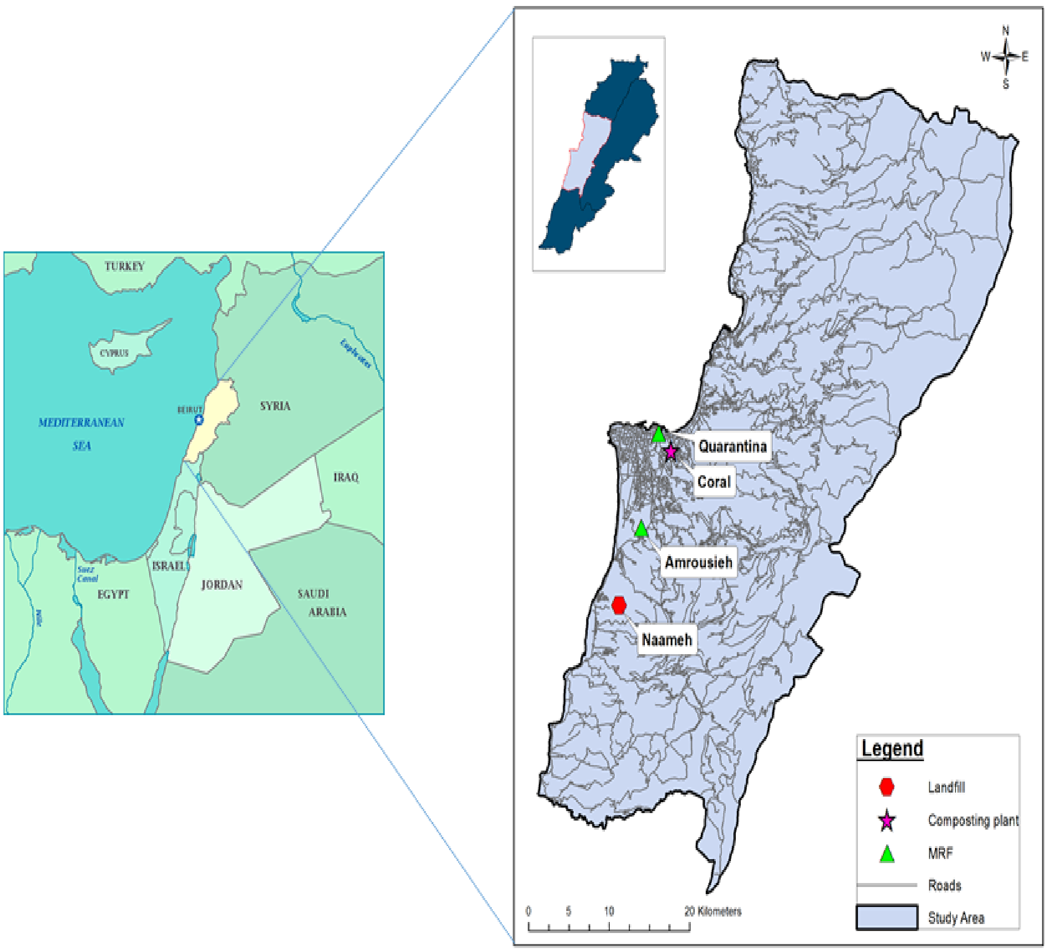

Figure 2. Map of pilot study area and MSW facilities

Table 4. MSW composition (LACECO/RAMBOLL, 2012)

Waste category (c)	Symbol	(%)
Food	F	53.4
Glass	G	3.4
Metals	M	2
Nappies	N	3.6
Others	O	4.6
Papers	P	15.6
Plastics	P_L	13.8
Textiles	T	2.8
Wood	W	0.8
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 diesel of 6,628,400 L/year (LACECO/RAMBOLL, 2012; SUKLEEN/SUKOMI, 2014), equivalent to 6.2 L/Ton of waste generated in 2013, which is within reported ranges (Larsen et al., 2009a; Nguyen & Wilson, 2009). The waste is then transferred into two materials recovery facilities (MRFs)2 where it is sorted into bulky items, inert material, biodegradable organics, and recyclables. The biodegradable fraction is sent for windrow composting2 with relatively low quality compost often rejected by consumers and hence mostly transferred along with other rejects to a sanitary landfill2 (Table 5). The latter is equipped with a gas collection and flaring system with LFG collection since 2001 at 3 Gg of CH4/year that reached 14 Gg of CH4/year in 2013. While direct GHG emissions are related to the decomposition of MSW through various processes and other activities3 at the management facilities, indirect emissions are related to activities outside these

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

[3] Average annual diesel fuel consumption (LACECO/RAMBOLL, 2012; SUKLEEN/SUKOMI, 2014): 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$_2$E/Liter (McDouall *et al.* 2001)

facilities mostly through electricity and fuel provision that were quantified for each process with associated emission factors[4].

Table 5. MSW management in Pilot test Area

Year	Waste generated (T/yr)[(a)]	Waste disposal sites: Naameh landfill (T/yr)[(b)]	Waste disposal sites: Burj Hammoud (T/yr)[(c)]	Waste disposal sites: Dumpsites (T/yr)[(d)]	Recycling (T/yr)[(e)]	Composting (T/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).

3. Validation and Comparative assessment

Several guidelines (IPCC 1996 and 2006)5, protocols (EpE)6, and models (WARM7, IWM and IWM-28) that examine GHG emissions based on specific waste management

[4] Average electricity consumption: 32 kWh/ton of waste composted (Manfredi *et al.*, 2009); 8 kWh/ton of waste landfilled (Boldrin, 2009) with corresponding emission factor EF_{elec} = 6.87 $MTCO_2E$ / kWh consumed (IEA, 2013) based on electricity provision from diesel and heavy fuel oil at thermal operating power plants (EDL, 2012). Emissions from fuel provision (extraction, processing, storage, and transportation of the fuel): $EF_{fuelpro_{CO_2}} = 0.00045$ $MTCO_2E$/Liter (Fruergaard, 2009)

[5] Used in countries reporting under the United Nations Framework Convention on Climate Change (IPCC, 1997; 2006).

[6] Used by European companies and local authorities to conduct annual inventories of GHG emissions (EPE, 2013)

[7] Used to estimate GHG emissions reductions in climate change impacts assessment (EPA, 2002; EPA, 2013; ICF, 2014)

[8] Accepted by Environment Canada to evaluate the performance of waste management processes (McDouall *et al.* 2001; EPIC and CSR 2004; Morrissey & Browne 2004; UWaterloo 2004; Mohareb *et al.* 2008; Batool & Chuadhry 2009)

processes, were used to cross validate simulated trends and cross compare between methods. Similar operational data were introduced in all methods to ensure a uniform basis for the comparative assessment.

4. Scenario Definition: Policy and Economic Analysis

Several scenarios were simulated to assess the influence of governmental policy alternatives (Table 6) in terms of variation in waste diverted to composting, incinerating, and landfilling or recycling target on GHG emissions reduction under the Clean Development Mechanism and define 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 cost of MSW management under each scenario is calculated by multiplying the tons of waste managed under each process by actual prices in the pilot test area (Table 7) and added to estimate the total cost of MSW management under each scenario for comparison.

Table 6. Alternative policy scenarios tested

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

S14	S11 + energy recovery	12	18	70	0

[(a)] With LFG collection and flaring

Offset of GHG emissions were quantified based on carbon market price ranging from 15.7 to 19.2 USD/MTCO$_2$E (Ecosystem Marketplace, 2011), where an average of 17.4 USD/MTCO$_2$E is adopted to assess associated benefits and allow cost savings estimation under CDM for reducing carbon footprint through regulated and voluntary global markets for trading or offsetting of carbon credits (El-Fadel, 2013).

Table 7. Cost of MSW management per source in USD/Ton of waste

	Collection[(a)]	Composting[(a)]	Sorting[(a)]	Landfilling[(a)]	Waste to Energy Landfilling[(b)]	Incineration[(b)]	Waste to Energy Incineration[(c)]
(USD/ Ton of waste)	31	31	26	43	38.7	110.7	84.9

[(a)] MoE/UNDP/Ecodit, 2011; LACECO/RAMBOLL, 2012
[(b)] Includes capital and operational costs (Source: Rabel et al., 2008; Hogg & European Commission, 2002)
[(c)] Includes sale of any net energy (electricity); excludes disposal costs of bottom and fly ash (non-hazardous and hazardous) (source: Rabel et al., 2008; Hogg & European Commission, 2002; Hoornweg & Perinaz/World Bank, 2012; WRAP, 2008)

RESULTS AND DESCUSSION

1. Model application: Baseline Scenario (S0)

Direct emissions from the waste sector for the year (2013) constituted the major contributor (96%) to GHG emissions (Table 8), while indirect emissions from electricity and fuel provision were less significant (4%). Landfilling remains associated with the highest contribution followed by collection and composting, with recycling contributing to GHG savings. GHG emissions from collection (0.023x106 MTCO2E/Year) contributed 3% of the total GHG emissions (0.911x106 MTCO2E/Year) and were considered as part of the overall indirect GHG emissions (0.039x106 MTCO2E/Year). The GWF of collection weighted on the basis of the mass of wet waste generated (1.069x106 Tons) includes direct and indirect emissions from fuel consumption (0.019 and 0.003 MTCO2E/Ton of ww collected, respectively) which are consistent with internationally reported values (Table 2) for developing economies (Friedrich and Trois, 2013a) and falls at the higher end of ranges reported for developed economies (Larsen et al., 2009a).

Table 8. Baseline GWF and total GHG emissions in 2013

Category	Collection	Recycling	Composting	Incineration	Landfilling	Total [b]
Waste (Tons x 10^6)	**1.069**	**0.071**	**0.111**	**0**	**0.887**	**1.069**
Overall Direct emissions	0.019		0.100	0	1.383	0.872
Waste degradation	…		*0.090*	*0*	*1.326*	
Fuel consumption	*0.019*		*0.010*	*0*	*0.057*	
Overall Indirect emissions	0.003		0.023	0		0.039
Upstream emissions	0.003		0.023	0	0.014	
Electricity consumption	-		*0.022*	*0*	*0.006*	
Fuel provision	*0.003*		*0.001*	*0*	*0.008*	
Downstream emissions	…		0	0	-0.202	
Electricity production	…	…	…	*0*	*0*	
Carbon storage	…	…	*0*[d]	…	*-0.202*	
Total GWF [a]	0.022	-2.655[c]	0.123		1.196	
Total GHG emissions S0 [b]	**0.023**	**-0.187**	**0.014**	**0**	**1.061**	**0.911**

(a) GWF expressed in $MTCO_2E$/Ton of waste in 2013 (GWP_{100}, IPCC 1995)
(b) Total GHG emissions expressed in $MTCO_2E$/Year*106
(c) Total GWF from direct and indirect downstream recycling processes
(d) Compost produced

The total net GWF of recycling (- 2.655 MTCO2E/Ton of ww recycled) includes direct and indirect downstream processes that contribute to GHG savings. The latter depend 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; US EPA, 2006; Larsen et al., 2009b). Similarly, the results are within the range of internationally reported values (-0.06 to -19.3 MTCO2E/Ton of ww recycled – see Table 2) because most reprocessing and production activities take place outside the country and hence recycling emission factors of various components relied on default factors reported by the USEPA (2012).

Direct GHG emissions from composting (0.100x106 MTCO2E/Year) due to waste degradation and fuel consumption by onsite operating equipment are higher than indirect emissions (0.023x106 MTCO2E/Year) from electricity consumption. The indirect downstream carbon storage is insignificant because the quality of the produced compost is low and hence, not used for land application. The total GWF from composting (0.123 MTCO2E/Ton of ww composted) is in line with values reported in other studies (Kim &Kim, 2010; Friedrisch & Trois 2013b). Waste separation at source can enhance the quality of compost produced, which could translate to savings in GHG emissions by substituting mineral fertilizers and carbon storage associated with the application of compost on land.

Finally, landfilling, where most of the waste is ending (83%) without energy recovery, was responsible for the maximum share of net emissions (1.196 MTCO2E/Ton of ww landfilled after including indirect savings from carbon storage (-0.202 MTCO2E/Ton of ww landfilled) with a minor contribution associated with upstream indirect emissions from electricity and fuel provision (0.014 MTCO2E/Ton of ww landfilled), which are comparable with reported values (Kim & Kim, 2010; Friedrich and Trois, 2013a). The similarity with literature reported values of various processes provides a validation for the model, which will be further ascertained below through the comparative assessment with other models.

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 throughout this period (Figure 3). The decreasing trend between 1998 and 2007 reflects changes in the adopted MSW management plan, which differed with time. Prior to 1997, a small fraction (~4%) of MSW was recovered for recycling and the majority of waste (~96%) was disposed of at uncontrolled dumpsites (see Table 5). In 1997-1998, a new integrated municipal solid waste management (IMSWM) 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 steeper 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 a steep 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 5). In 2013, waste recovery was upgraded and landfilling decreased (5%) explaining the drop in total GHG emissions.

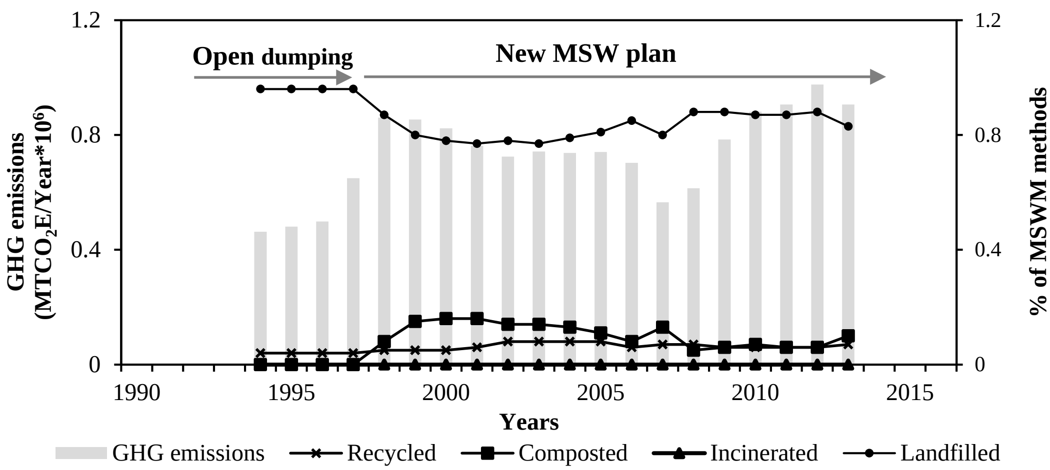

Figure 3. Temporal variation in GHG emissions (direct and indirect) and municipal solid waste management (MSWM) methods

2. Validation and Comparative assessment

While the various models exhibited in between differences that can be attributed to data requirements and scope of accounting (Figure 4), several models predicted the same general trend from 1994 to 2013 (WARM, IWM, IWM-2, and IPCC 1996).WARM was the nearest to the developed UOD model, both falling within the overall range of other models. However, prior to 1997 the two models do not follow the same trend because WARM does not account for emissions from open dumping that occurred during this period. Similarly, WARM does not account for upstream emissions from fuel and electricity provision and other GHGs (such as N2O emissions from flaring) (see Table 9). The IPCC-2006 guidelines and EpE protocols did not capture adequately the changes in management process and resulted in the lowest emissions (most optimistic) whereas the highest emissions were predicted by the IPCC 1996 guidelines (most conservative) because of relying on the theoretical yield that overestimates emissions (IPCC, 2006). Direct emissions (0.434 $x10^6$ and $1.332x10^6$ MTCO2E/Year) accounted for 98 to 87% of total emissions whereas indirect emissions (0.02 $x10^6$ and $0.089x10^6$ MTCO2E/Year) ranged between 2 to 13% of total emissions (Table 9). The variability confirms the differences in scopes of accounting methods and systems' boundaries (direct and indirect), emission factors of various waste categories, and parameters used to describe waste management processes. The developed model offers users the advantage of disaggregation and independent process evaluation depending on the reporting desired (Life cycle inventory including direct and indirect upstream and downstream processes or national reporting, which includes direct emissions only). In addition, it allows the user to select emission factors and input parameters in a flexible way that better reflects country specific conditions, while accounting for different types of waste materials, GHGs, and detailed contribution from different waste management processes.

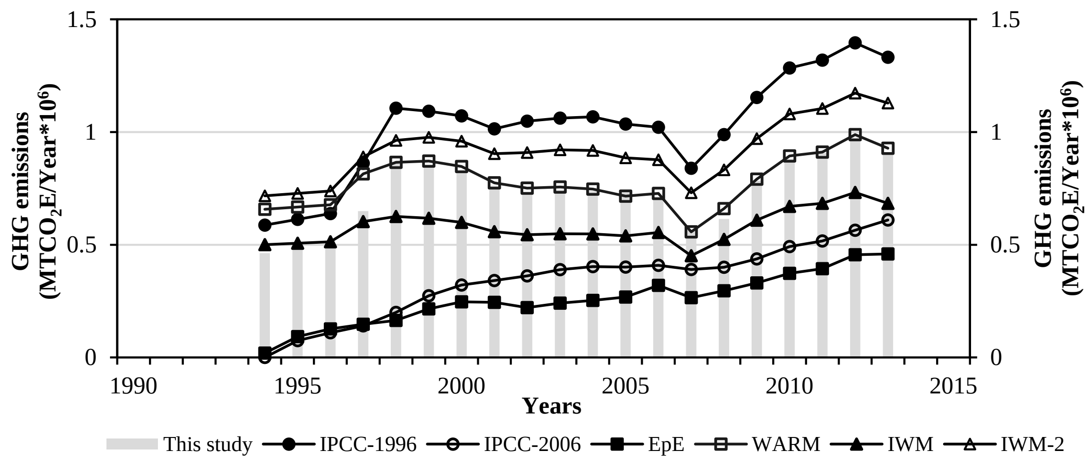

Figure 4. Validation and comparative assessment

Table 9. GHG emissions from MSW management using various accounting methods

Category	Waste (Tons x 10^6)	IPCC		EpE-Protocol	LCA			This Study
Per Source Type		1996	2006		IWM2	WARM	IWM	
Collection	*1.069*	…	…	0.018	0.021	0.020	0.070	0.023
Recycling	*0.071*	…	…	-0.187	-0.073	-0.187	-0.118	-0.187
Composting	*0.111*	…	0.044	0.014	0.001	0.006	0.007	0.014
Incineration	*0*	0	0	0	0	0	0	0
Landfilling	*0.887*	1.332	0.566	0.615	1.179	1.094	0.724	1.061
Per Type of accounting								
Overall Direct emissions		1.332	0.610	0.434	1.107	0.913	0.594	0.872
Overall Indirect emissions		…	…	0.025	0.021	0.020	0.089	0.039
Total GHG emissions		**1.332**	**0.610**	**0.459**	**1.128**	**0.933**	**0.683**	**0.911**

Note: GHG emissions are expressed in ($MTCO_2Ex10^6$/Year) (GWP_{100}, IPCC 1995)

3. Scenario Analysis: Policy and Economic Implications

The results of the baseline scenario were used to test the impacts of policy options to decrease GHG emissions under the Clean Development Mechanism (Table 6). Scenarios with landfilling (S0 to S9) resulted in greater emissions in comparison with scenarios involving incineration (S10 to S14) (Figure 5). Maximizing waste recycling and composting coupled with energy recovery from landfilling or incineration minimizes the overall emissions by 32 and

127% (with respect to S0), respectively9 (Table 11). Note that additional energy recovery from landfilling (S1, S5, and S9 in comparison to S0, S4, and S8 in Table 11) did not contribute significantly to GHG emission reduction (<4%). However, upgrading LFG collection system up to 62% reduced the actual GHG emissions by 58% (S2) with additional GHG savings (73% less with respect to S0) from energy recovery (S3).

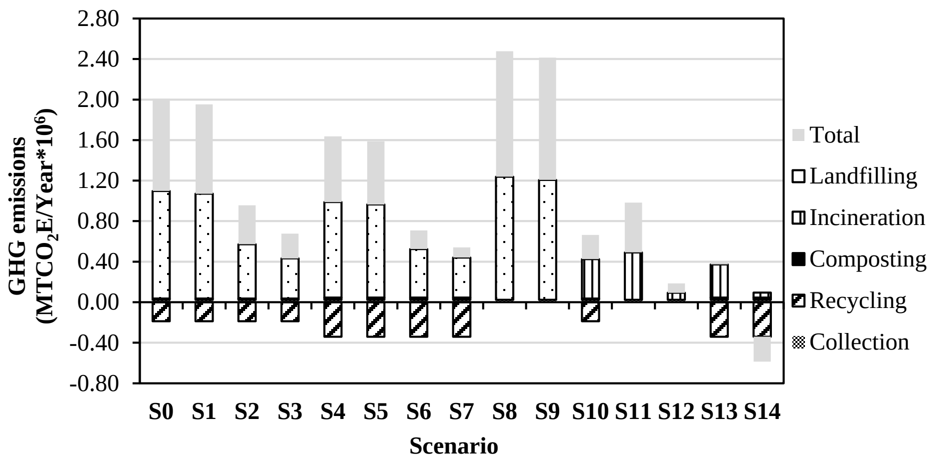

Figure 5. Impact of policy options on GHG emissions in 2013

The potential of GHG reduction from alternative scenarios can be constrained by relatively higher costs of these scenarios depending on the technology adopted and whether GHG reductions are considered in the economic valuation (Table 11). 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 (45% with carbon credit). Incineration with any variation (S10 to S14) increases the cost significantly in the absence of carbon credit (up to 174%). Optimizing emission reduction through incineration (S14) reduces emissions most

[9] Maximizing waste recycling and composting coupled with energy recovery minimizes the overall emissions from complete landfilling or incineration by 50 and 150% with respect to complete landfilling (S4) or complete incineration (S7)

(-127%) at the expense of an overall cost increase by only 21% if carbon credit is taken into account (Table 11). Note however that other externalities (i.e. real estate depreciation, potential air and groundwater pollution with potential health impacts) may affect significantly the economic valuation of various scenarios. Similarly, possible changes in costs due to economy of scale are not accounted for.

Table 10. Scenario analysis: Economic implications

Scenario	Average cost (USD)	Cost variation[a] (%)	Total emissions ($MTCO_2E$/Year)	Avoided emissions [b] ($MTCO_2E$/Year)	Avoided emissions %	Credit of emissions [c] (USD)	Adjusted cost (USD)	Adjusted Cost variation [d] (%)
S0	43,247,769	0	910,511	0	0	-	43,247,769	0
S1	39,433,047	-9	882,827	-27,684	-3	-482,671	38,950,376	-10
S2	43,247,769	0	384,586	-525,925	-58	-9,169,503	34,078,266	-21
S3	39,433,047	-9	244,816	-665,695	-73	-11,606,384	27,826,662	-36
S4	37,939,865	-12	648,052	-262,459	-29	-4,575,973	33,363,892	-23
S5	37,939,865	-12	623,634	-286,877	-32	-5,001,706	32,938,158	-24
S6	41,157,100	-5	184,157	-726,354	-80	-12,663,980	28,493,120	-34
S7	37,939,865	-12	100,437	-810,074	-89	-14,123,638	23,816,226	-45
S8	45,960,508	6	1,238,610	328,099	36	5,720,401	51,680,909	19
S9	41,364,457	-4	1,206,656	296,145	33	5,163,289	46,527,746	8
S10	103,307,464	139	238,176	-672,335	-74	-11,722,161	91,585,303	112
S11	118,321,586	174	491,450	-419,061	-46	-7,306,337	111,015,249	157
S12	90,745,281	110	92,529	-817,982	-90	-14,261,509	76,483,772	77
S13	91,809,855	112	32,948	-877,563	-96	-15,300,312	76,509,542	77
S14	72,506,442	68	-246,296	-1,156,807	-127	-20,168,933	52,337,509	21

[a] Cost variation with respect to current MSW management cost (S0) without carbon credit
[b] Emission reduction with respect to reference baseline scenario (S0)
[c] Carbon credit based on 17.4 USD/$MTCO_2E$
[d] Cost variation with respect to current MSW management cost (S0) with carbon credit

CONCLUSION

A UOD-based framework for GHG emissions estimation from the waste sector was developed and validated using literature reported GWFs and a cross comparative assessment with several methods at a regional pilot scale. 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. Optimizing composting and recycling coupled with upgrading LFG collected for energy recovery from landfilling reduced equivalent emissions by 89% at a corresponding saving of 12 and 45% without or with carbon credit, respectively. Optimizing composting and recycling coupled with energy recovery from incineration reduced equivalent emissions by 127% at a corresponding increased cost of 21 and 68% with or without carbon credit, respectively. The results provide guidelines for policy and decision makers on the economic viability of investment in carbon credit under the Clean Development Mechanism.

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Annex A: Estimation of GHG emissions from MSW management processes

a. Collection

Emissions from waste collection were estimated using the annual fuel consumption (Vfuel) instead of distance traveled because it is more representative as collection trucks use the engine to power the compactor during waste collection and roads tend to have different topographical conditions that affect fuel consumption (Chen and Lin, 2008; Friedrich, 2013a). Emissions from waste collection consist of direct GHGs emitted from fuel consumption during the operation activity, in addition to indirect upstream emissions (e.g. provision of fuel) (Equation a).

$$E_C = M_C * V_{fuel_C} * \left[\sum_{g=CH_4}^{N_2O} \left(EF_{fuel_g} * GWP_g \right) + EF_{fuelpro_{CO_2}} \right] \quad \text{(a)}$$

$\mathrm{K} = \mathrm{C}$; and $g \in \{CH_4;\ CO_2;\ N_2 0\}$

Where

E_C	Direct *D* and indirect *ID* GHG emissions for collection in inventory year *t* ($MTCO_2E$/yr)
GWP_g	Global warming potential of GHG *g* for a 100-year time horizon ($MTCO_2E$ of gas g /MT of gas *g*)
V_{fuel_k}	Volume of fuel consumed during MSW management method *k* by onsite mobile equipment and combustion facilities in inventory year *t* (Liters/ton treated/ yr)
EF_{fuel_g}	Emission factor for fuel combustion for GHG *g* (Metric tons of g/Liter of fuel)
$EF_{fuelpro_{CO_2}}$	Emission factor for provision of fuel for CO_2 ($MTCO_2$/Liter of fuel)
M_C	Mass of MSW collected in inventory year *t* (Tons/yr)

b. Recycling

Direct emissions from remanufacturing of recyclables (Equation b) and avoided emissions from manufacturing virgin material (Equation c) are combined to estimate recycling emissions (Equation d).

$$E_{R\,D} = \sum_{c=G}^{W} \sum_{g=CH_4}^{N_2O} f_{R_c} * M_C * EF_{rm_{cg}} * (1 - rrm)(1 - rrr_c) GWP_g \quad \text{(b)}$$

$$E_{R\,ID} = \sum_{c=G}^{W} \sum_{g=CH_4}^{N_2O} f_{R_c} * M_C * EF_{vm_{cg}} * (1 - rrm)(1 - rrr_c) GWP_g \quad \text{(c)}$$

$$E_R = \sum_{c=G}^{W} \sum_{g=CH_4}^{N_2O} \left[f_{R_c} * M_C * \left(EF_{rm_{cg}} - EF_{vm_{cg}} \right) * (1 - rrm)(1 - rrr_c) \right] * GWP_g \quad \text{(d)}$$

K = R, $g \in \{CH_4;\ CO_2;\ N_20\}$, and c $\in$ {G; M; P; P_L; T; W}

Where

E_R	Direct *D* and indirect *ID* GHG emissions forrecycling in inventory year *t* (MTCO_2E/yr)
$EFrm_{c\,g}$	Emission factor of GHG g from waste category *c* from re-manufacturing of recyclables *rm* (Tons of *g*/ton of *rm*)
$EFvm_{c\,g}$	Emission factor of avoided GHG *g* from waste category c from virgin manufacturing *vm* (Tons of *g*/ton of *vm*)
rrm	Fraction of residues from recyclable materials
rrr_c	Fraction of residues from remanufacturing of recyclables and from virgin material manufacturing waste category *c*
f_{R_c}	Fraction of waste category *c* recycled

c. Composting

Direct GHG emissions from waste decomposition ($E_{Co\,D}$) consist of biogenic CO2 (considered neutral) CH4 and N2O as well as emissions from fuel combustion in mechanical turning of compost piles and on-site mobile equipment (Equation e). Indirect emissions from composting ($E_{Co\,ID}$) include upstream emissions from electricity consumption ($Elec_{Co}$) and the provision of fuel, as well as avoided emissions from carbon storage associated with the application of compost to soils (Equation f).

$$E_{C_o\,D} = f_{Co} * \sum_{g=CH_4}^{N_20} \left(M_F * EF_{C_o\,F\,g} * GWP_g\right) + M_{C_o} * V_{fuel_{C_o}} \sum_{g=CH_4}^{N_20} \left(EF_{fuel_g} * GWP_g\right) \quad \text{(e)}$$

$$E_{C_o\,ID} = \sum_{g=CH_4}^{N_20} (M_{C_o} * Elec_{C_o} * EF_{elec_g} * GWP_g) + \left(M_{C_o} * V_{fuel_{C_o}} * EF_{fuelpro_{CO_2}}\right) \quad \text{(f)}$$

$g \in \{CH_4;\ CO_2;\ N_20\}; (i = \text{Dor ID}; c = F; k = C_o)$

Where

E_{C_O}	Direct *D* and indirect *ID* GHG emissions for composting in inventory year *t* ($MTCO_2E$/yr)
GWP_g	Global warming potential of GHG *g* for a 100-year time horizon ($MTCO_2E$ of gas g /MT of gas *g*)
$EF_{C_O\,F\,g}$	Emission factor for GHG *g* from each ton of food waste composted (Metric Tons of *g*/ ton composted)
V_{fuel_K}	Volume of fuel consumed during MSW management method *k* by onsite mobile equipment and combustion facilities in inventory year *t* (Liters/ton treated/ yr)
EF_{fuel_g}	Emission factor for fuel combustion for GHG *g* (Metric tons of g/Liter of fuel)
$EF_{fuelpro_{CO_2}}$	Emission factor for provision of fuel for CO_2 ($MTCO_2$/Liter of fuel)
$Elec_{Co}$	Electricity consumed during composing in inventory year *t* (kWh/ton of ww treated)
EF_{elec_g}	Emission factor of electricity consumed for GHG *g* emitted based on national electricity grid (Tons of g /kWh)
M_F	Mass of food waste generated in year *t* (Tons/yr)
f_{C_O}	Fraction of MSW composted
M_{C_O}	Mass of MSW composted in inventory year *t* (Tons/yr)

d. Incineration

Direct emissions from incineration ($E_{I\,D}$) are estimated using Equation g whereas indirect emissions ($E_{I\,ID}$) involve avoided emissions from electricity production (Equation h) which depends on the: (1) energy content of mixed MSW or of waste category c burned ($Elecprod_{I\,c}$) in KWh/Ton of waste (Table A1), (2) combustion system efficiency, a, in converting the energy content of MSW materials to recovered electricity, and (3) the emission factor of electricity avoided ($EF_{elec\ g}$).

$$E_{I\,D} = f_I * \sum_{c=F}^{W} \sum_{g=CO_2}^{N_2 0} (M_c * EF_{I\,c\,g} * GWP_g) \quad \text{(g)}$$

$$E_{I\,ID} = f_I * \sum_{c=F}^{W} \sum_{g=CO_2}^{N_2 0} (Elecprod_{I\,c} * M_c * a * b * EF_{elec\,g} * GWP_g) \quad \text{(h)}$$

$g \in \{CH_4;\ CO_2; N_2 0\}$, $c \in \{F; G; G_A; M; N; O; P; P_L; T; W\}$, $b = f_I * M_c$; (K = I, i = D or ID)

Where

$E_{I\,D}$	Direct GHG emissions for Incineration in inventory year *t* ($MTCO_2E$/yr)
$E_{I\,ID}$	Indirect GHG emissions for incineration in inventory year *t* ($MTCO_2E$/yr)
GWP_g	Global warming potential of GHG *g* for a 100-year time horizon ($MTCO_2E$ of gas g /MT of gas *g*)
$EF_{I\,c\,g}$	Emission factor for GHG *g* from each ton of waste category *c* incinerated (Metric Tons of *g*/ ton treated)
$Elec_{prod_K}$	Power potential during MSW management method k in inventory year *t* [Electricity produced: Mass category c incinerated (kWh/ton of ww incinerated)]
EF_{elec_g}	Emission factor of electricity recovered for GHG *g* avoided based on national electricity grid (tons of g /kWh)
M_c	Mass of MSW category *c* generated in year *t* (Tons/yr)
c	*F*= Food waste; *G*= Glass; *M*= Metals; *O*= others; *P*= Mixed Paper; P_L= Plastics; *T*= Textiles; *W*= Wood
f_I	Fraction of MSW incinerated
a	Mass burn combustion system efficiency (fraction) (a=0.178)
b	Mass of waste category *c* incinerated ($M_c * f_I$)

Table A1. Energy content of waste incineration (EPA, 2012)

$Elecprod_{I\,c}$ (kWh/Ton of waste Incinerated)							
P	F	PL	G	T	W	M	O
4660	1377	9086	-138	4455	4865	-205	2930

F= Food waste; G= Glass; M= Metals; O= others; P= Mixed Paper; PL= Plastics; T= Textiles; W= Wood

e. Landfilling

Direct GHG emissions from landfilling ($E_{L_f\,D}$) consist of emissions from waste degradation, fuel used for onsite activities (i.e. mobile equipment, electric generators), or flaring of methane R (Equation i) which allows the estimation of methane emissions ($E_{L_f\,c\,D\,CH_4}$) in accordance to the theoretical yield assuming that all potential CH4 emissions are released in the same year of waste deposition.

$$E_{L_f\,D} = E_{L_f\,c\,D\,CH_4} - R + E_{L_f\,R\,D\,N_2O} + \sum_{g=CH_4}^{N_20} \left(M_{Lf} * V_{fuel_{L_f}} * EF_{fuel_g} * GWP_g\right) \quad \text{(i)}$$

$$E_{L_f\,c\,D\,CH_4} = \begin{cases} f_{L_f} * \sum_{c=F}^{W} M_c * EF_{L_f\,c\,CH_4} * GWP_{CH_4} & \text{for K = Lf, i = D, c = \{F; G; G}_A\text{; M; N; P; P}_L\text{; T; W\}, g} = CH_4 \\ M_O * (1 - f_l) * EF_{L_f\,O\,CH_4} * GWP_{CH_4} & \text{for K = Lf, i = D, c = O, g} = CH_4 \end{cases}$$

$$E_{L_f\,R\,D\,N_2O} = R * EF_{L_f\,N_2O} * GWP_{N_2O}$$

Where

$E_{L_f\,c\,D\,CH_4}$ Direct *CH_4* emitted during landfilling from waste of category c in inventory year *t* (MTCO$_2$E/yr)

$EF_{L_f\,c\,CH_4}$ Emission factor for *CH_4* from each ton of waste category *c* landfilled (Metric Tons of *g*/ ton landfilled)

$E_{L_f\,R\,D\,N_2O}$ Direct *N_2O* emitted during combustion of recovered methane *R* in inventory year *t* (MTCO$_2$E/yr)

$EF_{L_f\,N_20}$ Emission factor of N_2O from methane combustion during flaring (MTCO$_2$E of N_2O/ MTCO$_2$E of R)

R Total recovered methane (MTCO$_2$E/yr), $R = fraction\ of\ CH4\ collected * amount\ of\ CH4\ generated$

GWP_{CH_4} Global warming potential of *CH_4* for a 100-year time horizon (MTCO$_2$E of gas g /MT of *CH_4*) (21)

$V_{fuel_{L_f}}$ Volume of fuel consumed during landfilling by onsite mobile equipment and combustion facilities in inventory year *T* (Liters/ton treated/ yr)

EF_{fuel_g} Emission factor for fuel combustion for GHG *g* (Metric tons of g/Liter of fuel)

M_c Mass of MSW category *c* generated in year *t* (Tons/yr)

c Category of MSW: *F*= Food waste; *G*= Glass; *G_A*= Garden waste; *M*= Metals; *O*= others; *P*= Paper; *P_L*= Plastics; *T*= Textiles; *W*= Wood

f_{L_f} Fraction of MSW landfilled

Indirect emissions from landfilling ($E_{L_f\,ID}$) of MSW are associated with electricity ($Elec_{L_f}$) and fuel provision, and avoided emissions from electricity production which depend on the (1) energy content of recovered methane being combusted ($Elecprod_{L_f}$) in kWh/ MT of

CH4 recovered (range between 216- 330), (2) capacity factor for electricity generation, a, and (3) the emission factor of electricity avoided ($EF_{elec\ g}$) (Equation j).

$$E_{Lf\ ID} = \left[\sum_{g=CH_4}^{N_2 0} (M_{L_f} * Elec_{L_f} * EF_{elec_g} * \ GWP_g) + \left(M_{L_f} * Vfuel_{L_f} * EF_{fuelpro_{CO_2}}\right)\right] - \sum_{g=CO_2}^{N_2 0} (Elecprod_{L_f} * R * a * EF_{elec\ g} * \ GWP_g) \qquad \text{(j)}$$

K = Lf, i = ID and g ∈ $\{CH_4;\ CO_2;\ N_2 0\}$, with b = R

Where

$E_{Lf\ ID}$ Net Indirect GHGs emissions for landfilling in inventory year *t* ($MTCO_2E$/yr)

$EF_{fuelpro_{CO_2}}$ Emission factor for provision of fuel for CO_2 ($MTCO_2$/Liter of fuel)

$Elec_{L_f}$ Electricity consumed during landfilling in inventory year *t* (kWh/ton of ww treated)

$Elec_{prod_{L_f}}$ Power potential during MSW management method *k* in inventory year *t* [Electricity produced: from CH_4 combusted (kWh/Metric Tons of CH_4 recovered)]

EF_{elec_g} Emission factor of electricity consumed or recovered for GHG *g* emitted or avoided based on national electricity grid (Metric tons of g /kWh)

M_{L_f} Mass of MSW landfilled in inventory year T (Tons/yr)

a Capacity factor for electricity generation (fraction) (a=0.85)

b Amount of recovered methane (MT of CH_4/yr) ($R = \ fraction\ of\ CH_4\ collected * amount\ of\ CH_4\ generated$

Data Collection

Table A-1. Data collection and sources

Type of data	Table A- 1	*Sources of data*
Inventory year		
General data		
Population	Millions	CAS surveys
Avg number of persons per household	Persons/ household	UNFPA Lebanon
GDP	Million US $	World bank
Precipitation rate	m^3	Meteorological interest in the Lebanese Civil Aviation Authority (LCAA)
National electricity grid	% &Type	EDL
MSW data		
Waste per capita	Kg/cap/yr.	Studies (Ayoub et al., 1994 and 2006; Fichtner, 2006; Sweep-net, 2010)
Waste composition	% or Tons/year	
Organic (food, yard)		
Glass		
Metals		Studies (Ayoub et al., 1994; Liban Consult, 1995 and 1997; Sukomi, 1998 and 2002; Sweep-net, 2010; LACECO/RAMBOLL, 2012)
Nappies		
Others		
Papers		
Plastics		
Textiles		
Wood		
Total amount Generated	Tons/year	Studies (MoE/UNDP/Ecodit, 2011; Sweep-net, 2010; CDR/LACECO, 2010)
MSW Management data		
Collection		
Percentage collected	%	Sweep-net, 2010
Commingled/ source separated MSW	%	Sweep-net, 2010
Amount of fuel consumption	Liters/year	LACECO/RAMBOLL, 2012; Personal interviews in SUKLEEN
Types and volume of collection vehicles	Types & m^3	LACECO/RAMBOLL, 2012; Interviews; site visits; unpublished sources
SWDS		
Percentage to SWDS	%	Summation of managed and unmanaged SWDS
Amount Landfilled (managed SWDS) and type of material	Tons/year or %	LACECO reports for Naameh, Globex & MORES for Zahle and BATCO for Tripoli
Unmanaged SWDS (open dumps) (deep/shallow)	%	MoE/UNDP study on dumpsites in 2010
Amount of CH_4 recovered from SWDS	Tons/year	Consultants reports for Gas flared in Naameh, Zahle and Tripoli
Leachate generated/collected	m^3/ %	LACECO reports
Biological treatment (composting, anaerobic digestion)		
Percentage treated	%	MoE reports
Total amount treated	Tons/year	MoE reports
Compost produced	Tons/year	MoE & LACECO reports
Compost marketable	%	MoE reports
Recycling/ Recovery		

Percentage of recovered/ recycled material	%	MoE reports
Amount of recovered material (glass, metals, plastic, textiles, etc.)	Tons/year	MoE reports
Incineration and open burning		
Percentage incinerated	%	MoE reports
Total plant input (include type of material)	Tons/year	MoE reports
Percentage to open burning	%	MoE reports
Cost data		
Transport and collection cost	$/Ton	
Revenue from recovered materials	$/Ton	MoE /CDR reports
Treatment processing (e.g. incineration, composting, etc.)	$/Ton of plant input	
Market price for compost	$/Ton	
Carbon credit	$/MTCO$_2$E	EU
Energy data (such as diesel fuel, and electricity)		
Electricity consumption per treatment option	kWh/Ton of plant input	Based on International Literature
Electricity production per treatment option	kWh/Ton of process input	Not applicable
Fuel consumption during treatment process (composting, sorting, landfilling etc.)	Liters/year	LACECO/RAMBOLL, 2012; SUKOMI; Interviews; site visits; unpublished sources
Fuel consumption by onsite equipment in treatment facilities	Liters/year	
Fuel consumption during collection	Liters/year	LACECO/RAMBOLL, 2012; SUKLEEN& SUKOMI; Interviews; site visits; unpublished sources
Fuel consumption during transfer to treatment facilities	Liters/year	
Transport distance (collection/transfer)	Miles or km	GIS software
Types of collection vehicles and onsite equipment in treatment facilities	Types &operating hours	LACECO/RAMBOLL, 2012; Interviews; site visits; unpublished sources

Table A-2. Population, generation rate and total MSW generated in GBA from 1994 to 2013

Year	*Population*[(a)]	*Generation rate (Kg/cap/d)*	*Total Waste generated (Tons/yr)*[(f)]
1994	1,531,021	0.83[(b)]	463,823
1995	1,556,283	0.83	471,476
1996	1,581,962	0.83	479,255
1997	1,939,996	0.83	587,722
1998	2,276,951	0.83	689,802
1999	2,261,273	0.90	742,828
2000	2,272,255	0.90	746,436
2001	2,314,202	0.90	760,215
2002	2,291,055	0.95	794,423
2003	2,374,957	0.95	823,516
2004	2,414,144	0.95	837,105
2005	2,399,346	0.95	831,973
2006	2,195,290	1.00[(c)]	801,281
2007	2,244,953	1.00	819,408
2008	2,268,418	1.00	827,973
2009	2,560,864	1.00	934,715
2010	2,624,879	1.05[(d)]	1,005,985
2011	2,699,103	1.05[(e)]	1,034,431
2012	2,743,638	1.05	1,051,499
2013	2,788,908	1.05	1,068,849

[(a)]Population data from CAS (Surveys of 1997, 2004, 2007, 2009) Palestinian Refugees were considered.
[(b)]Ayoub et al., 1994 and 1996
[(c)]Fichtner, 2006
[(d)]Sweep-net report on the solid waste management in Lebanon (2010)
[(e)]Laceco report (quantities collected during the year 2011)
[(f)]Except the caza of Jbeil; These amounts reflect the waste as weighted at the sorting plants receiving the waste collected from Service Area 1 (LACECO/RAMBOLL, 2012)

MSW composition

Several studies (Ayoub et al., 1994; Liban Consult, 1995 and 1997; Sukomi, 1998 and 2002; Sweep-net, 2010; LACECO/RAMBOLL, 2012) were carried out at various times for the analysis of MSW composition in Lebanon. While some studies were conducted at the source of waste generation, others were carried out at the primary deposit stage and some at the processing plants receiving the collected waste. Table A-3 summarizes results of MSW waste composition as reported in these different studies.

Table A-3. MSW composition as reported in different studies

Category of MSW generated c	*Composition (%)*						
	Ayoub et al., 1994[(a)]	*Liban Consult 1995*[(b)]	*Liban Consult 1997*[(c)]	*Sukomi 1998*[(d)]	*Sukomi 2002*	*Sweep-Net 2010*	*LACECO 2012*[(e)]
Organic	61.3	52-63	63.5	61.7	60.04	52.5	53.4
Paper & cardboard	12.05	15-18	15.1	13.7	10.9	16	15.6
Plastics	3.45	10-12	10.4	11.1	11.6	11.5	13.8
Metals	2.7	2-4	2.0	2.9	2.2	5.5	2
Textiles	2.45	2-4	2.7	3.3	2.1	3	2.8
Glass	3.85	7-9	5.1	5.2	4.9	3.5	3.4
Wood	-	-	-	-	0.9	3	0.8
Diapers	-	-	-	-	5.0	-	3.6
Others	14.2	2-3	1.2	2.3	2.0	5	4.6

[(a)]Study conducted by the department of civil and environmental engineering at AUB, determined the waste composition from samples collected directly from households during wet and dry seasons.
[(b)]The sampling was conducted in different areas in Lebanon during summer months, which reflects the high proportion of organic wastes generated (higher consumption of fruits and vegetables as compared to winter season).
[(c)]The study was conducted in Zahle region in order to assess the EIA of Zahle Landfill.
[(d)]This survey was conducted at different intervals of time (in winter and in summer) after the reception of waste at the MRF.
[(e)]The most recent study validated accurate by MoE, samples were collected from different districts in GBA and Mount Lebanon for a period of two weeks to determine average waste composition.

Table A-4. Average fuel consumption of street sweeping and collection vehicles in pilot area

Types of vehicles	*Number of units*	*Average fuel consumption (Liters/year)*
Pick up 99	5	73,000
Pick up02	3	54,750
Pick up Renault	5	91,250
Pick up 2008	10	182,500
Pick up 2009	10	182,500
Pick up hino	35	511,000
Pick up lveco	2	36,500
Roll Off	6	153,300
Lifter	3	54,750
Six Wheel	60	1,314,000
Crane Boom	5	109,500
Renault Sukleen 2010	27	591,300
E-R-F-L 64&65 series	42	919,800
DAFF 02	10	219,000
DAFF 09	18	394,200
E-R-F-L 64&65 Series	14	306,600
BIG-BITE	2	51,100
Mini Compactor Sukleen	15	328,500
Pickup IVECO	4	58,400
E-R-F9	4	73,000
Mini Renault	3	65,700
Mini DAFF 02	34	682,550
Sweepers Renault	6	76,650
Sweepers	2	21,900
Sweepers Mini	7	76,650
Total	**332**	**6,628,400**

Data based on: LACECO Architects & Engineers/RAMBOLL, 2012; SUKLEEN, 2014; site visits and interviews

Table A-5. Average fuel consumption for collection of MSW as reported by different studies

Sources	***Country***	***Diesel fuel consumption (L/Ton of ww)***
Chen and Lin 2008	Taiwan	5.9
Larsen et al. 2009a	Denmark	1.4-10.1
	High density urban areas with apartment buildings	1.6-3.6
	Medium density urban with single households	1.4-5.7
	Rural areas	6.3-10.1
Nguyen and Wilson 2010	Canada	
	High density urban	2.8-3.6
	Low density urban	13.2-16
Friedrich and Trois 2013	South Africa	4.1-5.7

Table A-6. MSW generation and management practices and fraction of methane recovered from 1994 to 2013

Year	***Total waste generated (Tons/year)***	***Fraction of MSW managed method***			
		Recycled[(a)]	*Composted*[(b)]	*Incinerated*	*To SWDS*
1994	463,823	0.04	0.00	0.00	0.96
1995	471,476	0.04	0.00	0.00	0.96
1996	479,255	0.04	0.00	0.00	0.96
1997	587,722	0.04	0.00	0.00	0.96
1998	689,802	0.05	0.08	0.00	0.87
1999	742,828	0.05	0.15	0.00	0.80
2000	746,436	0.05	0.16	0.00	0.78
2001	760,215	0.06	0.16	0.00	0.77
2002	794,423	0.08	0.14	0.00	0.78
2003	823,516	0.08	0.14	0.00	0.77
2004	837,105	0.08	0.13	0.00	0.79
2005	831,973	0.08	0.11	0.00	0.81
2006	801,281	0.06	0.08	0.00	0.85
2007	819,408	0.07	0.13	0.00	0.80
2008	827,973	0.07	0.05	0.00	0.88
2009	934,715	0.06	0.06	0.00	0.88
2010	1,005,985	0.06	0.07	0.00	0.87
2011	1,034,431	0.06	0.06	0.00	0.87
2012	1,051,499	0.06	0.06	0.00	0.88
2013	1,068,849	0.07	0.10	0.00	0.83

[(a)]Recycled fraction excludes (organic and mixed MSW)
[(b)]Composting fraction only includes organic waste (food and yard wastes)

Table A-7. Estimated quantities of Recyclables collected from the sorted Waste (source: LACECO, 21012)

Year	*Plastics*	*Paper*	*Metals*	*Glass*	*Wood*	*Textiles*	*Total*
2000	7,935	16,534	9,593	4,270	1,525	340	40,199
2001	9,720	19,699	10,661	5,310	2,281	532	48,203
2002	17,504	26,981	12,556	5,268	3,131	804	66,244
2003	16,350	29,000	12,795	5,430	3,639	966	68,181
2004	18,148	29,096	11,921	5,724	3,887	1,281	70,058
2005	17,131	28,116	10,234	4,916	3,611	1,583	65,592
2006	13,329	21,891	8,512	3,216	2,955	1,619	51,522
2007	17,020	26,996	9,291	2,241	3,418	1,757	60,723
2008	16,809	27,162	8,590	2,229	3,229	1,962	59,981
2009	15,895	25,770	9,349	2,144	3,974	2,493	59,625
2010	17,228	27,764	8,111	2,274	4,561	2,791	62,730
2011	16,022	32,025	7,234	2,303	4,203	3,245	65,032

Table A-8. Fractions by weight of managed and unmanaged solid waste disposal sites

	To SWDS		
Year	*Managed*[(a)]	*Unmanaged deep*[(b)]	*Unmanaged shallow*[(c)]
1994	-	0.80	0.20
1995	-	0.85	0.15
1996	-	0.89	0.11
1997	0.20	0.78	0.02
1998	1.00	-	-
1999	1.00	-	-
2000	1.00	-	-
2001	1.00	-	-
2002	1.00	-	-
2003	1.00	-	-
2004	1.00	-	-
2005	1.00	-	-
2006	1.00	-	-
2007	1.00	-	-
2008	1.00	-	-
2009	1.00	-	-
2010	1.00	-	-
2011	1.00	-	-
2012	1.00	-	-
2013	1.00	-	-

[(a)]Managed fraction of MSW includes waste quantities delivered to Naameh sanitary landfills (Source: reporting from Consultants/Operators on Managed sites (LACECO in Naameh, Globex) and from personal interviews with MoE).
[(b, c)]Unmanaged SWDS, that as defined by the IPCC guidelines can be classified into two categories: deep (>5 m) and/or high water table at near ground level; and shallow (<5 m) burned all the time (Source: these fractions were collected from a study conducted by MoE/UNDP on dumpsites in 2010; El-Fadel, 2012).

Table A-9 Methane gas recovered from Naameh landfill

Year	*CH_4 recovered gaz (Gg/year)*[(a)]	*Fraction of CH_4 Recovered*
1994	-	-
1995	-	-
1996	-	-
1997	-	-
1998	-	-
1999	-	-
2000	-	-
2001	3.00	0.06
2002	4.00	0.07
2003	5.00	0.09
2004	6.66	0.12
2005	9.84	0.17
2006	10.94	0.18
2007	16.90	0.30
2008	16.19	0.26
2009	16.76	0.23
2010	15.07	0.20
2011	16.11	0.20
2012	14.39	0.18
2013	14.00	0.18

[(a)]The amounts of methane gas recovered are estimated from consultants' reports for gas flared in Naameh Landfills

Table A-10. Types, number, and average fuel consumption of onsite equipment operating for landfilling activities

Types	*Number of units*	*Fuel consumption (L/day)*	*Fuel consumption (L/year)*
Truck	4	30	43,800
Rollers	10	200	730,000
Bales transportation vehicles	35	170	2,171,750
Bulldozer	32	140	1,635,200
bopcat	7	70	178,850
pocklen	40	250	3,650,000
shredders	2	500	365,000
Pick ups	40	40	584,000
Total	170		**9,358,600**

Data based on: LACECO, 2012; SUKOMI; Personal interviews and observations

Table A-11. Types, number and average fuel consumption of Electrical generators operating for landfilling

Types	***Number of units***	***Fuel consumption (L/h)***	***Total fuel consumption (L/year)***
800 KVA	1	130	569,400
20 KVA	3	5	65,700
1000 KVA	1	160	700,800
80 KVA	1	15	65,700
150 KVA	1	25	109,500
200 KVA	8	35	1,226,400
300 KVA	2	45	394,200
600 KVA	8	110	3,854,400
60 KVA	1	10	43,800
100 KVA	1	18	78,840
135 KVA	1	22	96,360
Total	28		**7,205,100**

Data based on: LACECO, 2012; SUKOMI; Personal interviews, site visits and observations

Table A-12. Types, number, and average fuel consumption of onsite equipment operating at composting plant

Types	***Number of units***	***Fuel consumption (L/day)***	***Fuel consumption (L/year)***
Bulldozer	5	140	255,500
Composting rotator disks	4	75	109,500
Total			**365,000**

Data based on: LACECO, 2012; SUKOMI; Personal interviews, site visits and observations