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Integrated waste management as a climate change stabilization wedge

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Anthropogenic sources of greenhouse gas emissions are known to contribute to global increases in greenhouse gas concentrations and are widely believed to contribute to climate change. A reference carbon dioxide concentration of 383 ppm for 2007 is projected to increase to a nominal 500 ppm in less than 50 years according to business as usual models. This concentration change is equivalent to an increase of 7 billion tonnes of carbon per year (7 Gt C year^{-1}). The concept of a stabilization wedge was introduced by Pacala and Socolow (*Science*, 305, 968–972, 2004) to break the 7 Gt C year^{-1} into more manageable 1 Gt C year^{-1} reductions that would be achievable with current technology. A total of fifteen possible 'wedges' were identified; however, an integrated municipal solid waste (MSW) management system based on the European Union's waste management hierarchy was not evaluated as a wedge. This analysis demonstrates that if the tonnage of MSW is allocated to recycling, waste to energy and landfilling in descending order in lieu of existing 'business-as-usual' practices with each option using modern technology and best practices, the system would reduce greenhouse gas emissions by more than 1 Gt C year^{-1}. This integrated waste management system reduces CO_2 by displacing fossil electrical generation and avoiding manufacturing energy consumption and methane emissions from landfills.

Keywords: Climate stabilization wedge, waste to energy, waste management, recycling, greenhouse gas

Introduction

Levels of atmospheric carbon dioxide (CO_2) and methane (CH_4) were observed at record highs in 2007. At concentrations of 383.1 ppm and 1789 ppb for CO_2 and CH_4, respectively, these concentrations represent increases of 37% for carbon dioxide and 156% for CH_4 compared against pre-industrial levels (WMO 2008). CH_4 is the second most important radiative forcing driver (18.5%) behind CO_2 (63%) (IPCC 2007). To date, international efforts have focused on stabilizing the global CO_2 atmospheric concentration at around 500 ppm to prevent the most detrimental impacts from climate change. Hansen *et al.* (2008) proposed a target concentration of 350 ppm of CO_2 to achieve climate stabilization.

There is wide consensus that concentrations of greenhouse gases (GHGs) must, at a minimum, be stabilized through a combination of actions; there is no single policy initiative or technology that achieves the large magnitude of reductions that will be required for climate stabilization. Pacala and Socolow (2004) introduced the idea of the stabilization triangle to focus policy efforts to stabilize atmospheric CO_2. The stabilization triangle can be subdivided into a series of manageable wedges, each driven by a different, currently available, technology or policy. Each wedge represents a reduction of one gigatonne of carbon equivalents per year (Gt C year^{-1}) in GHG emissions relative to business as usual (BAU) practices. Seven wedges together would *stabilize* world-wide greenhouse gas *emissions* at today's emission rate, roughly 7 Gt C year^{-1}. Additional wedges or advanced technology could then be used to gradually reduce GHG emissions to a point

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of net zero GHG emissions, the only possible mechanism to eventually stabilize atmospheric GHG concentrations. Pacala and Socolow introduced fifteen stabilization wedges in six categories: energy efficiency (vehicles, buildings, power plants); fuel shift (switching from coal power to nuclear, wind or natural gas); CO_2 capture and storage; nuclear fission, renewable energy (wind, photovoltaic, biogas) and forests and agricultural soils (reduced deforestation and tillage). Integrated municipal solid waste (MSW) management consisting of recycling, waste-to-energy and advanced landfilling is presented herein as another stabilization wedge, particularly as it relies on currently available technologies and practices.

Carbon mitigation mechanisms attributable to recycling, WTE and advanced landfilling were evaluated to avoid any potential overlap with existing wedges. For example, recycling of wood products is considered to be a GHG mitigation strategy because it sequesters carbon by reducing harvesting pressures on existing forests. However, inclusion of this carbon sequestration factor would be duplicative, since forestry is already part of an existing wedge category. Conversely, the biomass portion of MSW had not been identified in an existing wedge, so its use as an energy source is included in this analysis.

Methodology

General methodology

The methodology used to evaluate carbon mitigation from an integrated waste management system is based on the approach established by Pacala and Socolow where carbon emissions in a 50-year period (2004 to 2054) are determined by the difference between two waste management scenarios. The first scenario is the Business-As-Usual (BAU) scenario in which MSW tonnage in 2054 is allocated to three MSW disposal options in the same percentage as 2004 except the total quantity is larger. BAU is defined as current practices unless there is a regulatory requirement in effect with the specific purpose of GHG mitigation. For example, European Union Directive 1999/31/EC (EU 1999), more commonly known as the Landfill Directive, was established in 1999 with the specific purpose of minimizing CH_4 emissions from the landfilling of biodegradable MSW. Therefore, the impact of this Directive is considered in the calculated carbon emissions for the 2054 BAU scenario. The BAU scenario for 2054 considered population growth, increased waste generation rates, the shift from open dumping to sanitary landfills in developing countries and the continuation of current practices in waste management.

The alternative to the BAU scenario is the Waste Wedge Scenario. The primary difference between the BAU and Waste Wedge Scenario is the proportion of MSW allocated to three disposal options: recycling and composting (herein referred to as 'recycling'), combustion with energy recovery known as waste-to-energy (WTE) and landfills. The difference between the carbon emissions in 2054 for the BAU and Waste Wedge Scenario defines the amount of carbon mitigation from an integrated waste management system that is based on the European Union waste hierarchy defined in Directive 2008/98/EC (EU 2008).

The European Union (EU) waste hierarchy includes five MSW management options including prevention, preparing for reuse, recycling, other recovery including energy recovery and disposal. The general concept of a stabilization wedge is to scale-up commercially available technologies to provide additional carbon mitigation. The Waste Wedge is based on recycling, WTE and landfilling. Waste prevention and reuse has been analyzed as a separate variable in a sensitivity analysis. There are a variety of other possible MSW disposal options including anaerobic digestion, mechanical–biological treatment (MBT) and alternative thermal treatment. Although these technologies may have important roles to play in an integrated waste management system, they were not directly considered in the wedge scenario due to inadequate life-cycle information that fully accounts for the energy and greenhouse gas impacts of upstream and downstream operations.

The re-allocation of MSW in the Waste Wedge Scenario follows the order of the waste hierarchy which identifies recycling as the preferred waste management methodology, followed by WTE. Landfilling is identified as the least preferable waste management technique. The amount of carbon mitigation attributable to the Waste Wedge is determined by comparing the total carbon emissions with BAU in 2054.

A life-cycle assessment (LCA) approach, as recommended by the IPCC (2007) and US Environmental Protection Agency (US EPA) (2006b), was used to calculate GHG emissions from each of the three disposal options. An LCA enables a comparison of emissions which occur over relatively short periods of time, such as those from recycling and WTE, with prolonged emission sources, such as landfills, which can emit CH_4 for 100 years or more.

The LCA methodology used calculation procedures based on version 8 of the US EPA Microsoft® Excel-based Waste Reduction Model (WARM) (US EPA 2006c). WARM includes default values for waste analysis and operation values for recycling, WTE and landfills that limit its ability to represent the variability of global waste management carbon emissions; therefore, several changes were made to accommodate this variability. Examples of WARM defaults include a constant thermal efficiency factor for WTE and the allocation of landfill gas management collection techniques. The US EPA has an alternative LCA tool, the Municipal Solid Waste Decision Support Tool (DST), that provides additional flexibility and a broader range of LCA impacts including energy, greenhouse gases and a set of criteria pollutants including SO_2, NO_x, particulate and CO (Harrison *et al.* 2001); however, the DST is not web available. The BAU assumptions, methodologies, and factors applied in lieu of WARM defaults for waste generation, waste management practices, landfilling, WTE, and recycling are discussed in subsequent sections.

After assessing the carbon mitigation in the Waste Wedge, a mitigation range was established based on changes to key

Table 1: MSW generation 2004 and 2054 and management practices by region in 2004.

Region	2004 waste generation (10^6 t C)	2054 waste generation (10^6 t C)	% landfilled	% WTE	% recycled
Africa	209.3	697.3	90%	0%	10%
Middle East	45.5	249.5	90%	0%	10%
C. America and Caribbean	18.0	71.6	89%	1%	10%
S. America	69.9	390.6	85%	5%	10%
E. Asia	400.9	1037.3	78%	12%	10%
S. Asia	231.0	882.0	90%	0%	10%
S-E Asia	122.4	368.6	85%	5%	10%
E. Europe	109.4	242.1	86%	3%	11%
N. Europe	11.8	13.4	21%	39%	40%
S. Europe	96.1	184.6	61%	10%	29%
W. Europe	126.9	192.8	35%	22%	43%
N. America	336.3	547.1	68%	6%	26%
Oceania	19.3	26.8	63%	22%	15%
Global	**1796.9**	**4903.5**	**76%**	**7%**	**17%**

technical variables (e.g. waste properties, waste generation). In addition, to ascertain the impacts of different policy initiatives and options, a total of seven sensitivity analyses were completed around the following policy variables.

- A Shifting the preponderance of non recycled MSW to WTE instead of the 2 : 1 WTE to landfill ratio.
- B Shifting the preponderance of non recycled MSW to landfills instead of the 2 : 1 WTE to landfill ratio.
- C Increasing the thermal efficiency of WTE.
- D25 Changing the Global Warming Potential from 21 to 25 to represent the 100-year GWP in IPCC's Fourth Assessment Report (2007).
- D72 Changing the Global Warming Potential from 21 to 72 to represent the 20-year GWP in IPCC's Fourth Assessment Report (2007).
- E Including the impact of carbon storage from recycling certain biomass materials.
- F Implementing a policy of waste reduction to reduce the amount of waste generated.

Waste generation rate, population and GDP

Predictions for population and gross domestic product (GDP) were based on the IPCC (2000) Special Report Emissions Scenarios (SRES) Scenario A1b disaggregated by country (van Vuuren *et al.* 2007). Country level data was then re-aggregated into thirteen regions. The 2004 waste generation rates were assumed to be equal to the 2000 IPCC default waste generation rates (IPCC 2006a). The waste generation rate for 2054 was determined by assuming linear growth until reaching 900 kg year^{-1} capita^{-1} when the country's inflation adjusted GDP per capita is predicted, as described above, to reach the 2004 US GDP per capita. Countries with per capita GDP exceeding that of the US were assumed to have no growth in their waste generation rates. In addition, the waste generation rates for the US and Iceland, both already above 900 kilograms per year (900 kg year^{-1}) per capita, were also held constant (Monni *et al.* 2008). Total waste generation (Table 1) was calculated by multiplying the per capita waste generation rate by the total population.

The IPCC waste generation rates reflect only the portion of the population whose waste is collected. The urban population may more accurately reflect the percentage of the population with waste collection; however, total population is a more accurate reflection of the total waste generation. Uncollected waste results in GHG emissions from partially or fully anaerobic waste decomposition or through combustion. Furthermore, collecting and combusting this waste with energy recovery can result in GHG savings from avoided fossil electricity or heat generation. Likewise, collecting and recycling this waste can result in GHG savings associated with the energy consumption and process emissions from producing a material from recycled inputs versus virgin materials. The waste generation rates may be different between rural areas without waste collection and urban areas with waste collection; however, comprehensive studies on the waste generation rates of rural populations were not available. Therefore waste generation rates are assumed to be comparable for rural and urban populations.

MSW management practices

The percentage of waste managed by recycling, landfilling, and combustion in 2004 were from IPCC (2006a), except for instances where country-specific information was judged to be more reliable or complete. Country-specific information was used from United States, Mexico, Canada for the North American region to develop a population-based weighted average percentage allocation to landfill, recycling, and combustion (Buenrostro & Bocco 2003, Statistics Canada 2004, IPCC 2006a, Simmons *et al.* 2006). Country-specific information from Stengler (2008) was also used in a comparable manner to develop the allocations for the four European regions. These peer-reviewed documents were used in place of IPCC defaults, consistent with IPCC recommendations to use country-specific information where available.

In all other cases, the percentage of waste materials managed through combustion in a particular region was determined using population-weighted, country-specific data from IPCC. The IPCC regional defaults were considered; however, they did not appear to always be consistent with the data provided for the individual countries. For example, the default percentage of waste managed by combustion for East Asia is 26%. A population-weighted average of Japan, China, and Korea, the three individual countries provided for the region is 12%, the figure used in this analysis.

Recycling rates were assumed to be 15% for Oceania and 10% for other regions outside North America and Europe. The 10% recycle rate is based on reports from India (Bhada & Themelis 2008) and China (Guo & Chen 2000, Lei & Wan 2007) that evaluated landfill waste pickers as an indispensable component of the recycle system.

The percentage of MSW managed by each practice was held constant for the 2054 BAU case, with the exception of the EU (represented by Eastern, Northern and Southern Europe), where the Landfill Directive will have a significant impact on waste management practices. Therefore, the 2054 European factors were adjusted to a recycling rate of 45%, a WTE rate of 30%, and landfilling rate of 25%. Waste management practices in the Eastern European region are dominated by Russia which is not in the EU.

Landfilling

Landfills predominately impact life-cycle GHG emissions through CH_4 emissions from anaerobic decomposition and avoided CO_2 emissions from fossil fuel-based electrical generation displaced by landfill gas to energy (LFGTE) operations. The Waste Wedge analysis used a Global Warming Potential (GWP) of 21 for CH_4 to be consistent with the UNFCCC convention.

The parameters included in modelling CH_4 emissions from landfills were total CH_4 generation potential, L_0 ($m^3\ t^{-1}$), the shift from aerobic to anaerobic landfills, the proportion of landfills with landfill gas (LFG) collection and energy recovery and LFG collection efficiency.

An L_0 of 100 $m^3\ t^{-1}$ was used for developed countries in 2004 and 2054. This value is consistent with the L_0 used for GHG inventories by US EPA (2009) and the United Kingdom Department for the Environment, Food and Rural Affairs (DEFRA 2004) and is also consistent when evaluating US average values for total carbon content (30%) and biomass fraction (66%) (Bahor *et al.* 2008). A US L_0 of 96 $m^3\ t^{-1}$ was derived from IPCC defaults (IPCC 2006b). The average L_0 value derived for predominately developed regions (i.e. Europe, North America, and Oceania) is 120 $m^3\ t^{-1}$, however, this includes high values from southern and western Europe and Australia that are based on incomplete data sets in which less than 70% of the waste stream is represented. When these regions are excluded from the calculation, the resultant L_0 is 99 $m^3\ t^{-1}$.

An L_0 of 100 $m^3\ t^{-1}$ was also used for emerging countries in 2004 and 2054. The average L_0 value derived from IPCC data for predominately emerging regions (i.e. Asia, Middle East, Africa, Central and South America) is 99 $m^3\ t^{-1}$. L_0 was calculated from IPCC defaults as follows (2006b):

$$L_0 = DOC * DOC_f * MCF * F * (16/12) * 1503 \qquad (1)$$

where *DOC* is the degradable organic fraction of waste based on country default waste composition and default *DOC* content for each waste component (IPCC 2006b); $DOC_f = 0.5$ is the fraction of DOC that can decompose (IPCC 2006b); $MCF = 1$ is the methane correction factor; $F = 0.5$ is the volume fraction of CH_4 in generated LFG (IPCC 2006b); 16/12 is the molecular weight ratio (CH_4/C); and 1503 is the conversion factor, $m^3\ CH_4\ t^{-1}\ CH_4$.

Another important consideration was the practice of aerobic landfilling (i.e. open dumping) currently prevalent in emerging regions. Over time, a greater proportion of landfills are expected to be anaerobic, sanitary landfills to manage public health concerns. This is an important and necessary transition to protect and preserve public health; however, it will also increase the amount of CH_4 generated from a tonne of MSW. For emerging regions in 2054, 80% of waste was assumed to be managed in anaerobic landfills versus 25% in 2004. All MSW in developed countries was assumed to be managed in sanitary (anaerobic) landfills (Monni *et al.* 2006).

Many landfills, especially in emerging countries, do not collect CH_4 for destruction, although LFG collection is expected to become more prevalent. The proportion of landfills with some form of LFG collection and destruction was assumed to increase in all regions from 2004 to 2054 (Table 2).

For those landfills that collect LFG, the reported collection efficiencies vary widely, with little information or consensus on either short-term or integrated life-cycle default values. The US EPA (1998) uses a default value of 75% and IPCC (2006b) cites default values as low as 20% with reference to measurements between 10 and 85% at active gas recovery projects and 10 and 80% at closed landfills. Spokas *et al.* (2006) reported LFG collection system efficiencies as a function of landfill cover conditions, which led to the French environmental agency's adoption of guideline values: 35% for an operating cell, 65% for a cell with temporary cover, 85% for a cell with final clay cover, and 90% for a cell with a geomembrane final cover.

Although these reported efficiencies represent short-term collection efficiencies, an integrated life-cycle efficiency that takes into account changes in LFG collection over time is necessary to conduct an LCA. Each area of a landfill evolves through discrete stages of LFG collection as that area is filled, covered, and closed. Kaplan *et al.* (2009) and DEFRA (2006) recognized the variability of LFG collection efficiency

Table 2: Landfill gas collection and destruction for various regions.

	2004			2054		
Region(s)	No LFG recovery	Flare	LFG to energy	No LFG recovery	Flare	LFG to energy
Emerging regions (Africa, Middle East, Central and South America, Asia)	90%	5%	5%	50%	25%	25%
Eastern Europe	80%	10%	10%	0%	50%	50%
North, South, and West Europe	50%	25%	25%	0%	50%	50%
North America and Oceania	50%	25%	25%	20%	40%	40%

The proportion of landfills with some form of LFG collection and destruction increased in all regions from 2004 to 2054.

Table 3: The 100-year integrated collection efficiency as determined from assigned stage collection efficiencies and first order decay model.

LFG collection stage		Stage length		Stage LFG collection efficiency			
		(years)	% of total CH_4 in stage	Emerging regions and Eastern Europe		Developed regions (except Eastern Europe)	
				2004	2054	2004	2054
1	Initial waste placement	3	13.9	0%	0%	0%	0%
2	Interim collection system	4	15.6	50%	50%	50%	50%
3	Final collection system	3	9.8	50%	75%	75%	75%
4	Final closure and system operation	30	47.1	50%	75%	75%	90%
5	Post LFG collection system operation	60	12.9	0%	0%	0%	0%
Approximate integrated LFG collection efficiency				35%	50%	50%	60%

over time. This analysis considers LFG collection efficiency to vary through five identifiable stages. Stage 1 is the period following initial waste placement when no collection occurs. During stage 2, interim collection, usually involving horizontal collector pipes, is functioning. In stage 3 the final collection system, probably involving vertical gas wells, is in place but final cover is not. Stage 4 is the post-closure period after final cover is installed. Finally stage 5 is the period with no collection after the system is switched off. Table 3 assigns collection efficiencies for each of these five stages to represent typical landfills based on the above-reported short-term collection efficiencies.

First-order decay models are widely used to predict CH_4 generation from landfills, (US EPA 2005, IPCC 2006b, UNFCCC/CCNUCC 2008). The percentage of total CH_4 generation potential generated during each stage is calculated from the solution to the definite integral of the first-order decay equation, bounded by the beginning and end of the landfill stage, in years. The equation is

$$\%CH_4 = 100 \times E \times [exp(-kt_1) - exp(-kt_2)] \quad (2)$$

where $\%CH_4$ is the methane generation as a percentage of the total methane generation potential, L_0; E is the instantaneous stage collection efficiency; k is the anaerobic decay rate constant (year^{-1}); t_1 is the beginning of LFG collection expressed as years from start of methane generation; t_2 is the end of LFG collection stage, expressed as years from start of methane generation.

The value for k, 0.05 year^{-1}, is the IPCC default for bulk waste in boreal and temperate climates (IPCC 2006b). The duration of each stage was estimated by applying the US EPA large landfill emission regulations (US EPA 1996) as typical of LFG collection system implementation schedules. The collection efficiency for each landfill stage is then applied to the CH_4 generated during each stage. The 100-year integrated efficiency of LFG capture is the sum of the percentage of the total CH_4 generation potential (L_0) collected during each LFG collection stage. Collection efficiencies from individual stages were derived from the aforementioned short-term collection efficiencies and other published data (Mosher *et al.* 1999, Morcet *et al.* 2003, Borjesson *et al.* 2007, Lohila *et al.* 2007).

In calculating CH_4 emissions from landfills, a soil oxidation factor of 10% was assumed (IPCC 2006b, US EPA 2006b). In addition, a 100% CH_4 destruction efficiency was assumed for both flares and internal combustion engines. In general, destruction efficiencies of 96–99% are achieved in practice. For LFGTE projects, an availability factor of 85% was assumed, and CO_2 emission factors for the emissions displaced by the electrical generation were determined for fossil-based grid electricity by country from International Energy Agency data, aggregated into the thirteen regions (IEA 2008).

Energy-from-waste

The LCA procedures applied to WTE facilities identify four major GHG-related processes (US EPA 2006b):

1. Anthropogenic, or fossil CO_2, GHG emissions from combustion of waste components (plastics, textiles, etc.) made from fossil fuels such as oil and natural gas.
2. Avoidance of CO_2 emissions from grid-based fossil fuel fired power plants displaced by WTE facility electrical generation.
3. Avoidance of landfill CH_4 emissions that would not be captured by a LFG collection system.
4. Avoidance of extraction and manufacturing GHG emissions due to ferrous metal recovery at WTE facilities for subsequent recycling.

Anthropogenic carbon emissions (FC) (t C year^{-1}) from WTE are directly determined by equation (3):

$$FC = M * C_t * C_f \tag{3}$$

where M is the annual combustion rate of MSW (t MSW year^{-1}); C_t is the total carbon content expressed as a percentage of total wet weight; and C_f is the fossil carbon as a percentage of total carbon in MSW.

Total and percentage fossil carbon content derived from IPCC (2006a) exhibit a range of 21 to 33% for C_t on a wet basis and a range of 16 to 43% for fossil carbon fraction, C_f. Our calculations are based on operational experience at WTE facilities in the US which have demonstrated an average total carbon content of 30% and fossil carbon fraction of 34% (Bahor *et al.* 2008). Both the total carbon and fossil carbon fractions used are higher than the MSW mass weighted average IPCC default values obtained of the regions for which sufficient waste composition data was available (IPCC 2006a). Use of these higher averages potentially overstates carbon emissions from WTE.

A higher heating value (HHV) of 11 630 kJ kg^{-1} (5000 BTU lb^{-1}) was used for developed countries, consistent with operational experience and published values (Bahor *et al.* 2008, European IPPC Bureau 2006). An HHV of 7670 kJ kg^{-1} (3300 BTU lb^{-1}) was used for emerging countries in 2004 to reflect the typically lower MSW heat content in developing countries, consistent with operating experience in China and published data for India (Bhada & Themelis 2008, Nie 2008).

The efficiency of WTE facilities, measured as the net electrical energy output divided by the total thermal energy input, is dependent on technology and moisture content. A nominal efficiency of 18% was used for existing facilities and a 9% efficiency value was selected for emerging countries. A value of 14% efficiency was selected for WTE in emerging regions where generally drier climates (Middle East and Africa) are expected to yield drier waste materials and better combustion efficiencies.

Calculation of CO_2 emissions displaced by WTE electrical generation was consistent with the method applied to LFGTE operations. This method underestimates carbon mitigation by not including all of the avoided indirect GHG emissions such as CH_4 and CO_2 emissions associated with the extraction and processing of fossil fuels.

Recycling

GHG emission reductions from recycling are the result of both avoiding GHG emissions from the production of goods from raw materials and from landfilling. US EPA estimates a GHG reduction of 0.87 t C t^{-1} (0.79 t C ton^{-1}) for every short ton of mixed recyclables. This emission factor is comprised of two major components: an energy factor of 0.14 t C t^{-1} (0.13 t C ton^{-1}) and a carbon storage factor of 0.73 t C t^{-1} (0.66 t C ton^{-1}) (US EPA 2006b).

The energy factor represents fossil fuel and electricity savings by manufacturing a product from recycled versus virgin inputs. The carbon storage factor represents the carbon sequestered in trees and other fibre resources that are left standing when primarily paper and cardboard products are manufactured from recycled materials. Carbon is sequestered when net forest carbon stocks increase over time. To avoid potential double counting with the forestry wedge, the GHG mitigation potential from carbon sequestration in forests has been omitted in this study. Therefore, the avoided energy factor of 0.14 t C t^{-1} of mixed recyclables was used for the Waste Wedge Scenario with carbon sequestration only being considered in the sensitivity analysis.

Waste Wedge Scenario

The Waste Wedge Scenario is based on two mechanisms to achieve reduction of GHG emissions including CO_2 and CH_4. The first mechanism is to allocate the tonnage of MSW to three MSW disposal options in accordance with the European Waste Hierarchy. Therefore the majority of MSW is allocated to recycling with the remainder being allocated to WTE and landfilling. The second mechanism is to use commercially demonstrated technology and best practices for each of the three options.

The MSW tonnage in the Waste Wedge Scenario was allocated in accordance with the waste hierarchy, starting with 65% being managed by recycling in all developed countries and 40% in emerging countries (Sander 2008). For MSW that was not recycled, $^2/_3$ of the waste remaining was managed by WTE and $^1/_3$ by landfills.

The technology used in the Waste Wedge Scenario is essentially the same as in the 2054 BAU case; however, a higher level of performance was assigned to both WTE and landfilling (Table 4). The efficiency of WTE was increased to 22% (on a HHV basis) in developed countries to correspond with better performing units. This efficiency factor is limited to a facility generating electrical power and is typical of newer units. Further efficiency improvements resulting in greater avoided fossil CO_2 are possible. As an example, certain European facilities operate in the 28 to 30% range with combined heating and power (CHP) providing even higher thermal efficiencies. Almost all landfills in the alternative scenario are assumed to have LFG collection and destruction with half of those landfills having energy recovery.

The potential range of the waste wedge was determined by varying five key technical variables. Table 5 provides the range of each variable and the value used in the analysis.

Table 4: Alternative scenario LFG collection by region.

Regions	Landfill CH_4 recovery			
	No LFG recovery	Flare	LFG to energy	WTE efficiency
Emerging (Africa, Middle East, Central and South America, Caribbean, Asia)	10%	45%	45%	20%
Europe	0%	10%	90%	22%
Other developed (N. America and Oceania)	10%	10%	80%	22%

Almost all landfills in the alternative scenario are assumed to have LFG collection and destruction with half of those landfills having energy recovery.

Table 5: Range in Waste Wedge results as a function of key technical variables.

Parameter	Low	Wedge	High
2054 global waste generation (Gt year^{-1})	4.40	4.90	5.40
Methane generation potential, L_0 (m^3 t^{-1})	85	100	115
Higher heating value (HHV, kJ kg^{-1})			
Developed countries	10 470	11 630	12 790
Emerging countries	6500	7670	8840
Recycling GHG reduction factor (t C t^{-1})	–0.12	–0.14	–0.16
MSW% fossil carbon	38%	34%	30%
Total carbon mitigation (Gt C year^{-1})	0.74	1.0	1.3

The total carbon mitigation factor presented includes the total impact from each of the five parameters. This is considered to be an extreme case because there could be offsetting parameters that would yield a result somewhere between the predicted range of 0.74 and 1.3 Gt C year^{-1}.

Seven sensitivity analyses were then run to evaluate the impact of policy-oriented parameters on the Waste Wedge. Sensitivity scenarios A and B consider the impact of polices that would direct MSW to either WTE or landfilling with landfills being required to operate with a higher LFG collection efficiency. In sensitivity scenario A, the preponderance of MSW remaining after recycling was allocated to WTE whereas in sensitivity scenario B, the preponderance of MSW not recycled was allocated to landfills. Table 6 presents the MSW

Table 6: MSW management practices in 2054 under Business as Usual, Wedge Scenario and sensitivity analyses.

Region	Wedge Scenario & Sensitivity Analysis											
	Business as Usual			Wedge Scenario			Sensitivity A			Sensitivity B		
	% Recycle	% Landfill	% WTE	% Recycle	% Landfill	% WTE	% Recycle	% Landfill	% WTE	% Recycle	% Landfill	% WTE
Africa	10%	90%	0%	40%	20%	40%	40%	10%	50%	40%	60%	0%
Middle East		90%	0%								60%	0%
C. Amer. & Caribbean		89%	1%								59%	1%
S. America		85%	5%								55%	5%
E. Asia		78%	12%								48%	12%
S. Asia		90%	0%								60%	0%
SE Asia		85%	5%								55%	5%
E. Europe	11%	86%	3%	65%	12%	23%	65%	0%	35%	65%	32%	3%
N. Europe	45%	25%	30%								5%	30%
S. Europe	45%	25%	30%								5%	30%
W. Europe	45%	25%	30%								5%	30%
N. America	26%	68%	6%	65%	12%	23%	65%	10%	25%	65%	29%	6%
Oceania	15%	63%	22%								13%	22%
Global	15%	79%	7%	46%	18%	36%	46%	9%	45%	46%	47%	7%

Table 7: GHG mitigation for the Waste Wedge Scenario and the seven sensitivity analyses.

GHG reductions (10^6 t C year^{-1})	Wedge Scenario	A	B	C	D25	D72	E	F
Source reduction	–	–	–	–	–	–	–	343
Recycling	589	589	589	589	656	1449	1711	530
Combustion (WTE)	373	481	12	386	440	1229	373	335
Landfilling	48	24	162	48	57	164	48	43
Total	1009	1094	763	1022	1153	2842	2132	1251

management practices in 2054 under BAU, Wedge Scenario, and sensitivity analyses A and B.

Sensitivity analysis C considered the impact if WTE facilities in the EU North America, Asia and Oceania achieved an average 30% thermal efficiency. This situation is comparable to the EU's recent decision to establish a non-dimensional factor that identifies WTE facilities with higher thermal efficiency whether by electrical generation, central heating and power, or a combination of each. Sensitivity analysis D25 considered the impact of the 100 year GWP of 25 for CH_4 relative to the 100-year GWP of 21 and sensitivity D72 considered a 20-year GWP of 72. Although current inventory and life-cycle calculations are based on the 100-year GWP, the IPCC has noted the importance of shorter time frame GWPs when the policy emphasis is to guard against short-term, non-linear responses. Conversely a focus on longer term responses requires longer term GWPs. (IPCC 1994).

Sensitivity scenario E considered the potential impact of carbon sequestration attributable to the recycling of forest-based commodities such as paper, cardboard and wood and sensitivity scenario F considered the GHG mitigation attributable to source reduction.

Results and discussion

Table 7 provides the GHG mitigation for the Waste Wedge and the seven sensitivity analyses with Figure 1 illustrating the Waste Wedge. The global allocation of MSW in the Waste Wedge Scenario was 46% to recycling, 36% to WTE and 18% to landfill. The results confirm the following statements.

- The Waste Wedge Scenario is a stabilization wedge by reducing GHG emissions by a nominal 1 Gt C year^{-1}.
- The GHG mitigation is consistent with the hierarchy with an advanced recycle rate being responsible for 58% of GHG mitigation, WTE being responsible for 37% of GHG mitigation and advanced landfill being responsible for the remaining 5%.

The CH_4 emissions from landfilling are the largest greenhouse gas emission for the BAU scenario, estimated at 0.95 Gt C year^{-1} with a range of 0.73–1.2 Gt C year^{-1}. These projections for landfill methane emissions are in the range of several other studies and published reports (IPCC 2000, Monni *et al*. 2006, US EPA 2006a).

The sensitivity analyses further illustrate how various waste management policies can impact carbon mitigation. In six out of the seven sensitivity analyses, the GHG mitigation

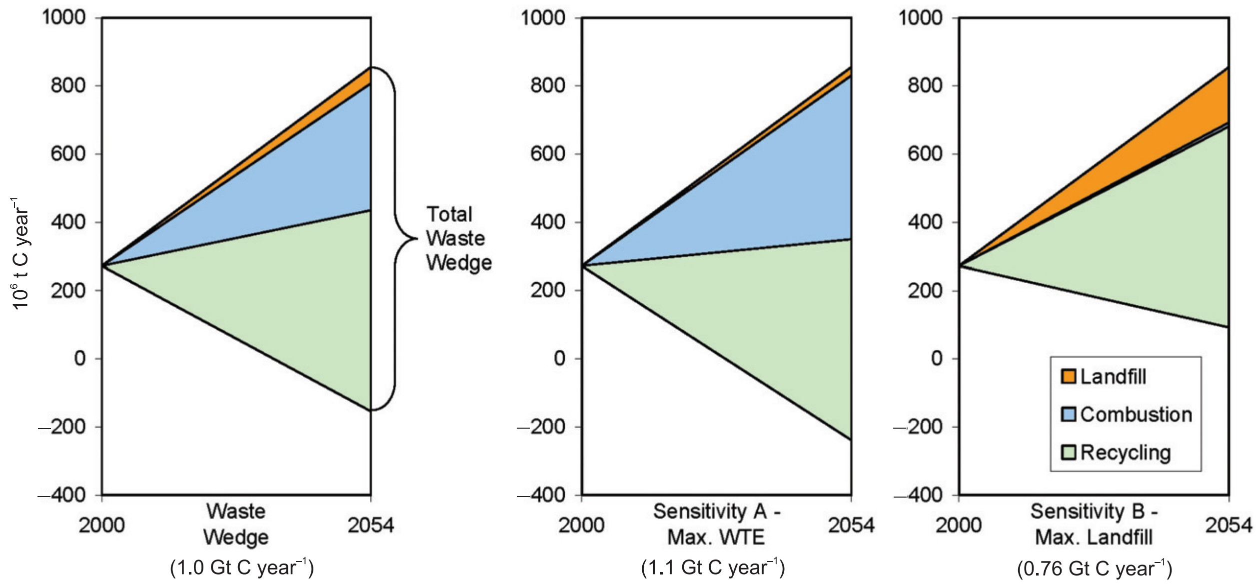
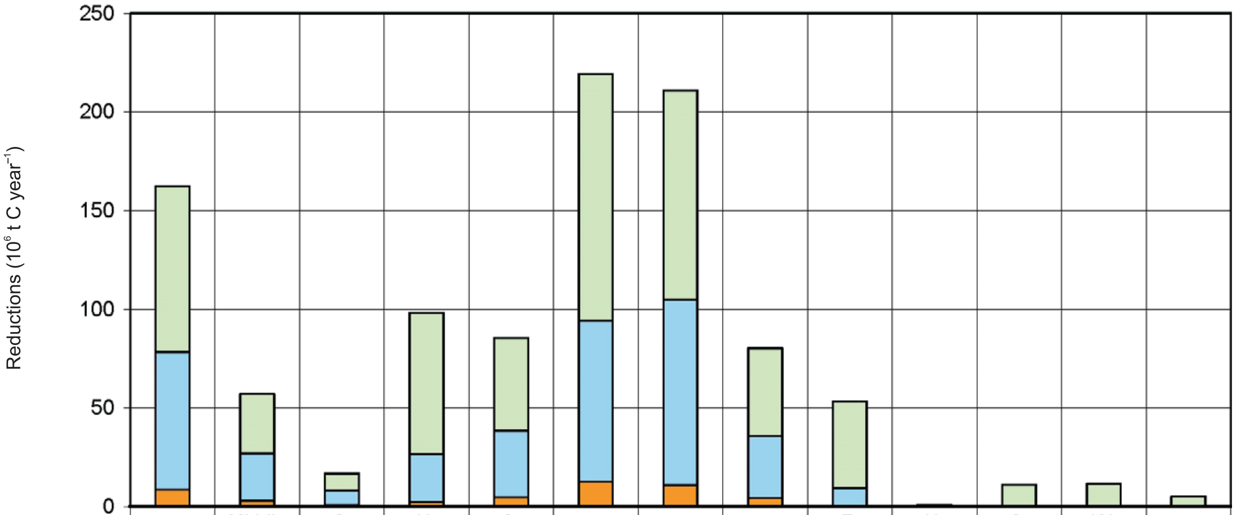


Fig. 1: Contribution of advanced landfilling, combustion with energy recovery, and recycling to the climate stabilization wedge and sensitivity analyses A and B.



	Africa	Middle East	C. America	N. America	S. America	E. Asia	S. Asia	SE Asia	E. Europe	N. Europe	S. Europe	W. Europe	Oceania
Recycling	84	30	9	72	47	125	106	45	44	1	11	11	5
Combustion	70	24	7	24	34	82	94	31	9	0	-1 *	-1*	0
Landfill	8	3	1	2	5	13	11	4	0	0	0	0	0

* Reflects a decrease in tons of waste allocated to combustion relative to BAU

Fig. 2: Wedge scenario GHG mitigation from combustion, recycling, and advanced recycling allocated to the geographical regions.

exceeds that presented in the Waste Wedge. Sensitivity analysis A demonstrates that additional carbon mitigation is possible (1.1 versus 1.0 Gt C year^{-1}) by diverting additional MSW from landfills. Conversely, a policy that encourages landfilling of MSW would reduce the size of the Waste Wedge. Sensitivity analysis B maintained the maximum recycle rate but maximized landfilling in place of WTE and yielded a GHG mitigation factor of only 0.76 Gt C year^{-1}.

Sensitivity analysis C considered a higher thermal efficiency for WTE. Although this policy change yielded an increase of only 0.012 Gt C year^{-1}, the additional electrical and/or steam energy from this increase provides an additional positive outcome of this option.

Sensitivity analyses D25 and D72 illustrate the increase in the Waste Wedge by applying the updated GWPs. Application of a 100-year GWP of 25 yields an increase of 0.14 Gt C year^{-1}. This is a 13% increase in the wedge by simply recognizing the best available scientific information on the GWP. Application of the 20-year GWP of 72 yields an increase of 1.8 Gt C year^{-1} (2.8 vs. 1.0).

There is a wide range of carbon mitigation attributable to recycling when including both energy and forest carbon sequestration. The Waste Wedge focused on the energy factor; however, many of the most commonly recycled materials are forest products such as paper and cardboard. These materials achieve their most significant recycling benefits not by reduced energy consumption but by preventing harvesting of fibre resources, predominately forests. When the benefit of carbon storage was included (sensitivity analysis E), the GHG mitigation of the MSW wedge increased from 1.0 to 2.1 Gt C year^{-1}. Carbon sequestration has already been considered by the forestry wedge already identified by Pacala and Socolow; however, recycling of forest products is an important mechanism to help achieve the identified forest wedge.

Source reduction was also considered by assigning a 10% reduction in the waste generated. Application of US EPA factors (2006b) to the avoided waste increases the wedge from 1.0 to 1. Gt C year^{-1}.

Figure 2 depicts the GHG mitigation potential of the Waste Wedge for the thirteen geographic sub-regions by waste management practice. The greatest potential for GHG mitigation is in Asia (0.51 Gt C year^{-1}) and the Americas (0.20 Gt C year^{-1}), driven by future population growth and, in the case of developing countries, a shift to sanitary anaerobic landfills for public health reasons. An illustrative metric for evaluating carbon mitigation is to divide the total mitigation by MSW tonnage. Two groups of regions emerge: southern, western and northern Europe exhibit a nominal 0.05 t C t^{-1} MSW and the rest of the world exhibits a range of 0.15 to 0.20 t C t^{-1} MSW. The low reduction per tonne, instead of implying a low mitigation potential in Europe, is an unmistakable testament to the success of European regulations aimed at mitigating waste management, including the Landfill Directive, the Packaging and Packaging Waste Directive (EU 1994) and various recycling directives.

Application of a LCA yields results that are useful for policy formulation, however LCA results are not appropriate for an annual inventory, compliance or carbon trading. Both recycling and WTE provide immediate and reasonably quantifiable emissions whereas 1 ton of MSW in a landfill has long-term impacts that are not immediately recognized in an annual inventory.

Several of the parameters modelled have significant uncertainty, especially when projecting out to 2054. Waste generation rate, the extent to which it is impacted by increases in national gross domestic product (GDP) and population growth are all key drivers in estimating the GHG emissions from waste management. In addition, although carbon mitigation by recycling and reduction are based on a comprehensive US EPA report (US EPA 2006b), this report does not address where and how the recycling process is operated or the incremental or marginal difference resulting from decreasing quality of the recycled materials as recycling rates increase. There is also uncertainty surrounding LFG collection and destruction practices. Currently, there is a very limited database on LFG collection for different landfill designs, stages, and methods of operation. However, the range analysis completed and the sensitivity analyses still identify significant reductions achievable through integrated solid waste management.

Conclusion

The Waste Wedge yields an annual carbon mitigation of 1 Gt C and qualifies as a stabilization wedge that can help stabilize atmospheric concentrations of greenhouse gases. An integrated waste management system based on the EU's waste hierarchy has already demonstrated success; however, application on a global basis can leverage the performance of commercially demonstrated technologies to make a significant contribution to global GHG emission mitigation. The major impediment to an integrated waste management system is the absence of national and international policies that would make it a performance standard.

Six of the seven sensitivity analyses demonstrate an increase in the size of the Waste Wedge, indicating that a variety of issues should be considered to take full advantage of the carbon mitigation by waste management. In general, diversion of MSW from landfilling to recycling and WTE will maximize carbon mitigation with the actual quantity being largely dependent on the Global Warming Potential for methane.

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