Municipal Solid Waste to Juniper Ridge Landfill: The Methane Threat

We have presented information concerning the greenhouse gases produced by trucking MSW, specifically carbon dioxide. There should also be concern of the amounts of methane that will be emitted during the lifetime of landfilled MSW.

Methane is produced by the anaerobic decomposition of organic wastes. MSW is over 50% organic. We have all heard that methane is a far more dangerous greenhouse gas than carbon dioxide when considering climate change. It is commonly said that methane has on the order of 23 times the warming potential of CO2. This number is derived from a 100 year time period. Over a 20 year span, methane poses as much as 72 times the negative effects of CO2. This is because while CO2 in the atmosphere lasts over a century, methane only persists in the atmosphere for 12 to 13 years. Therefore, reducing methane emissions now, or before they begin, can have a large positive impact over a relatively short time span, thus greatly reducing man-made climate impact. Landfills are the single largest source of anthropogenic (man-made) greenhouse gases in North America.

Since MSW has a much higher organic content than the other wastes coming into JRL, introducing massive amounts of curbside garbage would produce much more methane. Once MSW is unloaded at JRL, it will be covered by other wastes and begin to decompose in the anaerobic environment, thus emitting methane.

Casella says in their application that with their management techniques, they capture on the order of 85% of methane emissions at JRL, and flaring the gas turns it into less-harmful CO2. EPA assumes landfill operators capture on average 75% or more of methane emissions. The best current information says that Casella and the EPA are mistaken on the amounts of methane captured. Following is an excerpt of a paper presented by the Center For A Competitive Waste Industry to the California Air Resources Board in 2007.

EXECUTIVE SUMMARY

Conventional wisdom, based upon statements by the Environmental Protection Agency (EPA), assumes landfill operators capture 75% or more of the methane gas (CH4) that is generated at their facilities. Because of that assumption of high collection efficiency, landfills have been thought to be responsible for only 2%-3% of anthropogenic, or manmade, greenhouse gases (GHG). This comment explains why the EPA assumption is demonstrably wrong, why the best available evidence does not support a value greater than 20%, and why the appropriate remedies that follow from this correction involve more diversion rather than better landfilling. Specifically-

- There are no field measurements of the efficiency of landfill gas collection systems.
- EPA's assumed 75% gas collection efficiency has no factual basis, is based upon fundamentally incorrect definitions, and uses biased selection from unsupported, and self-serving, guesses as the basis for its assumption.

- The best evidence of typical lifetime capture rates based upon correct definitions does not support a value greater than 20%, as further attested to by the International Panel on Climate Change.
- Correcting the capture rate from 75% to 20% increases landfills' responsibility for anthropogenic greenhouse gas emissions from approximately 2%-3% to 8%-9% or more.
- Because gas collection is actually very poor, the case for diverting decomposable discards from the landfill becomes clear.

The paper goes on to explain that the high percentage rates come from a one-time snapshot of a landfill at its most functional point. There is a lot of methane emitted before the landfill is capped. The larger threat comes after the useful life of the gas extraction and is referred to as a "second wave". After the landfill is decommissioned, there is settling and deterioration of the cover. This allows more rain to enter the pile, and the added moisture accelerates decomposition, and the gas escapes thru breaches in the cover or liner. Remember, all landfills eventually leak.

When you consider the total environmental effects of Casella's plan to truck southern Maine's MSW to JRL in Old Town, it reinforces the wisdom of our Waste Hierarchy in that incineration is far preferable to landfilling MSW. Far more energy is extracted from incinerating a ton of garbage than from putting it in a pile and making electricity with the methane produced, and likewise fewer greenhouse gas emissions are released by incineration per unit of energy production. It bears mentioning that Casella's plan to heat the University of Maine Campus with gas from JRL has not progressed since proposed many years ago, and shows no sign of happening anytime soon. Once again, the best solution for disposing of the former MERC's MSW in Maine is to redistribute it to our other waste to energy plants.

Information Sources:

Anderson, Peter N., 2007, Center for a competitive Waste Industry, Comments to the California Air Resources Board on Landfills' Responsibility for Climate Change and the Appropriate Response to those Facts. http://competitivewaste.org/documents/LNDFL-LFG-GHG-CA-ARB-5_000.pdf

Bogner, J., M. Abdelrafie Ahmed, C.Diaz, A. Faaij, Q. Gao, S.Hashimoto, K Mareckova, R. Pipatti, T. Zhang, Waste Management , in Climate Change 2007: Mitigation. Contribution of Working Group III to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change [B. Metz, O.R. Davidson, P.R. Bosch, R.Dave, L.A. Myer(eds)], Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://www.ipcc.ch/pdf/assessment-report/ar4/wg3/ar4-wg3-chapter10.pdf

Kaplan, P.O., J. DeCarolis, and S. Thornloe. Is it Better to Burn or Bury Waste for Clean Electricity Generation? Environ. Sci. Technol. 2009, 43 (6), 1711-1717. DOI: 10.1021/es802395e 10 February 2009.

Sierra Club Report on Landfill-Gas to Energy, Prepared by the Sierra Club LFGTE Task Force, 2010. http://clubhouse.sierraclub.org/conservation/policy/lfgterepfinal.pdf

From the Beginning: The Waste Hierarchy and Juniper Ridge Landfill

We have included the statutes which lay out the State of Maine Waste Policy and Waste Hierarchy. When the process began in 2003 to change the West Old Town Landfill, owned by the local paper mill and restricted to that mill's waste stream, into a State-owned multi-waste landfill, it was clear from the beginning that our Waste Hierarchy was to be followed. In testimony by George McDonald, Manager of the Waste Management & Recycling Program at the State Planning Office, he told the Natural Resources Committee what the intent was of SPO in owning this landfill. One of his bullet points: "Support the waste management hierarchy in the State, to the greatest extent possible." This was on June 3rd, 2003, at the hearing for LD 1626, which authorized the State to own what became known as Juniper Ridge Landfill.

On June 13, 2003, SPO issued a "Request for Proposals (RFP): Contract For Landfill Operations". On Page 4 of that RFP, under Scope of Services, at the top it said: "The Scope of Services under this contract will include those listed below. The landfill will be operated on a basis consistent with the State's waste management hierarchy, which establishes the following priority for the management of wastes: Reduce, Reuse, Recycle, Compost, and Landfill." Casella was the sole bidder and became JRL Operator. It was known to them before they bid that the Waste Hierarchy was to be zealously applied.

The Operating Services Agreement between the State of Maine and Casella was signed on Feb. 4, 2004. On Page 24, section 2.13: "Waste Management Hierarchy. Casella agrees to use its best efforts to achieve the following goals: (a) to operate the Landfill following the State's solid waste management hierarchy (reduce, reuse, recycle, compost, incinerate, landfill)". On Page 37 of the OSA, it reads: "13.5 Casella covenants and agrees to operate Landfill and otherwise conduct all aspects of its business at the Landfill in compliance with all applicable laws and regulations and permits." Certainly Casella knew that the state statutes on Hierarchy would apply here.

On April 9, 2004 DEP issued a permit to SPO and Casella which amended the original paper mill landfill license when the State became owner. On Page 50 of that document it says "In signing the OSA, Casella agreed, in part, to use its best efforts to operate the landfill following the State's solid waste management hierarchy." This is the license being considered for amendment now. On Page 59, it says 16. With regard to the acceptance of MSW for disposal, consistent with its proposal, the applicant:

A. Shall not dispose of unprocessed MSW from any source other than bypass from the following sources: PERC incinerator in Orrington and the Maine Energy incinerator in Biddeford; waste delivered under an interruptible contract with PERC; or waste delivered in excess of processing capacity at other MSW incinerators in Maine

In summary, Casella knew well in advance of becoming Operator at JRL that the Waste Hierarchy was to be the Law of the Landfill. Their contract with the state requires compliance, as does their existing license. The State of Maine's only functional State-Owned Landfill should certainly be following our State Waste Policy.

DATED Feb. 28, 2013

BY: Edward S. Spencer
Edward S. Spencer
Old Town, Maine

STATE OF MAINE
PENOBSCOT, ss.

February 28, 2013

Personally appeared the above-named Edward Spencer and made oath as to the truth of the foregoing statements.

Before me,

Laura Sanborn
Notary Public State of Maine
Laura Sanborn
Notary Public Maine
My Commission Expires July 13, 2015

SIERRA CLUB REPORT ON LANDFILL-GAS-TO-ENERGY

Prepared by the Sierra Club LFGTE Task Force
January 5, 2010

Executive Summary

The Landfill Gas to Energy (LFGTE) Task Force was asked to evaluate whether LFGTE facilities decrease or increase net greenhouse gas (GHG) emissions. We have unanimously concluded that reliance on landfill gas to generate electricity results in increased net GHG emissions. This is clearly the case when considering the fate of new wastes that could be diverted to waste management facilities more appropriate than landfills, and is almost certainly true for wastes already buried in landfills that collect landfill gas and flare it.

Our conclusions reinforce existing Sierra Club policy that supports diversion of the organic fraction of our discards from landfills so that uncontrolled methane is not generated in the first instance. They also suggest that, in existing landfills with or without LFGTE facilities, regulations should be significantly strengthened to reduce methane emissions as much as possible.

Modern solid waste landfills generate and release significant amounts of methane, a potent contributor to global warming. When decomposable organic trash (e.g., food scraps, yard waste, and more) break down under the oxygen poor conditions in today's covered landfills, a complex mixture of combustible gases is produced. About half of that gas mixture is methane and, left undisturbed, much of it seeps out of the ground and is released to the environment over time.

More than a decade ago, the Environmental Protection Agency began requiring most larger solid waste landfills to install landfill gas collection and flaring systems, in part as a way to reduce methane emissions and their contribution to climate change. Collection and flaring of landfill gas, they reasoned, may result in some reduction in human contributions to climate change if they result in reduced fugitive releases of methane to the environment and in effective conversion of captured methane to carbon dioxide, a less potent greenhouse gas (GHG).

Enterprising landfill operators, encouraged by an EPA outreach program, are using the collected landfill gases to generate electricity and to produce additional revenue by selling that electricity to power companies. Conventional wisdom suggests that LFGTE facilities should also help to reduce global warming impacts by reducing the need to produce electricity from coal and other dirtier fuels.

Our analysis leads us to conclude that conventional wisdom is mistaken.

Findings

1) **For new wastes, disposal of decomposable organic wastes in landfills, including those with associated LFGTE facilities, clearly results in the release of substantially more greenhouse gases (and other environmental pollutants) than diversion of these wastes from land filling to other**

treatments.

When organic wastes are buried in today's landfills, methane is always produced and a substantial portion of that methane leaks into the environment.

2) **Management practices commonly employed in conjunction with LFGTE systems tend to increase fugitive methane emissions, to shift their timing toward the present (compared with standard landfill gas collection and flaring), and to reduce collection efficiency.** (See Background #5)

   In particular, raising the moisture content of the landfill, the "wet cell" method, accelerates the decomposition of wastes, making room for more wastes and increasing the volume and concentration of methane produced. It also shifts methane generation forward in time, which is counterproductive to achieving the near-term reductions in GHG emissions that many scientists believe are necessary for successful control of climate change. (Some landfills that do not employ LFGTE also use the wet cell method to create space for more wastes.)

4) **Contrary to conventional wisdom, it appears the relatively small CO_2 reduction benefit that might be achieved by replacing fossil fuel electricity with LFGTE electricity is greatly outweighed by the increase in fugitive methane emissions resulting from altered landfill management practices.**

   That makes LFGTE facilities counterproductive as part of a climate change mitigation strategy.[1] Because the very things necessary to reduce methane emissions from LFGTE facilities conflict with incentives to maximize revenue from the generation of electricity, it does not appear likely that landfill managers will improve practices sufficiently in the foreseeable future to result in a net GHG benefit from LFGTE. (See Background #7)

5) **While efforts to divert organic discards from landfills are developed and implemented, methane will continue to be generated from wastes that are already in place, and from future organic discards that those programs fail to divert.**

   While the site is actively managed, several operational changes should immediately be made at landfills to (1) increase the amount of landfill gases that are captured, (2) avoid measures intended to augment the concentration of methane in landfill gas, and (3) cease using methods that shift overall gas generation from the future to the present unless a high percentage of that gas can be captured. (See APPENDIX B.). More research is needed on how to manage landfills to stabilize the site so that fugitive methane emissions do not continue after active maintenance ends (the "second wave", which greatly increase lifetime emissions), That should not be at the price of significantly increasing fugitive methane emissions in the critical near term when we

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[1] For LFGTE to result in any net GHG emission benefit, the management system would have to be improved dramatically so that virtually no methane or hazardous air and water pollutants escape and new monitoring methods would have to be employed to verify fugitive emission levels. Even then the amount of credit for LFGTE should be based on the net reduction of GHG emissions on a life-cycle analysis basis, taking account of the degree that fossil fuels are actually displaced by the energy from LFGTE.

confront a tipping point. (Present proposals directed at the second wave are discussed further in Background #9)

6) **Current landfill regulation does not deal adequately with methane emissions or with other pollutants, including toxics that are generated in landfills and are either poorly regulated or not regulated at all.** Specific recommendations for improvements in Club policy and in federal and state landfill regulations require further exploration and should be aggressively pursued. (See Background #8)

7) **The contribution of methane emissions from landfills and other sources to global climate change has typically been underestimated.**

   If mitigation strategies are to achieve the near-term large reductions necessary to prevent catastrophic climate change impacts, then curbing methane emissions is an important opportunity for near-term mitigation of those impacts and should be given a high priority. This opportunity is not fully recognized in Kyoto Protocol procedures and in most current mitigation programs. The latest Intergovernmental Panel on Climate Change's scientific report does explain the greater role of methane and indicates that globally the climate impact of current methane emissions over the next 20 years is almost as great as CO_2 emissions. (See Background #4)

Recommendations

While there remain a number of unresolved questions about LFGTE, the Task Force believes there is more than sufficient evidence for the Club to take action in the following areas:

Recommendation No. 1 – ***The Sierra Club should resist legislative and policy initiatives that encourage LFGTE projects or that allow LFGTE facilities to receive credit in GHG emission reduction programs. Club policies and initiatives should be examined and revised as appropriate to be consistent with that objective.***

The Task Force recommends amendment of the *2006 Energy Resources Policy* (which currently does not address LFGTE) by adding a new subsection under "*VII. Resources for the Transition to a Clean Energy Future, E. Resources Opposed by the Sierra Club*".

Recommendation No. 2 – ***The Sierra Club should continue to advocate the elimination of organic discards from landfills as a long-term solid waste management goal and as a component of our global climate change campaigns. The Sierra Club should explore and support solid waste management policies, laws, regulations, strategies and technologies that could help to facilitate that transition.***

This recommendation reinforces and expands upon the general principles in the Club's

Zero Waste: Cradle-to-Cradle Principles for the 21st Century Policy of Feb. 2008. It also suggests the need for Club guidance and perhaps policy dealing with treatment methods for organics in the waste stream as alternatives to land disposal. The draft *Zero Waste Guidance on Landfills* does not deal with all of those issues and this Task Force has had only preliminary discussions of those options. .

Recommendation No. 3 – ***Because separate collection and management of decomposable organic wastes is not fully achievable in the near term and does not help with wastes already in the ground, the Sierra Club should pursue improvement of landfill management regulation and practices aimed at reducing emissions of methane and other pollutants.***

This is a recommendation for action and does not require a policy change. Specific recommendations for Club policies and guidance that address the most feasible and desirable ways to achieve reductions should be pursued on a priority basis. As a first step, Appendix B lists some changes in landfill regulations that would help to reduce fugitive emissions of methane.

Recommendation No. 4 – ***The Sierra Club should seek to elevate the attention given to curbing methane generation and release from landfills and other sources as part of our global warming and energy campaigns.***

This recommendation reaches beyond the scope of the Board's charge to this Task Force, but it is clear to us that methane emission reductions could and should be an integral part of any effective GHG emissions reduction strategy.

Appendix A – Background

There are eight underlying concepts that are necessary to understand these issues:

1. *Substantial volumes of methane are generated from the decomposable organic fraction of our buried discards.* Between half and two-thirds of our household and commercial discards are organic. Those wastes consist chiefly of yard trimmings, soiled paper and food scraps, with lesser quantities of pet waste, diapers, textiles and wood. When garbage and its organic fraction are buried and compacted in the ground and then covered, they decompose anaerobically (i.e. in oxygen-starved conditions), and methane (CH_4) is produced among the decomposition byproducts.

   A ton of wet organic material buried in a landfill is reflective of what one family might throw out in a year and will generate approximately 500 pounds of methane spread out over decades. Some fraction of that methane will escape from the landfill into the atmosphere, whether or not some of the methane is collected and burned. Those escaped landfill gases are commonly known as *fugitive* or *uncontrolled* emissions.

2. *Only a part of landfill gas is captured with collection systems in place.* In most large landfills, Environmental Protection Agency (EPA) regulations require the installation of gas collection systems after 5 years of first waste emplacement and continuing for a period of less than 30 years after closure. (See Figure 1) Because gas escapes from the top, sides and bottom of landfills, and because landfills often cover several hundred acres and are piled with wastes as much as several hundred feet deep, capturing all the gas is extremely challenging, even for the period when there is any gas collection. In addition, technology to measure fugitive emissions over a wide area has not been available. As a result, reliable representative measurements of the effectiveness of collection systems are not available and it has not been feasible to establish direct, enforceable methane emission limits.

   EPA estimates, without supporting data, that the best collection systems capture about 78% of the gases during the relatively small fraction of a landfill's emitting lifetime that they are installed and functional. But, the Intergovernmental Panel on Climate Change (IPCC) expressed the view that, over the long term, including the extensive times when there is little or no gas collection, the average fraction captured may be as low as 20%.

   The difference between these two values is due at least in part to the assumptions used to frame the estimates. The EPA's estimates are based on what they believe the best systems should achieve during the limited time that they operate. The IPCC's are based on average systems operating over the entire period that gas is generated.

   In particular, the major pathways for uncontrolled landfill gas emissions occur after the site is closed and set-aside funds for postclosure maintenance are gone. Based on studies that indicate moisture only reaches "23% to 34% of the waste mass"[1], and the fact that high moisture levels are necessary for effective decomposition, most gas will be generated after the cover fails, rainfall re-enters the site, and a second major wave of gas generation ensues without any controls. Consequently, landfills are a much greater source of greenhouse gases than EPA has acknowledged.

3. *None of the alternatives to land filling presents a significant methane problem.* In contrast to substantial methane generated by landfills, some fraction of which escapes, none of the commercial alternatives to the landfilling of organic wastes produces significant volumes of uncontrolled methane. These commercial alternatives include processing the organics by windrow (composting), open vessel aerobic decomposition, enclosed aerobic chambers, enclosed anaerobic chambers with methane collection, pyrolysis, and combustion/incineration.

4. *Methane is carbon dioxide on steroids.* The difference between releases of CH_4 (from landfills alone) and CO_2 (from almost any other alternative) holds enormous consequences for climate change. Methane emissions have at least 25 times the warming potential of CO_2 emissions when climate impacts are counted over the longer term (i.e., using the 100-year "GWP").[2] In the near term, as we confront a possible tipping point, it is arguable that methane should be counted more heavily, as much as 72 times CO_2 (using the 20-year GWP). Total methane emissions from all sources are estimated to represent about 9% of CO_2-equivalent GHG emissions in the U.S. and 14% of global GHG emissions based on the longer 100-year GWP time horizon. **But the IPCC estimates that, based on a 20-year time horizon, global methane emissions in 2000 were nearly equal to CO_2 emissions in their impact on global warming.**[3] (See Figure 2 for a graphic illustration of IPCC's analysis of the integrated impact of global emissions.) Landfills are estimated by EPA to account for about 24% of total methane emissions in the U.S. (The Task Force suspects the actual percentage may be higher.) Landfills are a much smaller percent of total methane emissions in most of the world, especially in developing nations.[4]

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[1] Debra Reinhart, *Prediction and Measurement of Leachate Head on Landfill Liners,* Florida Center for Solid and Hazardous Waste Management (Report #98-3) (1998), at p. viii. Other data from leachate recirculating landfills suggests that even in these wet cells "efficiency of the leachate recirculation system at distributing leachate throughout the waste body in the recirculation cell were [still] low." J.W.F. Morris, et al., *Findings from long term monitoring studies at MSW landfill facilities with leachate recirculation,* WASTE MANAGEMENT 23 (2003), at p. 653.

[2] The "Global Warming Potential" or GWP was adopted in the Kyoto Protocol as a method for comparing emissions of different greenhouse gases (GHG) by weight. It is an integrated measure of impact over a specified time period and 100 years was adopted in the Kyoto Protocol (the "100-year GWP"), although some policy analysts advocate shorter time periods for counting impacts such as 20 years—the "20-year GWP". A ton of methane emissions has 25 times the integrated impact on global warming as a ton of CO_2 using the 100-year GWP and 72 times using the 20-year GWP.

[3] Figure 2.22, p. 206, Chap. 2, Report of Working Group I: "Physical Basis of Climate Change", Fourth Assessment Report of the Intergovernmental Panel on Climate Change, 2007.

[4] Stacy C. Jackson, "Parallel Pursuit of Near-Term and Long-Term Climate Mitigation," 326 Science 526 (2009); and James Hansen, "Greenhouse gas growth rates," 101 PNAS 46 (November 16, 2004), p. 161094. For more recent information about further heightening of methane's warming potential, see, Drew T. Shindell, et al., "Improved Attribution of

5. *Changes in landfill operation linked to LFGTE increase uncontrolled methane releases.* In recent years, the landfill industry has made widespread operational changes to increase revenues from energy production but with potentially significant impacts on our climate. These unfortunate practices were never contemplated in EPA's landfill rules and have never been officially vetted for their GHG implications.

For example, many landfills with associated LFGTE facilities are recirculating leachate and adopting other management practices intended to accelerate organic waste decomposition and accelerate landfill subsidence. This is called "wet cell" operation in contrast with the traditional "dry tomb" designs. The increased moisture can result in increased methane concentrations in collected landfill gas by almost half. This operational change shifts the timing of methane generation closer to the present, when it would otherwise be spread over many decades.

Many LFGTE landfills also delay installation of the cover that keeps out rainfall and reduce negative pressure in the gas collection system as additional tactics to maintain optimum conditions for methane production. The result is landfill gas with a higher methane concentration and reduced gas collection efficiency, increasing both the volume of fugitive emissions and the methane concentration in those emissions. For citations, see footnote 4. There are alternative landfill practices that theoretically might achieve better emissions control. Potential examples include a few small publicly owned and closed landfills and a small demonstration project operated to maximize gas capture at the same time energy is generated.[5] However those methods tend to make LFGTE less profitable. Without any current way to enforce proper operation, the economic incentive on an operator would be to act in ways that wind up increasing emissions in order to restore profitability. If comprehensive and practical monitoring systems were later developed and demonstrated to reliably measure all fugitive emissions, and not just those from the surface while the unit is open, then there may be grounds for reconsideration.

6. *Landfills are responsible for significant GHG emissions*. EPA GHG emission inventories estimate landfill methane emissions at about 2% of total anthropogenic (i.e. manmade) GHG emissions in the U.S in 2005. It appears that, depending upon which assumptions are adopted (i.e. high vs. low gas collection efficiency, long vs. short term time periods for measuring impacts (GWP), and wet cell vs. dry tomb management), landfills' may be responsible for a much greater impact -- up to approximately 12% of total GHG emissions. Using the latest IPCC 20-year GWP of 72 to weight methane instead of the earlier IPCC 100-year value of 21 used by EPA will, by itself, increase the estimated percentage of GHG emissions by more than three times.

Climate Forcing Emissions, 326 Science 716 (2009).

[5] Augenstein, Don, "Landfill Operation for Carbon Sequestration and Maximum Methane Emission Control: Controlled Landfilling Demonstration Cell Performance for Carbon Sequestration, Greenhouse Gas Emission Abatement and Landfill Methane Energy", Final Report, Institute for Environmental Management (IE M), February 26, 2000.

7. *Purported GW benefits of LFGTE are dubious.* The landfill industry contends that recovery of the methane from landfill gas for the generation of electricity will reduce net GHG emissions. The gain from LFGTE is alleged to occur because the electricity generated at the landfill offsets the need to generate power from dirtier combustion sources, thus avoiding the associated emissions of carbon dioxide and other harmful pollutants. That view is widely shared by politicians, EPA, and some environmental organizations. The Task Force is persuaded that this CO_2 benefit is greatly outweighed by an increase in fugitive (uncontrolled) methane emissions resulting from the altered landfill management methods apparently practiced at most LFGTE projects.

Because of the much greater potency of methane as discussed in Background #4 above, additional leakage (compared with conventional collection and flaring) of only a very small percentage of the methane generated is sufficient to overwhelm the relatively small CO_2 reduction from electricity production. When LFGTE is compared with non-landfill waste treatment options, the high leakage rates of all landfill management methods (at least 22% or more even by EPA's most optimistic estimates) makes the comparison much more unfavorable to LFGTE. An additional uncertainty is the source of electricity generation that is likely to be displaced by LFGTE, but the Task Force's conclusions do not depend on challenging the industry assumption that it would displace dirty fossil energy.

8. *Landfill gas emissions are a major source of un(der)regulated pollution.* In addition to the potent greenhouse gas, methane, landfill gases contain compounds that contribute to regional smog and hazardous pollutants harmful to human health. Because methods for measuring fugitive emissions over large non-point sources have not been available, setting emissions performance standards (which depend upon direct emissions measurements) at landfills has not been possible.

As a poor substitute for direct measurement, methane concentration levels at the surface of landfills are normally measured quarterly along a grid, at points about 100 feet apart, beginning after there is a final cover in place.[6] But, this test is effectively useless at landfills with low permeability covers because the greatest emissions are localized at a few tears in the cover and are not diffused uniformly across the surface. Conclusions based on these inadequate testing methods will fail to detect most gas leaks at landfills with composite covers.

Consequently, current regulations and emission inventories are unreliable and probably ineffective. Better empirical measurements are critical to achieving optimal improvements in regulation, although a number of feasible immediate improvements are described in Appendix B.[7]

Finally, regulations do not adequately address substantial emissions that occur after active management and regulation cease, as described below in #9.

9. *Landfills may emit substantial methane for decades after active management has ceased.* Some in industry advocate leachate recirculation

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[6] 40 CFR §60.755(c).

[7] 40 CFR§ 98.343.

during active landfill operation as a way to reduce the levels of undigested waste in closed landfills, and thus reduce post-closure, "second wave" landfill gas generation and release. The result, however, is significantly increased fugitive methane emissions earlier in the life of the landfill and during the time when there is, as NASA has stated, an urgent need to reduce and not increase methane emissions.[8] Landfills that accept decomposable organic wastes should be required to begin gas collection sooner (perhaps within 2 years of the start of waste deposition, rather than the currently required five years), in order to better manage these early emissions.

In addition, lessening the effects of the second wave of landfill gas, without front-loading the system with near-term methane releases, is critical. More effective post-closure requirements and aggressive research and development efforts might be able to identify better methods for preventing second wave gas releases.

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[8] James Hansen, *Greenhouse gas growth rates*, 101 PNAS 46 (November 16, 2004), p. 161094

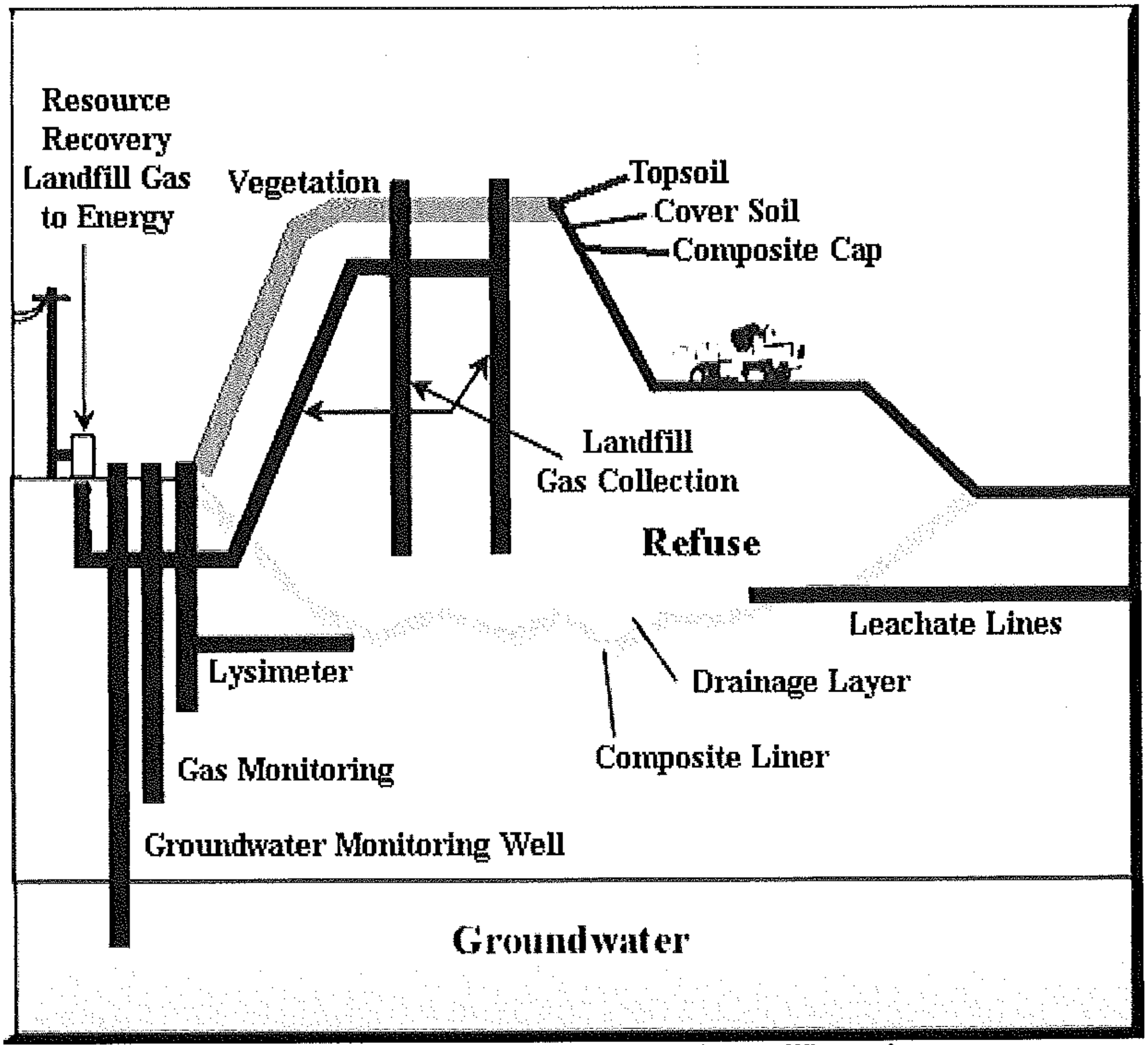

Figure 1. Profile of landfill with gas collection system. Source: **Wisconsin Department of Natural Resources.**

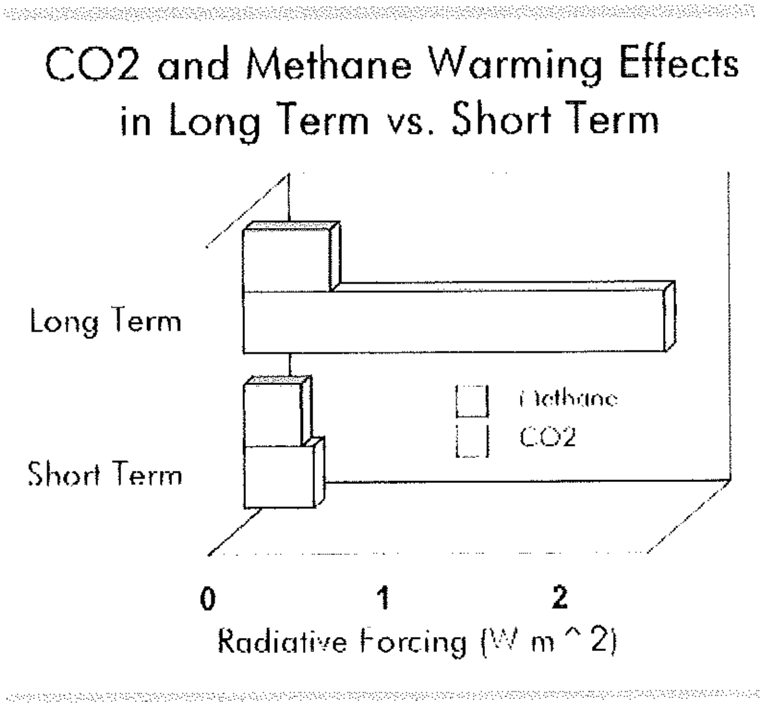

Figure 2. Integrated climate impacts of year 2000 total global emissions of $CO_2$and Methane on radiative forcing evaluated over long-term (100-year) and short-term (20-year) time horizons. "Radiative forcing" is a term used to describe the warming effect of a greenhouse gas in the atmosphere. It is the difference between the incoming radiant energy from the sun and the outgoing radiant energy in the atmosphere. Source: IPCC Fourth Assessment and Center for Competitive Waste Industry.

APPENDIX B

SOME ESSENTIAL ELEMENTS OF AN EFFECTIVE LANDFILL GAS EMISSIONS CONTROL REGULATION

Preface. The existing landfill air rule effectively leaves the detail of LF gas management design and operation to the landfill owner. Because there is no reliable system to monitor emissions, effective control of the pollutants in landfill gas requires the use of landfill management practices designed to minimize the generation and release of problem pollutants. Some of those better practices cost more to implement, and thus are often ignored.

Of course, the most effective way to avoid release of landfill gas pollutants is to divert decomposable organic wastes for responsible treatment elsewhere. As long as landfills continue to accept organic wastes, and until the organic wastes buried already are fully decomposed, landfill gas will continue to be a problem, and much better regulation of the management of landfills and landfill gas will be essential.

The Sierra Club's Landfill Gas to Energy Task Force has reviewed the technical literature, most of which is produced by the industry itself and by its consultants. The Task Force has identified those industry-recommended practices its members believe can help to improve gas collection and reduce gas emissions. They are presented here as examples of the kinds of improved practices that are supported by some in the industry and that could be viewed as a useful starting point for the development improved landfill gas regulations.

The new requirements should apply to all landfills large enough to capture gas effectively, unless a case specific showing is made that a specific requirement is not technically feasible at a particular site (independent of cost considerations), or at a separable part of that site. Before any such determination is made, adequate notice and a meaningful opportunity for public comment must be provided.

These examples are offered to assist activists and staff who are attempting to address relevant issues. They are examples based on the industry literature that highlight important regulatory and management issues, but they are not necessarily considered to be sufficient by the Sierra Club. The Sierra Club has not yet developed policy recommendations in this area, but may choose to do so in the future.

These examples are generally directed at two strategies for reducing fugitive methane emissions. The first is direct capture of more of the gases generated, and the other is reduced methane generation, especially in the near term.

INCREASED GAS CAPTURE

1. **Early Horizontal collectors.** Landfill operators should be required to

install horizontal gas collectors in active waste-receiving areas with each elevation change (usually daily) prior to installation of vertical gas wells, but delay operation of the collectors until there is sufficient depth and cover to apply vacuum. [SCS, A-1 and A-3 (p. 4).] Horizontal collectors should be spaced to overlap each pipe's zone of influence when negative pressures are applied under conditions without a low permeability cover. Co-utilizing horizontal collectors for gas collection and liquid recirculation should be prohibited.

> Background. *Gas is traditionally collected with rigid vertical pipes, which are perforated, and drilled into the waste mass for most of its depth. The pipes are connected with headers and lines to a fan that pulls gas from the surrounding waste mass. However, substantial gas is released before these vertical pipes can be made functional, and flexible horizontal pipes are a means to collect some of this early gas to reduce fugitive emissions.*

2. **Vertical well density.** Landfill operators should be required to reduce the spacing of vertical wells from the current 300' to 350' apart common today to not more than 150'. [SCS, A-2 (p. 4).]

> Background. *The effectiveness of gas collection systems is in significant part a function of how close the gas wells are spaced: in general, the closer they are to each other, the more gas will be collected. When gas collection began in the mid 1990s, wells were commonly about 150 feet apart. In more recent years, common spacing for gas wells has spread to 300-350 feet apart. The result has been less effective gas collection.*

3. **Multiple wells in same bore holes.** Landfill operators should be required to install multiple vertical wells for different depths in the same bore hole in order to allow for distinct and optimal negative pressures at each level. [SCS, A-5, at p. 4.]

> Background. *Landfills can often be 300 feet deep. With increasing depths, the density of the surrounding wastes increase as well, and that means more vacuum forces are needed to pull gas from the same distance from the collection pipe. However, if the same force needed to draw gas at the lower depths were used in higher depths, air would also be drawn from the surface. When more than 5% oxygen mixes with methane in landfill gas, dangerous conditions are created, which necessitates turning down the system to avoid fires and explosions, but reducing collection effectiveness as well.*

4. **Leachate collection system to gas collection system connection.** Landfill operators should be required to connect the gas collection system to the leachate collection system at the high side on bottom of landfill. .[SCS, A-4 (p. 4).]

> Background. *Landfill gas follows the path of least resistance, which can be at the bottom of the landfill through the pathways created by the leachate lines and their gravel packs intended to remove leachate. Good practice is to collect*

gas from the leachate take outs to prevent it being released into the atmosphere.

5. **Multiple seals around bore holes.** Landfill operators should be required to utilize at least three sets of seals, including bentonite, clay and well bore seal, where collection wells penetrate the final composite cover in order to minimize air infiltration and maximize vacuum forces. [SCS A-6, at p. 5.] Methane leak rates around the seals at each well head should be checked at least monthly during typical atmospheric conditions and, if methane levels are significantly above background, the seals should be repaired. [40 CFR §60.755(c)]

> <u>*Background.*</u> *Ironically, much of the gas that escapes does so through the seals around the gas collection wells. Continuing subsidence at the surface cracks the original seals, and they need continuing maintenance to prevent leakage.*

6. **Enhanced monitoring.** The procedures intended to detect leaks provided under 40 CFR 60.755(c) should be replaced with optical remote scanning (ORS) over all surface areas of the landfill, including but not limited to areas around gas collection wells and side slopes. EPA needs to develop standards for the method.

> <u>*Background.*</u> *The existing method for assessing performance of the gas collection system is based upon checking quarterly for methane concentration levels at the surface at 100 foot intervals on a grid. This method is often called the "sniff test." Because gas escapes from landfills with a final cover primarily through tears and cracks in the plastic sheet, most leaks are probably missed. This deficiency is exacerbated when the area near well seals, where there most often are leaks, is avoided. New scanning systems are more effective at assessing methane levels across the flat, horizontal surface. It is important to improve the capability of optical systems for assessing leaks on the side slopes where more leaks occur than through the top face.*

REDUCED METHANE GENERATION

7. **Installation of vertical collectors, maximum slopes and final cover.** Each landfill cell should be designed to reach final grade in not more than two years from first waste emplacement. The active vertical collectors should be installed at that time and connected with headers to a vacuum system. Not more than one year after reaching final grade, a final low permeability cover (less than 1×10^{-5} cm/sec.) should be installed. If a geomembrane is used to provide a low permeability barrier, exterior side slopes should not be steeper than 4:1 to facilitate stabilization of the clay and dirt layers in a final cover over the underlying geomembrane. [Oonk, at p. 11; SCS C-1 and D-6, at p 6-7; 56 Federal Register 104, at p. 2447.]

> <u>*Background.*</u> *Although the original proposed landfill gas management rule (1991) would have required installation of gas collection within two years, the final rule (1996) relaxed that requirement to five years in order to*

> *accommodate the industry's desire to build larger mega-fills that often required longer to reach final grade. This created a conflict between the goals of optimizing gas collection and optimizing the operator's financial scale efficiencies. Similarly, several states have found that the industry standard used for the steepness of the side slopes (3:1 or three horizontal units to 1 vertical) cannot be stabilized in part because the overlying dirt slides off the slippery plastic cover sheet. At least three states have required more gradual side slopes (4:1) to help stabilize the dirt cover.*

8. **Delay any recirculation of leachate.** Leachate recirculation should be prohibited, at least until after an expendable low-permeability cover and active gas collection system have been installed. [Augenstein, at p. 4.]

> Background. *In order to induce settling, which enables the landfill owner to resell space for disposal a second time, operators have been recirculating leachate. Increased moisture levels accelerate decomposition and increase compressive forces, but the result is also increased gas generation and higher methane concentration levels during the early period of landfill operation when gas collection either is not yet installed, or is not yet fully functional. In addition, if there is no low permeability cover, the gas collection system vacuum will pull air from the surface along with methane from the surrounding wastes. Too much oxygen infiltration results in a flammable mixture. To avoid fires, the vacuum pressures must be reduced to avoid pulling air from the surface. However, this also means that the negative pressures fail to reach horizontally as far, leaving more areas of the landfill uncontrolled.*

9. **De-water flooded vertical wells.** In addition to monitoring the composition of gas collected for oxygen and nitrogen intrusion landfill operators should be required to monitor gas volumes to detect gas wells that may be flooded, and to pump out flooded wells. [SCS A-8, at p. 5.]

> Background. *Moisture in landfills, especially prior to installation of the final cover, can flood the gas collection piping, which compromises the ability to collect gas. Monitoring for reduced gas flows as an indicator of this condition, and then remedying the situation is important to a properly functioning gas collection system.*

SOURCES

Don Augenstein, et. al., *Improving Landfill Methane Recovery -- Recent Evaluations and Large Scale Tests* (2007).

Hans Oonk, *Expert Review of First Order Draft of Waste Chapter to IPCC's Fourth Assessment Report* (2008).

SCS Engineers, *Technologies and Management Options for Reducing Greenhouse Gas Emissions From Landfills* (2008).

U.S. Environmental Protection Agency, 40 CFR Part 60 WWW (proposed and final rule).

Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology, Office of Research and Development, U. S. Environmental Protection Agency,
Washington, DC, (EPA/600/R-07/032), February 2007

U.S. Environmental Protection Agency, *Draft AP-42, Sec* ***2.4 Municipal Solid Waste Landfills,*** **Oct. 2008.**

Appendix C - Annotated Bibliography
References and Contacts

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NOTE: Documents listed here were consulted by the Task Force during the course of its review. Listing does not constitute an endorsement of their contents or conclusions. Items marked with double asterisk (**) are available on the Clubhouse web site at:

****

Intergovernmental Panel on Climate Change, Fourth Assessment Report, Report of Working Group I: "Physical Basis of Climate Change", Figure 2.22, p. 206, Chap. 2e, 2007. [*This referenced figure and page describes the original modeling that concluded that methane was almost as important as CO_2 in affecting climate change over a 20-year time horizon--page and figure attached separately.*]** *Chapter 2 is available for downloading at: Full Working Group I Report is available at:*

Augenstein, Don, "Landfill Operation For Carbon Sequestration and Maximum Methane Emission Control: Controlled Landfilling Demonstration Cell Performance for Carbon Sequestration, Greenhouse Gas Emission Abatement and Landfill Methane Energy", Final Report, Institute for Environmental Management (IEM), February 26, 2000. [*This describes the Yolo County pilot project funded by DOE in detail after several of operation—see later update on continuing project below.*]**

"Yolo County, California Controlled Landfill Program: Results -- 12 Years' Operation", Don Augenstein, (presenter), Ramin Yazdani, Jeff Kieffer, Kathy Sananikone, John Benemann, Landfill Learning Session, World Bank, Washington, DC, May 8, 2006. [*This powerpoint presentation (in pdf format) is an update of results from the same Yolo County pilot project described above.*]**

"Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990 – 2006, April 15, 2008, U.S. Environmental Protection Agency. [*This annual report provides the basis for computing percentages of methane emissions and landfill gas in the U.S.; downloadable from EPA website at*]

IPCC, "Contribution of Working Group III to the Fourth Assessment Report: Technical Summary", 2007
[*This technical summary provides the overview of contributions of methane and waste management activities to global greenhouse gas emissions and discusses mitigation policies in general terms. More detailed discussion of landfill gas is in the following document.] Available for download at:*

IPCC, Fourth Assessment Report, Chapter 10: Waste Management, Section 10.5.1 Reducing landfill CH4 emissions, 2007. [*This section discusses emission estimates and mitigation methods for landfill gas and provides the basis for the lower end of the capture ratio cited in the Task Force Report; IPCC reports can be downloaded from the IPCC web site.] Chapter 10 on Waste Management available for downloading at:*

"Evaluation of Fugitive Emissions Using Ground-Based Optical Remote Sensing Technology", EPA/600/R-07/032, February 2007. [*This EPA Report describes testing of* *two instruments that are the basis of a new fugitive gas monitoring method.]***

"Technologies and Management Options for Reducing Greenhouse Gas Emissions From Landfills", SCS Engineers , APRIL 2008 , California INTEGRATED WASTE MANAGEMENT BOARD *[This report is a guidance document for landfill operators of landfills and may be useful as we consider what improvements in operations should be recommended for consideration by EPA; however, we did not use this explicitly in reaching the conclusions in our report.]***

"Background Information Document for Updating AP42 Section 2.4 for Estimating Emissions from Municipal Solid Waste Landfills", Prepared by Eastern Research Group, Inc., for U.S. EPA, EPA/600/R-08-116, Sep. 2008. *[This indicates EPA's latest information on landfill emissions in preparation for planned updating of their AP-42 emission factor documents; we did not find it terribly useful in preparing the Report.]***

"Stop Trashing the Climate: Full Report", June 2008, Institute for Local Self-Reliance, by Brenda Platt, Institute for Local Self-Reliance, David Ciplet, Global Anti-Incinerator Alliance/Global Alliance for Incinerator Alternatives, Kate M. Bailey and Eric Lombardi, Eco-Cycle, available at . [*Provides the environmental case for zero waste approach and against landfilling.*]

Center for a Competitive Waste Industry, Comments to the California Air Resources Board on Landfills' Responsibility for Climate Change and the Appropriate Response to those Facts (2007). Available at [This report provides an explanation of the issues underlying a full understanding of landfill gas generation, capture and energy recovery that is not reflected in waste industry or most EPA reports.]

Chad Leatherwood (ERG), Memorandum to Brian Guzzone, Meg Victor, U.S. Environmental Protection Agency, Re: Review of Available Data and Industry Contacts Regarding Landfill Gas Collection Efficiency, Dated November 18, 2002 *[When EPA is asked for the basis for its assumed 75% collection efficiency factor, it references this memorandum prepared for EPA by its contractor, ERG. The Task Force does not agree with the conclusions of this memo, but cites it to illustrate one of the problems.]***

SCS Engineers, Current MSW Industry Position and State-of-the-Practice on LFG Collection Efficiency, Methane Oxidation, and Carbon Sequestration in Landfills. 2007. **Available online at**
[Waste Industry position on landfill gas presented to the California Air Resources Board]

Center for Competitive Waste Industry, Critique of SCS Engineers Report Prepared for California's Landfill Companies on Gas Collection Performance. 2008. Available online at . *[Critique of waste industry position.]*

U. S. Environmental Protection Agency Documents –

Methane Emissions in the United States: Estimates for 1990 (Report to Congress) (EPA 430-R-93-003)(1993)

Compilation of Air Pollutant Emission Factors (AP-42)(Fifth Edition 1998)

Development of Construction and Use Criteria for Sanitary Landfills (EPA530/SW-19D-73)(1973)

Draft Background Paper: Changes to the Methodology for the Inventory of Methane Emissions from Landfills (August 26, 2004)

Geosynthetic Clay Liners Used in Municipal Solid Waste Landfills (EPA 530-F-97-002)(Revised December 2001)

Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste (EPA 530-R-98-013)(September 1998)

Landfill Methane Outreach Program, Creating Partnerships and Power from Landfill Gas (EPA-430-F-02-013)(2002)

"Measurement of Fugitive Emissions at Bioreactor Landfill", EPA-600/R-05/096 August 2005. [*This earlier EPA Report describes testing of the new monitoring methods at a bioreactor landfill.]**

U.S. Methane Emissions 1990-2020: Inventories, Projections, and Opportunities for Reductions (EPA 430-R-00-013)(September 1999)

Solid Waste Management And Greenhouse Gases: A Life-Cycle Assessment of Emissions and Sinks (EPA530-R-02-006)(June 2002)

Turning a Liability into an Asset: A Landfill Gas-to-Energy Project Development Handbook (EPA 430-B-96-004(September 1996)

Office of Air Quality Planning and Standards and Office of Air and Radiation, *Emission Factor Documentation for AP-42, Section 2.4, Municipal Solid Waste Landfills* (Revised 1997)

[These are the primary EPA documents that reference landfill gas emissions.]

Persons Consulted

Susan Thorneloe, EPA Office of Research and Development, re: monitoring methods. *(mainly she just sent us references and did not answer direct questions.)*

Larry Bingham. He was on the original engineering team that designed the first landfill-gas-to-energy system at the Los Angeles County Sanitation District's Palo Verde landfill in 1974, and who operated LFGTE systems for many years.

OTHER ONLINE RESOURCES

&

[*These sites may be useful for background information on landfill methane and also to* *understand how EPA is actively positioning LFGTE as a solution (hence the need for Club action on this issue).*

&

The bibliography (end note) list in the Institute for Local Self Reliance report "Stop Trashing the Climate" includes hundreds of entries, many of which re-enforce the conclusions reached by the Task Force.

MAINE STATE PLANNING OFFICE
WASTE MANAGEMENT & RECYCLING PROGRAM

REQUEST FOR PROPOSALS ("RFP"): CONTRACT FOR LANDFILL OPERATIONS

I. RFP Summary

1. Date Issued: June 13, 2003
2. Name and Location of Project: RFP "State Planning Office WM&R # 1, Contract for Landfill Operations." Old Town, Maine 04468.
3. Department: Maine State Planning Office, Waste Management & Recycling Program
4. Contact Person: George MacDonald, State Planning Office, Waste Management & Recycling Program. Tel: (207) 287-8934. Address: 38 State House Station, Augusta, ME 04333-0038. E-mail:george.macdonald@maine.gov
5. Pre-bid Conference: A pre-bid conference will be held on June 23, 2003 at 10:00 a.m. at the GP West Old Town landfill facility. At the pre-bid conference respondents will be provided an opportunity to question the State and Georgia-Pacific Corporation ("GP") representatives and to tour the landfill site. A written summary of questions covered at the pre-bid conference will be distributed to all potential bidders who have received a copy of the RFP from the contact person. The State will not be bound by oral answers provided at the conference.
6. Proposals/Deadline/Non-Refundable Bid Processing Fee: Respondents must send three (3) sealed copies of their proposal, each clearly marked "Proposal: State Planning Office WM&R # 1, Contract for Landfill Operation," to the Division of Purchases, Burton M. Cross Building, 4th Floor, 111 Sewall Street, 9 State House Station, Augusta, ME 04333-0009, no later than 2:00 p.m., Eastern Daylight Time (EDT) on July 9, 2003. Proposals must include a $10,000 non-refundable bid processing fee, payable by certified check or money order to "State of Maine, State Planning Office." Please note that only proposals actually received by the Division of Purchases prior to the stated time will be considered. Bidders submitting proposals by mail are responsible for allowing adequate time for delivery. Proposals received after the 2:00 p.m. local time deadline, or without the non-refundable bid-processing fee, will be rejected, without exception. Faxed and/or electronically submitted proposals will not be accepted.
7. Bid Opening: Bids will be opened at 2:00 p.m. local time on July 9, 2003, at the Division of Purchases, Burton Cross Building, 4th Floor, 111 Sewall Street, Augusta, Maine 04333.
8. Award: The State Planning Office plans to announce the successful bidder of this landfill operator proposal, if any, on or before August 15, 2003.
9. Questions: Any questions regarding the RFP must be submitted in writing to the contact person listed below on or before June 25, 2003:

George MacDonald
State Planning Office
Waste Management & Recycling Program
38 State House Station
Augusta, ME 04333-0038
george.macdonald@maine.gov

All persons requesting a copy of this RFP will be mailed a complete packet of all submitted questions and responses on or before July 1, 2003.

Disclosure of data: *According to State procurement law, the content of all proposals, correspondence, addenda, memoranda, working papers, or any other medium which discloses*

III. Scope of Services

The Scope of Services under this contract will include those listed below. The landfill will be operated on a basis consistent with the State's waste management hierarchy, which establishes the following priority for the management of wastes: Reduce, Reuse, Recycle, Compost, Incinerate, Landfill. Proposals shall include how the operator intends to implement this hierarchy in regard to the wastes that will be accepted at the landfill, other than those waste streams and volumes currently being disposed of at the landfill. The successful bidder will be expected to enter into agreements for the fulfillment of the services and related actions as presented below, as may be modified upon mutual agreement, within the proposal.

Contract Period: No fewer than 15 and no more than 30 years, but bidders may propose a term of years falling between 15 and 30 years in length. The successful bidder will be expected to enter into a standard State of Maine Agreement to Purchase Services (BP54), a blank copy of which is attached to this RFP for informational purposes as *Exhibit E*. Submission of a proposal in response to this RFP will be understood as the Bidder's acceptance of the standard contract's terms and conditions.

1. Contract Period: No fewer than 15 and no more than 30 years, but bidders may propose a term of years falling between 15 and 30 years in length.
2. Services to GP: The operator will enter into agreements with GP to provide the following services:
    a. Solid Waste Disposal:
        i. The operator will provide disposal capacity to GP and to any successor operator of GP's current Old Town paper mill for (a) all mill waste currently licensed for disposal at the landfill from the GP paper mill in Old Town, and (b) non-hazardous ash from the proposed GP biomass facility for the duration of the contract.
        ii. GP's tipping fees for its mill waste and biomass facility ash will be fixed for the term of the contract as follows: (a) tipping fee for the first 50,000 tons per year of mill wastes and ash will be a maximum of $10 per ton for the first 5 years, and thereafter, for the duration of the contract, adjusted with an annual CPIU (U.S.-national) escalator. The tipping fee for mill wastes and ash beyond 50,000 but less than 75,000 tons shall be a maximum of $40.00 per ton for the first 5 years, and thereafter, for the duration of the contract, adjusted with an annual CPIU (U.S.-national) escalator. Tipping fees for mill wastes and biomass ash over the 75,000 ton maximum will be assessed a tip fee at the then prevailing market rate. The annual escalator for mill waste shall carry a floor of 1% and will be capped at 5% per year.
        iii. Assumption of the contract between GP and Lincoln Pulp and Paper ("Lincoln") under which GP agreed to accept the biomass ash from Lincoln (or its successor at its Lincoln mill) for up to 6000 tons per year at no cost until such time as the current built capacity of the Landfill is filled. Thereafter, the operator will provide disposal for that quantity of biomass ash from Lincoln on the same terms as biomass ash is disposed of from the Georgia-Pacific mill.
        iv. The operator will provide GP with a credit for unused disposal capacity if mill waste and biomass ash disposed is less than 50,000 tons per year. This credit will be extended by allowing GP, at its option, to (a) during any year

Legislative Committee Records

Resolve: State Purchase of Landfill

Includes Statements of Support

And Text of Resolve as Passed

ACTIVITY SHEET

COMMITTEE: Natural Resources

LD #: LD 1626

TITLE Resolve, To Authorize the State To Purchase a Landfill in the City of Old Town

* * *

HEARING DATE: 6/03/03

WORK SESSION DATES: 6/4/03

REPORTED OUT DATE: 6/11/03

COMMITTEE REPORT: OTP-AM - ONTP

TESTIMONY SIGN IN SHEET

Joint Standing Committee on Natural Resources

LD: ____1626____

Date: _____June 3, 2003

Name	Town/Affiliation	Proponent	Opponent	Neither
DUNLAP	OLD TOWN	✓		
George MacDonald	SPO	✓		
John Lord	City of Old Town	✓		
Jack Cashman	Gov. office	✓		
Alan Reynolds	City of Old Town	✓		
Grey				
James E. Bostic Jr	GP	✓		
Ralph Feck	G.P.	✓		
Mike St. Peter	G.P. Local 80	✓		

TESTIMONY OF
GEORGE MACDONALD, MANAGER

WASTE MANAGEMENT AND RECYCLING PROGRAM
MAINE STATE PLANNING OFFICE

SPEAKING IN SUPPORT OF LD 1626

"Resolve, To Authorize the State to Purchase a Landfill in the City of Old Town"
HEARING: June 3, 2003

Honorable Senator Martin, Honorable Representative Koffman, Distinguished Members of the Natural Resources Committee:

I am George MacDonald, Manager of the Waste Management & Recycling Program at the State Planning Office. I am here today to testify in support of LD 1626.

State law directs the State Planning Office to plan for the development of disposal facilities sufficient to meet the needs of the State, as well as to recommend such facilities' development when four years or fewer of disposal capacity remains within the State. That policy guided the State's acquisition of the landfill site in T 2 R 8, commonly referred to as 'Carpenter Ridge', and that policy remains in effect today.

What is now before us is the unique opportunity to address an array of needs, locally and statewide. The proposed purchase of this operating landfill is part of the ongoing discussions with the current owners of the paper mill in Old Town, the Georgia-Pacific Corporation. Significantly, however, the purchase of this operating landfill not only will assist in these discussions with Georgia-Pacific, but also will provide the State with a well-qualified landfill site – one that is well situated and in compliance with rules and regulations promulgated by the Maine Department of Environmental Protection that are applicable to landfill operations.

During the current Legislative session, this Committee supported a bill, L.D. 803, which directed the State Planning Office to search for additional disposal capacity within the State, and then report our search progress and recommendations back to you within six months. Even though that bill has died, perhaps your commitment to the underlying goal and concept of that legislation can support the Resolve before you.

The intent of this Office is for the State of Maine to own this landfill, and, through the use of contracts:

- Ensure that the landfill is in full compliance with DEP rules and regulations, pertaining to both siting and operations of landfills;
- Provide long-term disposal options for the Old Town paper mill and entities with which that mill has contracts, for the current type and volume of waste being filled at the site;
- Engage the services of a qualified landfill operator to manage the site;
- Enter into a "Host Community Benefit" agreement with the City of Old Town;
- Recognize and address market power concerns related to the operation of the landfill;
- Support the waste management hierarchy in the State, to the greatest degree possible;
- Permit the delivery of other acceptable wastes to the site; and,
- Structure this arrangement to reduce the state's liability, financially and environmentally, to the greatest extent possible.

Our hope is that, with your support, we will be able to achieve this acquisition.

At this point, others and I are willing to try to answer questions you may have about this opportunity the State now has before it.

Thank you.

10

Waste Management

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Table of Contents

EXECUTIVE SUMMARY

Post-consumer waste is a small contributor to global greenhouse gas (GHG) emissions (<5%) with total emissions of approximately 1300 $MtCO_2$-eq in 2005. The largest source is landfill methane (CH_4), followed by wastewater CH_4 and nitrous oxide (N_2O); in addition, minor emissions of carbon dioxide (CO_2) result from incineration of waste containing fossil carbon (C) (plastics; synthetic textiles) (high evidence, high agreement). There are large uncertainties with respect to direct emissions, indirect emissions and mitigation potentials for the waste sector. These uncertainties could be reduced by consistent national definitions, coordinated local and international data collection, standardized data analysis and field validation of models (medium evidence, high agreement). With respect to annual emissions of fluorinated gases from post-consumer waste, there are no existing national inventory methods for the waste sector, so these emissions are not currently quantified. If quantified in the future, recent data indicating anaerobic biodegradation of chlorofluorocarbons (CFCs) and hydrochlorofluorocarbons (HCFCs) in landfill settings should be considered (low evidence, high agreement).

Existing waste-management practices can provide effective mitigation of GHG emissions from this sector: a wide range of mature, environmentally-effective technologies are available to mitigate emissions and provide public health, environmental protection, and sustainable development co-benefits. Collectively, these technologies can directly reduce GHG emissions (through landfill gas recovery, improved landfill practices, engineered wastewater management) or avoid significant GHG generation (through controlled composting of organic waste, state-of-the-art incineration and expanded sanitation coverage) (high evidence, high agreement). In addition, waste minimization, recycling and re-use represent an important and increasing potential for indirect reduction of GHG emissions through the conservation of raw materials, improved energy and resource efficiency and fossil fuel avoidance (medium evidence, high agreement).

Because waste management decisions are often made locally without concurrent quantification of GHG mitigation, the importance of the waste sector for reducing global GHG emissions has been underestimated (medium evidence, high agreement). Flexible strategies and financial incentives can expand waste management options to achieve GHG mitigation goals – in the context of integrated waste management, local technology decisions are a function of many competing variables, including waste quantity and characteristics, cost and financing issues, infrastructure requirements including available land area, collection and transport considerations, and regulatory constraints. Life cycle assessment (LCA) can provide decision-support tools (high evidence, high agreement).

Commercial recovery of landfill CH_4 as a source of renewable energy has been practised at full scale since 1975 and currently exceeds 105 $MtCO_2$-eq. yr. Because of landfill gas recovery and complementary measures (increased recycling, decreased landfilling, use of alternative waste-management technologies), landfill CH_4 emissions from developed countries have been largely stabilized (high evidence, high agreement). However, landfill CH_4 emissions from developing countries are increasing as more controlled (anaerobic) landfilling practices are implemented; these emissions could be reduced by both accelerating the introduction of engineered gas recovery and encouraging alternative waste management strategies (medium evidence, medium agreement).

Incineration and industrial co-combustion for waste-to-energy provide significant renewable energy benefits and fossil fuel offsets. Currently, >130 million tonnes of waste per year are incinerated at over 600 plants (high evidence, high agreement). Thermal processes with advanced emission controls are proven technology but more costly than controlled landfilling with landfill gas recovery; however, thermal processes may become more viable as energy prices increase. Because landfills produce CH_4 for decades, incineration, composting and other strategies that reduce landfilled waste are complementary mitigation measures to landfill gas recovery in the short- to medium-term (medium evidence, medium agreement).

Aided by Kyoto mechanisms such as the Clean Development Mechanism (CDM) and Joint Implementation (JI), as well as other measures to increase worldwide rates of landfill CH_4 recovery, the total global economic mitigation potential for reducing landfill CH_4 emissions in 2030 is estimated to be >1000 $MtCO_2$-eq (or 70% of estimated emissions) at costs below 100 US\$/tCO_2-eq/yr. Most of this potential is achievable at negative to low costs: 20–30% of projected emissions for 2030 can be reduced at negative cost and 30–50% at costs <20 US\$/tCO_2-eq/yr. At higher costs, more significant emission reductions are achievable, with most of the additional mitigation potential coming from thermal processes for waste-to-energy (medium evidence, medium agreement).

Increased infrastructure for wastewater management in developing countries can provide multiple benefits for GHG mitigation, improved public health, conservation of water resources, and reduction of untreated discharges to surface water, groundwater, soils and coastal zones. There are numerous mature technologies that can be implemented to improve wastewater collection, transport, re-use, recycling, treatment and residuals management (high evidence, high agreement). With respect to both waste and wastewater management for developing countries, key constraints on sustainable development include the local availability of capital as well as the selection of appropriate and truly sustainable technology in a particular setting (high evidence, high agreement).

10.1 Introduction

Waste generation is closely linked to population, urbanization and affluence. The archaeologist E.W. Haury wrote: 'Whichever way one views the mounds [of waste], as garbage piles to avoid, or as symbols of a way of life, they…are the features more productive of information than any others.' (1976, p.80). Archaeological excavations have yielded thicker cultural layers from periods of prosperity; correspondingly, modern waste-generation rates can be correlated to various indicators of affluence, including gross domestic product (GDP)/cap, energy consumption/cap, , and private final consumption/cap (Bingemer and Crutzen, 1987; Richards, 1989; Rathje et al., 1992; Mertins et al., 1999; US EPA, 1999; Nakicenovic et al., 2000; Bogner and Matthews, 2003; OECD, 2004). In developed countries seeking to reduce waste generation, a current goal is to decouple waste generation from economic driving forces such as GDP (OECD, 2003; Giegrich and Vogt, 2005; EEA, 2005). In most developed and developing countries with increasing population, prosperity and urbanization, it remains a major challenge for municipalities to collect, recycle, treat and dispose of increasing quantities of solid waste and wastewater. A cornerstone of sustainable development is the establishment of affordable, effective and truly sustainable waste management practices in developing countries. It must be further emphasized that multiple public health, safety and environmental co-benefits accrue from effective waste management practices which concurrently reduce GHG emissions and improve the quality of life, promote public health, prevent water and soil contamination, conserve natural resources and provide renewable energy benefits.

The major GHG emissions from the waste sector are landfill CH_4 and, secondarily, wastewater CH_4 and N_2O. In addition, the incineration of fossil carbon results in minor emissions of CO_2. Chapter 10 focuses on mitigation of GHG emissions from post-consumer waste, as well as emissions from municipal wastewater and high biochemical oxygen demand (BOD) industrial wastewaters conveyed to public treatment facilities. Other chapters in this volume address pre-consumer GHG emissions from waste within the industrial (Chapter 7) and energy (Chapter 4) sectors which are managed within those respective sectors. Other chapters address agricultural wastes and manures (Chapter 8), forestry residues (Chapter 9) and related energy supply issues including district heating (Chapter 6) and transportation biofuels (Chapter 5). National data are not available to quantify GHG emissions associated with waste transport, including reductions that might be achieved through lower collection frequencies, higher routing efficiencies or substitution of renewable fuels; however, all of these measures can be locally beneficial to reduce emissions.

It should be noted that a separate chapter on post-consumer waste is new for the Fourth Assessment report; in the Third Assessment Report (TAR), GHG mitigation strategies for waste were discussed primarily within the industrial sector (Ackerman, 2000; IPCC, 2001a). It must also be stressed that there are high uncertainties regarding global GHG emissions from waste which result from national and regional differences in definitions, data collection and statistical analysis. Because of space constraints, this chapter does not include detailed discussion of waste management technologies, nor does this chapter prescribe to any one particular technology. Rather, this chapter focuses on the GHG mitigation aspects of the following strategies: landfill CH_4 recovery and utilization; optimizing methanotrophic CH_4 oxidation in landfill cover soils; alternative strategies to landfilling for GHG avoidance (composting; incineration and other thermal processes; mechanical and biological treatment (MBT)); waste reduction through recycling, and expanded wastewater management to minimize GHG generation and emissions. In addition, using available but very limited data, this chapter will discuss emissions of non-methane volatile organic compounds (NMVOCs) from waste and end-of-life issues associated with fluorinated gases.

The mitigation of GHG emissions from waste must be addressed in the context of integrated waste management. Most technologies for waste management are mature and have been successfully implemented for decades in many countries. Nevertheless, there is significant potential for accelerating both the direct reduction of GHG emissions from waste as well as extended implications for indirect reductions within other sectors. LCA is an essential tool for consideration of both the direct and indirect impacts of waste management technologies and policies (Thorneloe et al., 2002; 2005; WRAP, 2006). Because direct emissions represent only a portion of the life cycle impacts of various waste management strategies (Ackerman, 2000), this chapter includes complementary strategies for GHG avoidance, indirect GHG mitigation and use of waste as a source of renewable energy to provide fossil fuel offsets. Using LCA and other decision-support tools, there are many combined mitigation strategies that can be cost-effectively implemented by the public or private sector. Landfill CH_4 recovery and optimized wastewater treatment can directly reduce GHG emissions. GHG generation can be largely avoided through controlled aerobic composting and thermal processes such as incineration for waste-to-energy. Moreover, waste prevention, minimization, material recovery, recycling and re-use represent a growing potential for indirect reduction of GHG emissions through decreased waste generation, lower raw material consumption, reduced energy demand and fossil fuel avoidance. Recent studies (e.g., Smith et al., 2001; WRAP, 2006) have begun to comprehensively quantify the significant benefits of recycling for indirect reductions of GHG emissions from the waste sector.

Post-consumer waste is a significant renewable energy resource whose energy value can be exploited through thermal processes (incineration and industrial co-combustion), landfill gas utilization and the use of anaerobic digester biogas. Waste has an economic advantage in comparison to many biomass resources because it is regularly collected at public expense

(See also Section 11.3.1.4). The energy content of waste can be more efficiently exploited using thermal processes than with the production of biogas: during combustion, energy is directly derived both from biomass (paper products, wood, natural textiles, food) and fossil carbon sources (plastics, synthetic textiles). The heating value of mixed municipal waste ranges from <6 to >14 MJ/kg (Khan and Abu-Ghararath, 1991; EIPPC Bureau, 2006). Thermal processes are most effective at the upper end of this range where high values approach low-grade coals (lignite). Using a conservative value of 900 Mt/yr for total waste generation in 2002 (discussed in Box 10.1 below), the energy potential of waste is approximately 5–13 EJ/yr. Assuming an average heating value of 9 GJ/t for mixed waste (Dornburg and Faaij, 2006) and converting to energy equivalents, global waste in 2002 contained about 8 EJ of available energy, which could increase to 13 EJ in 2030 using waste projections in Monni et al. (2006). Currently, more than 130 million tonnes per year of waste are combusted worldwide (Themelis, 2003), which is equivalent to >1 EJ/yr (assuming 9 GJ/t). The biogas fuels from waste – landfill gas and digester gas – typically have a heating value of 16–22 MJ/Nm³, depending directly on the CH_4 content. Both are used extensively worldwide for process heating and on-site electrical generation; more rarely, landfill gas may be upgraded to a substitute natural gas product. Conservatively, the energy value of landfill gas currently being utilized is >0.2 EJ/yr (using data from Willumsen, 2003).

An overview of carbon flows through waste management systems addresses the issue of carbon storage versus carbon turnover for major waste-management strategies including landfilling, incineration and composting (Figure 10.1). Because landfills function as relatively inefficient anaerobic digesters, significant long-term carbon storage occurs in landfills, which is addressed in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Landfill CH_4 is the major gaseous C emission from waste; there are also minor emissions of CO_2 from incinerated fossil carbon (plastics). The CO_2 emissions from biomass sources – including the CO_2 in landfill gas, the CO_2 from composting, and CO_2 from incineration of waste biomass – are not taken into account in GHG inventories as these are covered by changes in biomass stocks in the land-use, land-use change and forestry sectors.

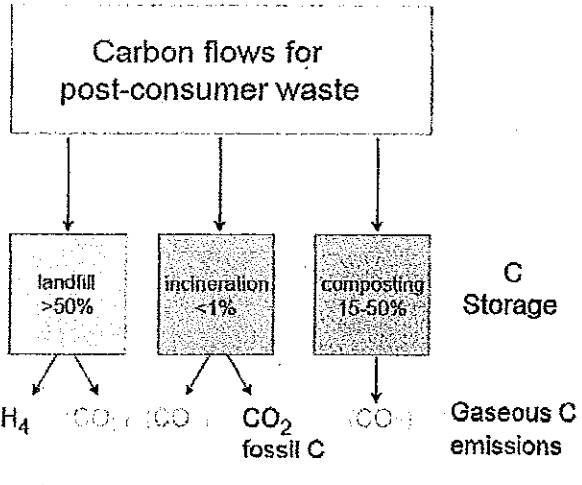

Figure 10.1: Carbon flows through major waste management systems including C storage and gaseous C emissions. The CO_2 from biomass is not included in GHG inventories for waste

References for C storage are: Huber-Humer 2004; Zinati et al., 2001; Barlaz, 1998; Bramryd, 1997; Bogner, 1992.

A process-oriented perspective on the major GHG emissions from the waste sector is provided in Figure 10.2. In the context of a landfill CH_4 mass balance (Figure 10.2a), emissions are one of several possible pathways for the CH_4 produced by anaerobic methanogenic microorganisms in landfills; other pathways include recovery, oxidation by aerobic methanotrophic microorganisms in cover soils, and two longer-term pathways: lateral migration and internal storage (Bogner and Spokas, 1993; Spokas et al., 2006). With regard to emissions from wastewater transport and treatment (Figure 10.2b), the CH_4 is microbially produced under strict anaerobic conditions as in landfills, while the N_2O is an intermediate product of microbial nitrogen cycling promoted by conditions of reduced aeration, high moisture and abundant nitrogen. Both GHGs can be produced and emitted at many stages between wastewater sources and final disposal.

It is important to stress that both the CH_4 and N_2O from the waste sector are microbially produced and consumed with rates controlled by temperature, moisture, pH, available substrates, microbial competition and many other factors. As a result, CH_4 and N_2O generation, microbial consumption, and net emission rates routinely exhibit temporal and spatial variability over many orders of magnitude, exacerbating the problem of developing credible national estimates. The N_2O from landfills is considered an insignificant source globally (Bogner et al., 1999; Rinne et al., 2005), but may need to be considered locally where cover soils are amended with sewage sludge (Borjesson and Svensson, 1997a) or aerobic/semi-aerobic landfilling practices are implemented (Tsujimoto et al., 1994). Substantial emissions of CH_4 and N_2O can occur during wastewater transport in closed sewers and in conjunction with anaerobic or aerobic treatment. In many developing countries, in addition to GHG emissions, open sewers and uncontrolled solid waste disposal sites result in serious public health problems resulting from pathogenic microorganisms, toxic odours and disease vectors.

Major issues surrounding the costs and potentials for mitigating GHG emissions from waste include definition of system boundaries and selection of models with correct baseline assumptions and regionalized costs, as discussed in the TAR (IPCC, 2001a). Quantifying mitigation costs and potentials (Section 10.4.7) for the waste sector remains a challenge due to national and regional data uncertainties as well as the variety of mature technologies whose diffusion is limited by local costs, policies, regulations, available land area, public perceptions and other social development factors. Discussion of technologies

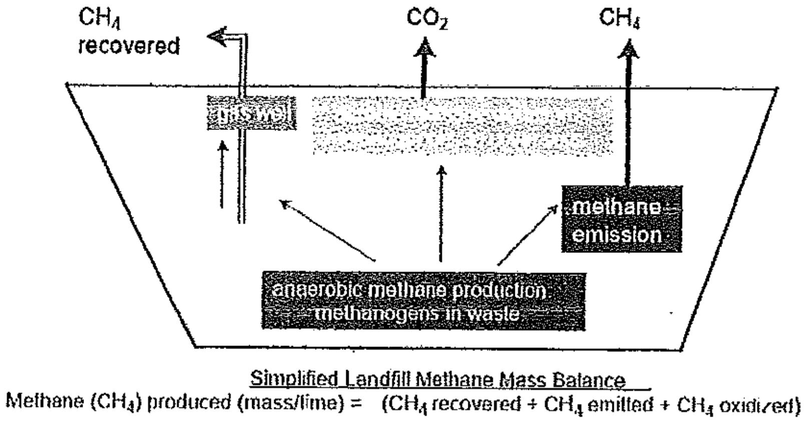

Figure 10.2: Pathways for GHG emissions from landfills and wastewater systems

Figure 10.2a: Simplified landfill CH4 mass balance pathways for CH_4 generated in landfilled waste, including CH_4 emitted, recovered and oxidized.
Note: Not shown are two longer-term CH_4 pathways: lateral CH4 mitigation and internal changes in CH_4 storage (Bogner and Spokas, 1993; Spokas et al., 2006) Methane can be stored in shallow sediments for several thousand years (Coleman, 1979).

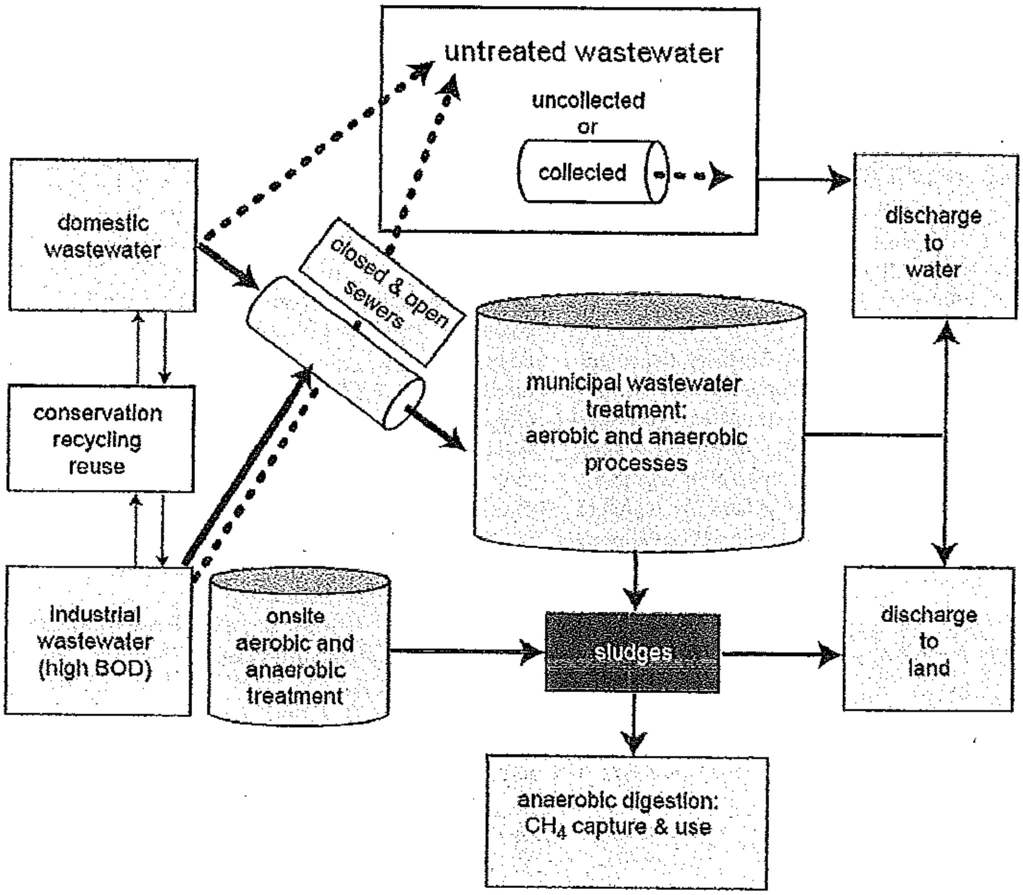

Figure 10.2b: Overview of wastewater systems
Note: The major GHG emissions from wastewater – CH_4 and N_2O – can be emitted during all stages from sources to disposal, but especially when collection and treatment are lacking. N_2O results from microbial N cycling under reduced aeration; CH_4 results from anaerobic microbial decomposition of organic C substrates in soils, surface waters or coastal zones.

and mitigation strategies in this chapter (Section 10.4) includes a range of approaches from low-technology/low-cost to high-technology/high-cost measures. Often there is no single best option: rather, there are multiple measures available to decision-makers at the municipal level where several technologies may be collectively implemented to reduce GHG emissions and achieve public health, environmental protection and sustainable development objectives.

10.2 Status of the waste management sector

10.2.1 Waste generation

The availability and quality of annual data are major problems for the waste sector. Solid waste and wastewater data are lacking for many countries, data quality is variable, definitions are not uniform, and interannual variability is often not well quantified. There are three major approaches that have been used to estimate global waste generation: 1) data from national waste statistics or surveys, including IPCC methodologies (IPCC, 2006); 2) estimates based on population (e.g., SRES waste scenarios), and 3) the use of a proxy variable linked to demographic or economic indicators for which national data are annually collected. The SRES waste scenarios, using population as the major driver, projected continuous increases in waste and wastewater CH_4 emissions to 2030 (A1B-AIM), 2050 (B1-AIM), or 2100 (A2-ASF; B2-MESSAGE), resulting in current and future emissions significantly higher than those derived from IPCC inventory procedures (Nakicenovic et al., 2000) (See also Section 10.3). A major reason is that waste generation rates are related to affluence as well as population – richer societies are characterized by higher rates of waste generation per capita, while less affluent societies generate less waste and practise informal recycling/re-use initiatives that reduce the waste per capita to be collected at the municipal level. The third strategy is to use proxy or surrogate variables based on statistically significant relationships between waste generation per capita and demographic variables, which encompass both population and affluence, including GDP per capita (Richards, 1989; Mertins et al., 1999) and energy consumption per capita (Bogner and Matthews, 2003). The use of proxy variables, validated using reliable datasets, can provide a cross-check on uncertain national data. Moreover, the use of a surrogate provides a reasonable methodology for a large number of countries where data do not exist, a consistent methodology for both developed and developing countries and a procedure that facilitates annual updates and trend analysis using readily available data (Bogner and Matthews, 2003). The box below illustrates 1971–2002 trends for regional solid-waste generation using the surrogate of energy consumption per capita. Using UNFCCC-reported values for percentage biodegradable organic carbon in waste for each country, this box also shows trends for landfill carbon storage based upon the reported data.

Solid waste generation rates range from <0.1 t/cap/yr in low-income countries to >0.8 t/cap/yr in high-income industrialized countries (Table 10.1). Even though labour costs are lower in developing countries, waste management can constitute a larger percentage of municipal income because of higher equipment and fuel costs (Cointreau-Levine, 1994). By 1990, many developed countries had initiated comprehensive recycling programmes. It is important to recognize that the percentages of waste recycled, composted, incinerated or landfilled differ greatly amongst municipalities due to multiple factors, including local economics, national policies, regulatory restrictions, public perceptions and infrastructure requirements

Box 10.1: 1971–2002 Regional trends for solid waste generation and landfill carbon storage using a proxy variable.

Solid-waste generation rates are a function of both population and prosperity, but data are lacking or questionable for many countries. This results in high uncertainties for GHG emissions estimates, especially from developing countries. One strategy is to use a proxy variable for which national statistics are available on an annual basis for all countries. For example, using national solid-waste data from 1975–1995 that were reliably referenced to a given base year, Bogner and Matthews (2003) developed simple linear regression models for waste generation per capita for developed and developing countries. These empirical models were based on energy consumption per capita as an indicator of affluence and a proxy for waste generation per capita; the surrogate relationship was applied to annual national data using either total population (developed countries) or urban population (developing countries). The methodology was validated using post-1995 data which had not been used to develop the original model relationships. The results by region for 1971–2002 (Figure 10.3a) indicate that approximately 900 Mt of waste were generated in 2002. Unlike projections based on population alone, this figure also shows regional waste-generation trends that decrease and increase in tandem with major economic trends. For comparison, recent waste-generation estimates by Monni et al. (2006) using 2006 inventory guidelines, indicated about 1250 Mt of waste generated in 2000. Figure 10.3b showing annual carbon storage in landfills was developed using the same base data as Figure 10.3a with the percentage of landfilled waste for each country (reported to UNFCCC) and a conservative assumption of 50% carbon storage (Bogner, 1992; Barlaz, 1998). This storage is long-term: under the anaerobic conditions in landfills, lignin does not degrade significantly (Chen et al., 2004), while some cellulosic fractions are also non-degraded. The annual totals for the mid-1980s and later (>30 MtC/yr) exceed estimates in the literature for the annual quantity of organic carbon partitioned to long-term geologic storage in marine environments as a precursor to future fossil fuels (Bogner, 1992). It should be noted that the anaerobic burial of waste in landfills (with resulting carbon storage) has been widely implemented in developed countries only since the 1960s and 1970s.

Box 10.1 continued

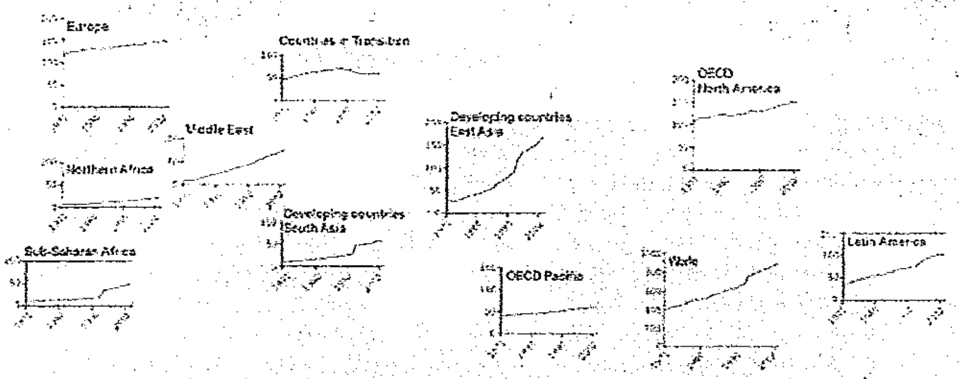

Figure 10.3a: Annual rates of post-consumer waste generation 1971 2002 (Tg) using energy consumption surrogate.

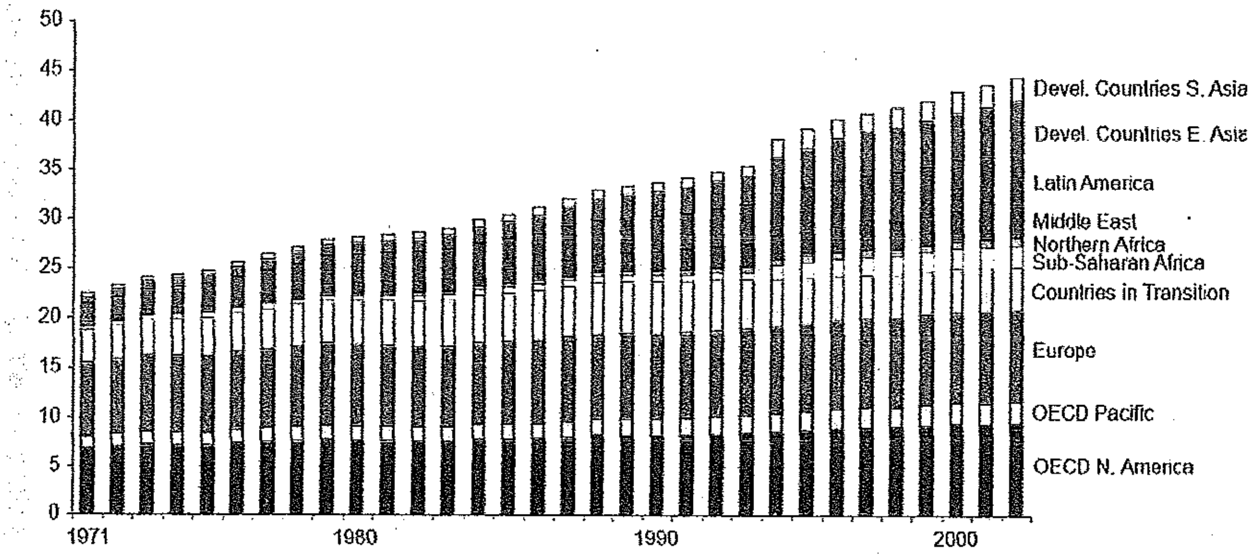

Figure 10.3b: Minimum annual rates of carbon storage in landfills from 1971 2002 (Tg C).

Table 10.1: Municipal solid waste-generation rates and relative income levels

Country	Low income	Middle income	High income
Annual income (US$/cap/yr)	825-3255	3256-10065	>10066
Municipal solid waste generation rate (t/cap/yr)	0.1-0.6	0.2-0.5	0.3 to >0.8

Note: Income levels as defined by World Bank (www.worldbank.org/data/wdi2005).

Sources: Bernache-Perez et al., 2001; CalRecovery, 2004, 2005; Diaz and Eggerth, 2002, Griffiths and Williams, 2005, Idris et al., 2003, Kaseva et al., 2002, Ojeda-Benitez and Beraud-Lozano 2003; Huang et al., 2006; US EPA 2003.

10.2.2 Wastewater generation

Most countries do not compile annual statistics on the total volume of municipal wastewater generated, transported and treated. In general, about 60% of the global population has sanitation coverage (sewerage) with very high levels (>90%) characteristic for the population of North America (including Mexico), Europe and Oceania, although in the last two regions rural areas decrease to approximately 75% and 80%, respectively (DESA, 2005; Jouravlev, 2004; PNUD, 2005; WHO/UNICEF/WSSCC, 2000, WHO-UNICEF, 2005; World Bank, 2005a). In developing countries, rates of sewerage are very low for rural areas of Africa, Latin America and Asia, where septic tanks and latrines predominate. For 'improved sanitation' (including sewerage + wastewater treatment, septic tanks and latrines), almost 90% of the population in developed countries, but only about 30% of the population in developing countries, has access to improved sanitation (Jouravlev, 2004; World Bank, 2005a, b). Many countries in Eastern Europe and Central Asia lack reliable benchmarks for the early 1990s. Regional trends (Figure 10.4) indicate improved sanitation levels of <50% for Eastern and Southern Asia and Sub-Saharan Africa (World Bank and IMF, 2006). In Sub-Saharan Africa, at least 450 million people lack adequate sanitation. In both Southern and Eastern Asia, rapid urbanization is posing a challenge for the development of wastewater infrastructure. The highly urbanized region of Latin America and the Caribbean has also made slow progress in providing wastewater treatment. In the Middle East and North Africa, the countries of Egypt, Tunesia and Morocco have made significant progress in expanding wastewater-treatment infrastructure (World Bank and IMF, 2006). Nevertheless, globally, it has been estimated that 2.6 billion people lack improved sanitation (WHO-UNICEF, 2005).

Estimates for CH_4 and N_2O emissions from wastewater treatment require data on degradable organic matter (BOD: COD[1]) and nitrogen. Nitrogen content can be estimated using Food and Agriculture Organization (FAO) data on protein consumption, and either the application of wastewater treatment, or its absence, determines the emissions. Aerobic treatment plants produce negligible or very small emissions, whereas in anaerobic lagoons or latrines 50–80% of the CH_4 potential can be produced and emitted. In addition, one must take into account the established infrastructure for wastewater treatment in developed countries and the lack of both infrastructure and financial resources in developing countries where open sewers or informally ponded wastewaters often result in uncontrolled discharges to surface water, soils, and coastal zones, as well as the generation of N_2O and CH_4. The majority of urban wastewater treatment facilities are publicly operated and only about 14% of the total private investment in water and sewerage in the late 1990s was applied to the financing of wastewater collection and treatment, mainly to protect drinking water supplies (Silva, 1998; World Bank 1997).

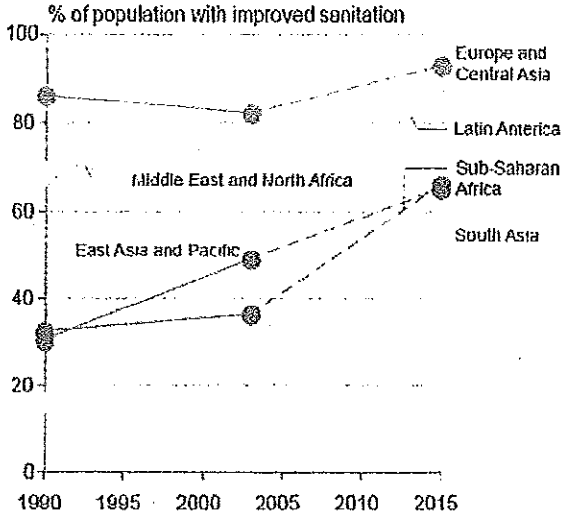

Figure 10.4: Regional data for 1990 and 2003 with 2015 Millenium Development Goal (MDG) targets for the share of population with access to improved sanitation (sewerage + wastewater treatment, septic system, or latrine)

Source: World Bank and IMF (2006)

Most wastewaters within the industrial and agricultural sectors are discussed in Chapters 7 and 8, respectively. However, highly organic industrial wastewaters are addressed in this chapter, because they are frequently conveyed to municipal treatment facilities. Table 10.2 summarizes estimates for total and regional 1990 and 2001 generation in terms of kilograms of BOD per day or kilograms of BOD per worker per day, based on measurements of plant-level water quality (World Bank, 2005a). The table indicates that total global generation decreased >10% between 1990 and 2001; however, increases of 15% or more were observed for the Middle East and the developing countries of South Asia.

10.2.3 Development trends for waste and wastewater

Waste and wastewater management are highly regulated within the municipal infrastructure under a wide range of existing regulatory goals to protect human health and the environment; promote waste minimization and recycling; restrict certain types of waste management activities; and reduce impacts to residents, surface water, groundwater and soils. Thus, activities related to waste and wastewater management are, and will continue to be, controlled by national regulations, regional restrictions, and local planning guidelines that address waste and wastewater transport, recycling, treatment, disposal, utilization, and energy use. For developing countries, a wide range of waste management legislation and policies have been implemented with evolving structure and enforcement; it is expected that regulatory frameworks in developing countries will become more stringent in parallel with development trends.

Depending on regulations, policies, economic priorities and practical local limits, developed countries will be characterized by increasingly higher rates of waste recycling and pre-treatment to conserve resources and avoid GHG generation. Recent studies have documented recycling levels of >50%

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[1] BOD (Biological or Biochemical Oxygen Demand) measures the quantity of oxygen consumed by aerobically biodegradable organic C in wastewater. COD (Chemical Oxygen Demand) measures the quantity of oxygen consumed by chemical oxidation of C in wastewater (including both aerobic/anaerobic biodegradable and non-biodegradable C).

Table 10.2: Regional and global 1990 and 2001 generation of high BOD industrial wastewaters often treated by municipal wastewater systems.

Regions	Kg BOD/day [Total, Rounded] (1000s)		Kg BOD/worker/ day		Primary metals (%)	Paper and pulp (%)	Chemicals (%)	Food and beverages (%)	Textiles (%)
Year	1990	2001	1990	2001	2001	2001	2001	2001	2001
1. OECD North America	3100	2600	0.20	0.17	9	15	11	44	7
2. OECD Pacific	2200	1700	0.15	0.18	8	20	6	46	7
3. Europe	5200	4800	0.18	0.17	9	22	9	40	7
4. Countries in transition	3400	2400	0.15	0.21	13	8	6	50	14
5. Sub-Saharan Africa	590	510	0.23	0.25	3	12	6	60	13
6. North Africa	410	390	0.20	0.18	10	4	6	50	25
7. Middle East	260	300	0.19	0.19	9	12	10	52	11
8. Caribbean, Central and South America	1500	1300	0.23	0.24	5	11	8	61	11
9. Developing countries, East Asia	8300	7700	0.14	0.16	11	14	10	36	15
10. Developing countries, South Asia	1700	2000	0.18	0.16	5	7	6	42	35
Total for 1-4 (developed)	13900	11500							
Total for 5-10 (developing)	12800	12200							

Note: Percentages are included for major industrial sectors (all other sectors <10% of total BOD).
Source: World Bank, 2005a.

for specific waste fractions in some developed countries (i.e., Swedish Environmental Protection Agency, 2005). Recent US data indicate about 25% diversion, including more than 20 states that prohibit landfilling of garden waste (Simmons et al., 2006). In developing countries, a high level of labour-intensive informal recycling often occurs. Via various diversion and small-scale recycling activities, those who make their living from decentralized waste management can significantly reduce the mass of waste that requires more centralized solutions; however, the challenge for the future is to provide safer, healthier working conditions than currently experienced by scavengers on uncontrolled dumpsites. Available studies indicate that recycling activities by this sector can generate significant employment, especially for women, through creative microfinance and other small-scale investments. For example, in Cairo, available studies indicate that 7–8 daily jobs per ton of waste and recycling of >50% of collected waste can be attained (Iskandar, 2001).

Trends for sanitary landfilling and alternative waste-management technologies differ amongst countries. In the EU, the future landfilling of organic waste is being phased out via the landfill directive (Council Directive 1999/31/EC), while engineered gas recovery is required at existing sites (EU, 1999). This directive requires that, by 2016, the mass of biodegradable organic waste annually landfilled must be reduced 65% relative to landfilled waste in 1995. Several countries (Germany, Austria, Denmark, Netherlands, Sweden) have accelerated the EU schedule through more stringent bans on landfilling of organic waste. As a result, increasing quantities of post-consumer waste are now being diverted to incineration, as well as to MBT before landfilling to 1) recover recyclables and 2) reduce the organic carbon content by a partial aerobic composting or anaerobic digestion (Stegmann, 2005). The MBT residuals are often, but not always, landfilled after achieving organic carbon reductions to comply with the EU landfill directive. Depending on the types and quality control of various separation and treatment processes, a variety of useful recycled streams are also produced. Incineration for waste-to-energy has been widely implemented in many European countries for decades. In 2002, EU WTE plants generated 41 million GJ of electrical energy and 110 million GJ of thermal energy (Themelis, 2003). Rates of incineration are expected to increase in parallel with implemention of the landfill directive, especially in countries such as the UK with historically lower rates of incineration compared to other European countries. In North America, Australia and New Zealand, controlled landfilling is continuing as a dominant method for large-scale waste disposal with mandated compliance to both landfilling and air-quality regulations. In parallel, larger quantities of landfill CH_4 are annually being recovered, both to comply with air-quality regulations and to provide energy, assisted by national tax credits and local renewable-energy/green power initiatives (see Section 10.5). The US, Canada, Australia and other countries are currently studying and considering the widespread implementation of 'bioreactor' landfills to compress the time period during which high rates of CH_4 generation occur (Reinhart and Townsend, 1998; Reinhart et al., 2002; Berge et al., 2005); bioreactors will also require the early implementation of engineered gas extraction. Incineration has not been widely implemented in these countries due to historically low landfill tipping fees in many regions, negative public perceptions and high capital costs. In Japan, where open space is very limited for construction of waste management infrastructure, very high rates of both recycling and incineration are practised and are expected to continue into the future. Historically, there have also been 'semi-aerobic' Japanese landfills with potential for N_2O generation (Tsujimoto et al., 1994). Similar aerobic (with air) landfill practices have also been studied or implemented in Europe and the US for reduced CH_4 generation rates as an alternative to, or in combination with, anaerobic (without air) practices (Ritzkowski and Stegmann, 2005).

In many developing countries, current trends suggest that increases in controlled landfilling resulting in anaerobic decomposition of organic waste will be implemented in parallel with increased urbanization. For rapidly growing 'mega cities', engineered landfills provide a waste disposal solution that is more environmentally acceptable than open dumpsites and uncontrolled burning of waste. There are also persuasive public health reasons for implementing controlled landfilling – urban residents produce more solid waste per capita than rural inhabitants, and large amounts of uncontrolled refuse accumulating in areas of high population density are linked to vermin and disease (Christensen, 1989). The process of converting open dumping and burning to engineered landfills implies control of waste placement, compaction, the use of cover materials, implementation of surface water diversion and drainage, and management of leachate and gas, perhaps applying an intermediate level of technology consistent with limited financial resources (Savage et al., 1998). These practices shift the production of CO_2 (by burning and aerobic decomposition) to anaerobic production of CH_4. This is largely the same transition that occurred in many developed countries in the 1950–1970 time frame. Paradoxically, this results in higher rates of CH_4 generation and emissions than previous open-dumping and burning practices. In addition, many developed and developing countries have historically implemented large-scale aerobic composting of waste. This has often been applied to mixed waste, which, in practice, is similar to implementing an initial aerobic MBT process. However, source-separated biodegradable waste streams are preferable to mixed waste in order to produce higher quality compost products for horticultural and other uses (Diaz et al., 2002; Perla, 1997). In developing countries, composting can provide an affordable, sustainable alternative to controlled landfilling, especially where more labour-intensive lower technology strategies are applied to selected biodegradable wastes (Hoornweg et al., 1999). It remains to be seen if mechanized recycling and more costly alternatives such as incineration and MBT will be widely implemented in developing countries. Where decisions regarding waste management are made at the local level by communities with limited financial resources seeking the least-cost environmentally acceptable solution – often this is landfilling or composting (Hoornweg, 1999; Hoornweg et al., 1999; Johannessen and Boyer, 1999). Accelerating the introduction of landfill gas extraction and utilization can mitigate the effect of increased CH_4 generation at engineered landfills. Although Kyoto mechanisms such as CDM and JI have already proven useful in this regard, the post-2012 situation is unclear.

With regard to wastewater trends, a current priority in developing countries is to increase the historically low rates of wastewater collection and treatment. One of the Millennium Development Goals (MDGs) is to reduce by 50% the number of people without access to safe sanitation by 2015. One strategy may be to encourage more on-site sanitation rather than expensive transport of sewerage to centralized treatment plants: this strategy has been successful in Dakar, Senegal, at the cost of about 400 US$ per household. It has been estimated that, for sanitation, the annual investment must increase from 4 billion US$ to 18 billion US$ to achieve the MDG target, mostly in East Asia, South Asia and Sub-Saharan Africa (World Bank, 2005a).

10.3 Emission trends

10.3.1 Global overview

Quantifying global trends requires annual national data on waste production and management practices. Estimates for many countries are uncertain because data are lacking, inconsistent or incomplete; therefore, the standardization of terminology for national waste statistics would greatly improve data quality for this sector. Most developing countries use default data on waste generation per capita with inter-annual changes assumed to be proportional to total or urban population. Developed countries use more detailed methodologies, activity data and emission factors, as well as national statistics and surveys, and are sharing their methods through bilateral and multilateral initiatives.

For landfill CH_4, the largest GHG emission from the waste sector, emissions continue several decades after waste disposal; thus, the estimation of emission trends requires models that include temporal trends. Methane is also emitted during wastewater transport, sewage treatment processes and leakages from anaerobic digestion of waste or wastewater sludges. The major sources of N_2O are human sewage and wastewater treatment. The CO_2 from the non-biomass portion of incinerated waste is a small source of GHG emissions. The IPCC 2006 Guidelines also provide methodologies for CO_2, CH_4 and N_2O emissions from open burning of waste and for CH_4 and N_2O emissions from composting and anaerobic digestion of biowaste. Open burning of waste in developing countries is a significant local source of air pollution, constituting a health risk for nearby communities. Composting and other biological treatments emit very small quantities of GHGs but were included in 2006 IPCC Guidelines for completeness.

Table 10.3: Trends for GHG emissions from waste using (a) 1996 and (b) 2006 IPCC Inventory guidelines, extrapolations, and projections ($MtCO_2$-eq, rounded)

Source	1990	1995	2000	2005	2010	2015	2020	2030	2050
Landfill CH_4[a]	760	770	730	750	760	790	820		
Landfill CH_4[b]	340	400	450	520	640	800	1000	1500	2900
Landfill CH_4 (average of [a] and [b])	550	585	590	635	700	795	910		
Wastewater CH_4[a]	450	490	520	590	600	630	670		
Wastewater N_2O[a]	80	90	90	100	100	100	100		
Incineration CO_2[b]	40	40	50	50	60	60	60	70	80
Total GHG emissions	1120	1205	1250	1345	1460	1585	1740		

Notes: Emissions estimates and projections as follows:

[a] Based on reported emissions from national inventories and national communications, and (for non-reporting countries) on 1996 inventory guidelines and extrapolations (US EPA, 2006).

[b] Based on 2006 inventory guidelines and BAU projection (Monni et al., 2006).

Total includes landfill CH_4 (average), wastewater CH_4, wastewater N_2O and incineration CO_2.

Overall, the waste sector contributes <5% of global GHG emissions. Table 10.3 compares estimated emissions and trends from two studies: US EPA (2006) and Monni et al. (2006). The US EPA (2006) study collected data from national inventories and projections reported to the United Nations Framework Convention on Climate Change (UNFCCC) and supplemented data gaps with estimates and extrapolations based on IPCC default data and simple mass balance calculations using the 1996 IPCC Tier 1 methodology for landfill CH_4. Monni et al. (2006) calculated a time series for landfill CH_4 using the first-order decay (FOD) methodology and default data in the 2006 IPCC Guidelines, taking into account the time lag in landfill emissions compared to year of disposal. The estimates by Monni et al. (2006) are lower than US EPA (2006) for the period 1990–2005 because the former reflect slower growth in emissions relative to the growth in waste. However, the future projected growth in emissions by Monni et al. (2006) is higher, because recent European decreases in landfilling are reflected more slowly in the future projections. For comparison, the reported 1995 CH_4 emissions from landfills and wastewater from national inventories were approximately 1000 $MtCO_2$eq (UNFCCC, 2005). In general, data from Non-Annex I countries are limited and usually available only for 1994 (or 1990). In the TAR, annual global CH_4 and N_2O emissions from all sources were approximately 600 Tg CH_4/yr and 17.7 Tg N/yr as N_2O (IPCC, 2001b). The direct comparison of reported emissions in Table 10.3 with the SRES A1 and B2 scenarios (Nakicenovic et al., 2000) for GHG emissions from waste is problematical: the SRES do not include landfill-gas recovery (commercial since 1975) and project continuous increases in CH_4 emissions based only on population increases to 2030 (AIB-AIM) or 2100 (B2-MESSAGE), resulting in very high emission estimates of >4000 $MtCO_2$-eq/yr for 2050.

Table 10.3 indicates that total emissions have historically increased and will continue to increase (Monni et al., 2006; US EPA, 2006; see also Scheehle and Kruger, 2006). However, between 1990 and 2003, the percentage of total global GHG emissions from the waste sector declined 14–19% for Annex I and EIT countries (UNFCCC, 2005). The waste sector contributed 2–3% of the global GHG total for Annex I and EIT countries for 2003, but a higher percentage (4.3%) for non-Annex I countries (various reporting years from 1990–2000) (UNFCCC, 2005). In developed countries, landfill CH_4 emissions are stabilizing due to increased landfill CH_4 recovery, decreased landfilling, and decreased waste generation as a result of local waste management decisions including recycling, local economic conditions and policy initiatives. On the other hand, rapid increases in population and urbanization in developing countries are resulting in increases in GHG emissions from waste, especially CH_4 from landfills and both CH_4 and N_2O from wastewater. CH_4 emissions from wastewater alone are expected to increase almost 50% between 1990 and 2020, especially in the rapidly developing countries of Eastern and Southern Asia (US EPA, 2006; Table 10.3). Estimates of global N_2O emissions from wastewater are incomplete and based only on human sewage treatment, but these indicate an increase of 25% between 1990 and 2020 (Table 10.3). It is important to emphasize, however, that these are business-as-usual (BAU) scenarios, and actual emissions could be much lower if additional measures are in place. Future reductions in emissions from the waste sector will partially depend on the post-2012 availability of Kyoto mechanisms such the CDM and JI.

Uncertainties for the estimates in Table 10.3 are difficult to assess and vary by source. According to 2006 IPCC Guidelines (IPCC, 2006), uncertainties can range from 10–30% (for countries with good annual waste data) to more than twofold (for countries without annual data). The use of default data and the Tier 1 mass balance method (from 1996 inventory guidelines) for many developing countries would be the major source of uncertainty in both the US EPA (2006) study and reported GHG emissions (IPCC, 2006). Estimates by Monni et al. (2006) were sensitive to the relationship between waste generation and GDP, with an estimated range of uncertainty for the baseline for 2030 of –48% to +24%. Additional sources of uncertainty include the use of default data for waste generation, plus the suitability of parameters and chosen methods for individual countries. However, although country-specific uncertainties may be large, the uncertainties by region and over time are estimated to be smaller.

10.3.2 Landfill CH_4: regional trends

Landfill CH_4 has historically been the largest source of GHG emissions from the waste sector. The growth in landfill emissions has diminished during the last 20 years due to increased rates of landfill CH_4 recovery in many countries and decreased rates of landfilling in the EU. The recovery and utilization of landfill CH_4 as a source of renewable energy was first commercialized in 1975 and is now being implemented at >1150 plants worldwide with emission reductions of >105 $MtCO_2$-eq/yr (Willumsen, 2003; Bogner and Matthews, 2003). This number should be considered a minimum because there are also many sites that recover and flare landfill gas without energy recovery. Figure 10.5 compares regional emissions estimates for five-year intervals from 1990–2020 (US EPA, 2006) to annual historical estimates from 1971–2002 (Bogner and Matthews, 2003). The trends converge for Europe and the OECD Pacific, but there are differences for North America and Asia related to differences in methodologies and assumptions.

A comparison of the present rate of landfill CH_4 recovery to estimated global emissions (Table 10.3) indicates that the minimum recovery and utilization rates discussed above (>105 $MtCO_2$-eq yr) currently exceed the average projected increase from 2005 to 2010. Thus, it is reasonable to state that landfill CH_4 recovery is beginning to stabilize emissions from this source. A linear regression using historical data from the early 1980s to 2003 indicates a conservative growth rate for landfill CH_4 utilization of approximately 5% per year (Bogner and Matthews, 2003). For the EU-15, trends indicate that landfill CH_4 emissions are declining substantially. Between 1990 and 2002, landfill CH_4 emissions decreased by almost 30% (Deuber et al., 2005) due to the early implementation of the landfill directive (1999/31/EC) and similar national legislation intended to both reduce the landfilling of biodegradable waste and increase landfill CH_4 recovery at existing sites. By 2010, GHG emissions from waste in the EU are projected to be more than 50% below 1990 levels due to these initiatives (EEA, 2004).

For developing countries, as discussed in the previous section (10.3.1), rates of landfill CH_4 emissions are expected to increase concurrently with increased landfilling. However, incentives such as the CDM can accelerate rates of landfill CH_4 recovery and use in parallel with improved landfilling practices. In addition, since substantial CH_4 can be emitted both before and after the period of active gas recovery, sites should be encouraged, where feasible, to install horizontal gas collection

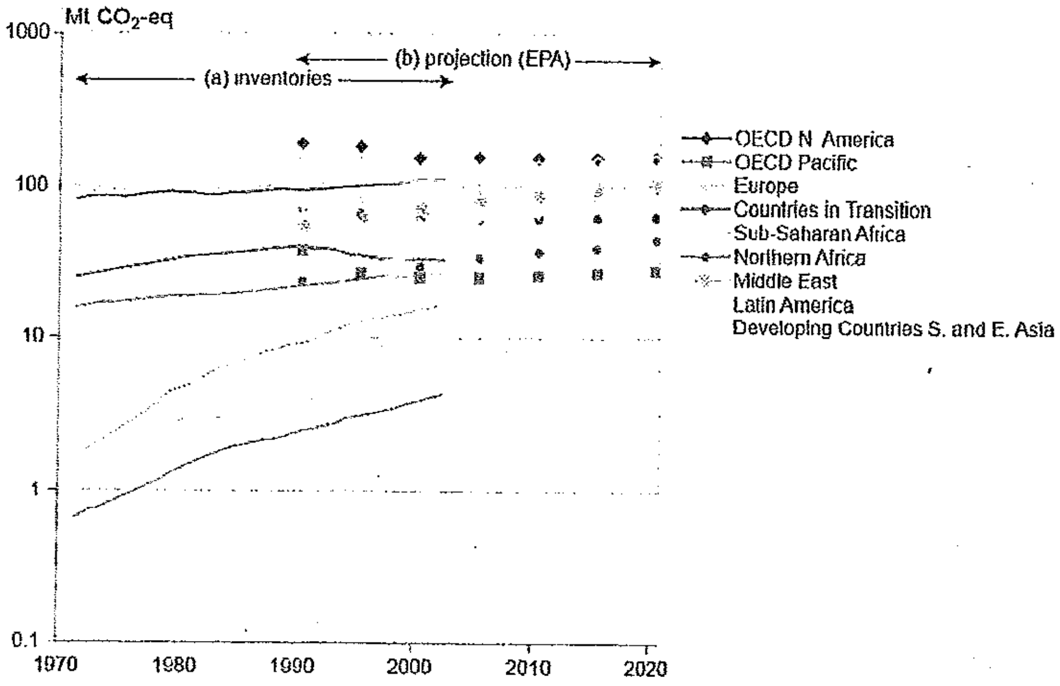


Figure 10.5: Regional landfill CH_4 emission trends ($MtCO_2$-eq).

Notes: Includes a) Annual historic emission trends from Bogner and Matthews (2003), extended through 2002; b) Emission estimates for five-year intervals from 1990–2020 using 1996 inventory procedures, extrapolations and projections (US EPA, 2006).

systems concurrent with filling and implement solutions to mitigate residual emissions after closure (such as landfill biocovers to microbially oxidize CH_4—see section 10.4.2).

10.3.3 Wastewater and human sewage CH_4 and N_2O: regional trends

CH_4 and N_2O can be produced and emitted during municipal and industrial wastewater collection and treatment, depending on transport, treatment and operating conditions. The resulting sludges can also microbially generate CH_4 and N_2O, which may be emitted without gas capture. In developed countries, these emissions are typically small and incidental because of extensive infrastructure for wastewater treatment, usually relying on centralized treatment. With anaerobic processes, biogas is produced and CH_4 can be emitted if control measures are lacking; however, the biogas can also be used for process heating or onsite electrical generation.

In developing countries, due to rapid population growth and urbanization without concurrent development of wastewater infrastructure, CH_4 and N_2O emissions from wastewater are generally higher than in developed countries. This can be seen by examining the 1990 estimated CH_4 and N_2O emissions and projected trends to 2020 from wastewater and human sewage (UNFCCC/IPCC, 2004; US EPA, 2006). However, data reliability for many developing countries is uncertain. Decentralized 'natural' treatment processes and septic tanks in developing countries may also result in relatively large emissions of CH_4 and N_2O, particularly in China, India and Indonesia where wastewater volumes are increasing rapidly with economic development (Scheehle and Doorn, 2003).

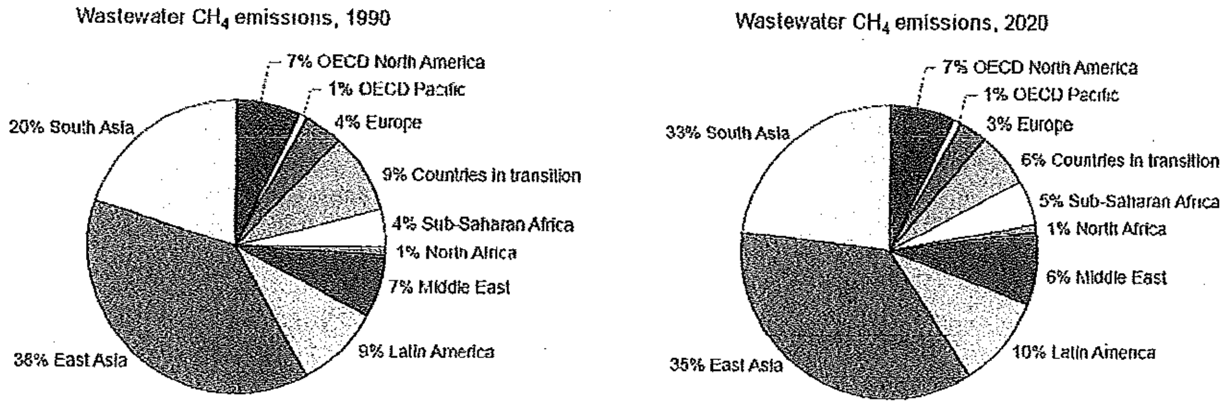


Figure 10.6a: Regional distribution of CH_4 emissions from wastewater and human sewage in 1990 and 2020. See Table 10.3 for total emissions.

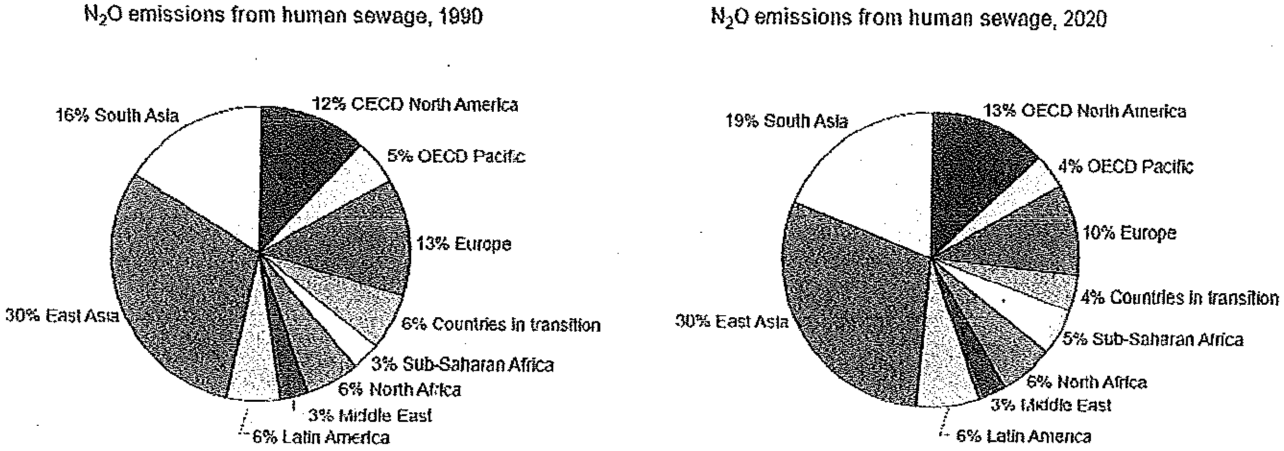


Figure 10.6b: Regional distribution of N2O emissions from human sewage in 1990 and 2020. See Table 10.3 for total emissions.

Notes: The US estimates include industrial wastewater and septic tanks, which are not reported by all developed countries.
Source: UNFCCC/IPCC (2004)

The highest regional percentages for CH_4 emissions from wastewater are from Asia (especially China, India). Other countries with high emissions in their respective regions include Turkey, Bulgaria, Iran, Brazil, Nigeria and Egypt. Total global emissions of CH_4 from wastewater handling are expected to rise by more than 45% from 1990 to 2020 (Table 10.3) with much of the increase from the developing countries of East and South Asia, the middle East, the Caribbean, and Central and South America. The EU has projected lower emissions in 2020 relative to 1990 (US EPA, 2006).

The contribution of human sewage to atmospheric N_2O is very low with emissions of 80–100 $MtCO_2$-eq/yr during the period 1990–2020 (Table 10.3) compared to current total global anthropogenic N_2O emissions of about 3500 $MtCO_2$-eq (US EPA, 2006). Emission estimates for N_2O from sewage for Asia, Africa, South America and the Caribbean are significantly underestimated since limited data are available, but it is estimated that these countries accounted for >70% of global emissions in 1990 (UNFCCC/IPCC, 2004). Compared with 1990, it is expected that global emissions will rise by about 20% by 2020 (Table 10.3). The regions with the highest relative N_2O emissions are the developing countries of East Asia, the developing countries of South Asia, Europe and the OECD North America (Figure 10.6b). Regions whose emissions are expected to increase the most by 2020 (with regional increases of 40 to 95%) are Africa, the Middle East, the developing countries of S and E Asia, the Caribbean, and Central and South America (US EPA, 2006). The only regions expected to have lower emissions in 2020 relative to 1990 are Europe and the EIT Countries.

10.3.4 CO_2 from waste incineration

Compared to landfilling, waste incineration and other thermal processes avoid most GHG generation, resulting only in minor emissions of CO_2 from fossil C sources, including plastics and synthetic textiles. Estimated current GHG emissions from waste incineration are small, around 40 $MtCO_2$-eq/yr, or less than one tenth of landfill CH_4 emissions. Recent data for the EU-15 indicate CO_2 emissions from incineration of about 9 $MtCO_2$-eq/yr (EIPPC Bureau, 2006). Future trends will depend on energy price fluctuations, as well as incentives and costs for GHG mitigation. Monni et al. (2006) estimated that incinerator emissions would grow to 80–230 $MtCO_2$-eq/yr by 2050 (not including fossil fuel offsets due to energy recovery).

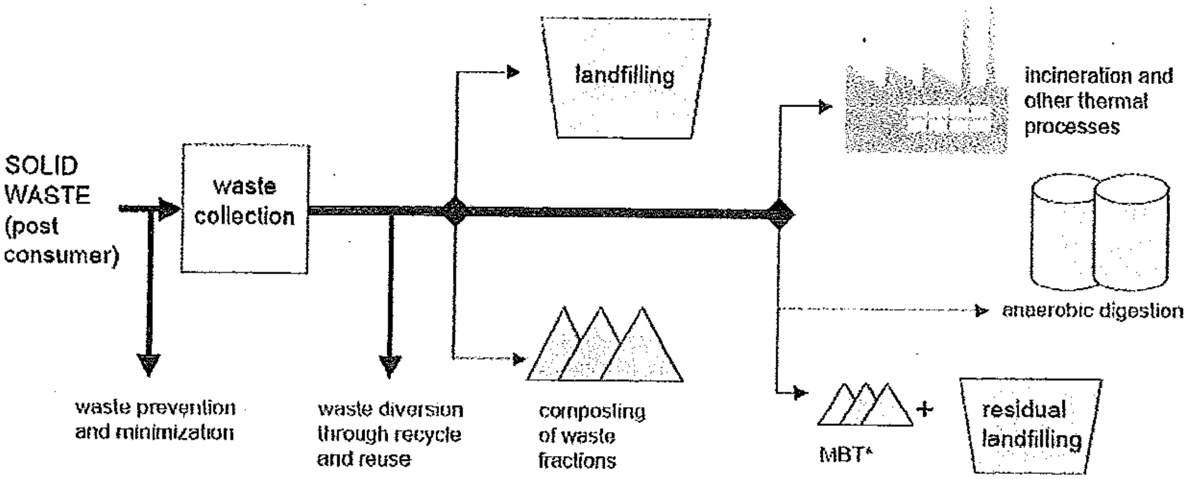
Major contributors to this minor source would be the developed countries with high rates of incineration, including Japan (>70% of waste incinerated), Denmark and Luxembourg (>50% of waste), as well as France, Sweden, the Netherlands and Switzerland. Incineration rates are increasing in most European countries as a result of the EU Landfill Directive. In 2003, about 17% of municipal solid waste was incinerated with energy recovery in the EU-25 (Eurostat, 2003; Statistics Finland, 2005). More recent data for the EU-15 (EIPCC, 2006) indicate that 20–25% of the total municipal solid waste is incinerated at over 400 plants with an average capacity of about 500 t/d (range of 170–1400 t/d). In the US, only about 14% of waste is incinerated (US EPA, 2005), primarily in the more densely populated eastern states. Thorneloe et al. (2002), using a life cycle approach, estimated that US plants reduced GHG emissions by 11 $MtCO_2$-eq/yr when fossil-fuel offsets were taken into account.

In developing countries, controlled incineration of waste is infrequently practised because of high capital and operating costs, as well as a history of previous unsustainable projects. The uncontrolled burning of waste for volume reduction in these countries is still a common practice that contributes to urban air pollution (Hoornweg, 1999). Incineration is also not the technology of choice for wet waste, and municipal waste in many developing countries contains a high percentage of food waste with high moisture contents. In some developing countries, however, the rate of waste incineration is increasing. In China, for example, waste incineration has increased rapidly from 1.7% of municipal waste in 2000 to 5% in 2005 (including 67 plants). (Du et al., 2006a, 2006b; National Bureau of Statistics of China, 2006).

10.4 Mitigation of post-consumer emissions from waste

10.4.1 Waste management and GHG-mitigation technologies

A wide range of mature technologies is available to mitigate GHG emissions from waste. These technologies include landfilling with landfill gas recovery (reduces CH_4 emissions), post-consumer recycling (avoids waste generation), composting of selected waste fractions (avoids GHG generation), and processes that reduce GHG generation compared to landfilling (thermal processes including incineration and industrial co-combustion, MBT with landfilling of residuals, and anaerobic digestion). Therefore, the mitigation of GHG emissions from waste relies on multiple technologies whose application depends on local, regional and national drivers for both waste management and GHG mitigation. There are many appropriate low- to high-technology strategies discussed in this section (see Figure 10.7 for a qualitative comparison of technologies). At the 'high technology' end, there are also advanced thermal processes for waste such as pyrolysis and gasification, which are beginning to be applied in the EU, Japan and elsewhere. Because of variable feedstocks and high unit costs, these processes have not been routinely applied to mixed municipal waste at large scale (thousands of tonnes per day). Costs and potentials are addressed in Section 10.4.7.



Technology:	Low to Intermediate	Low to Intermediate	High
Unit Cost: (per t waste)	Low to Intermediate	Low to Intermediate	High
Energy Balance	Negative to positive	Negative to positive Composting: negative to zero Landfill CH_4 utilization: positive	Negative to positive MBT (aerobic): negative MBT (anaerobic): positive Anaerobic digestion: positive Incineration: positive (highest)

Figure 10.7: Technology gradient for waste management: major low- to high-technology options applicable to large-scale urban waste management
Note: MBT=Mechanical Biological Treatment

10.4.2 CH_4 management at landfills

Global CH_4 emissions from landfills are estimated to be 500–800 $MtCO_2$-eq/yr (US EPA, 2006; Monni et al. 2006; Bogner and Matthews 2003). However, direct field measurements of landfill CH_4 emissions at small scale (<1m²) can vary over seven orders of magnitude (0.0001–>1000 g CH_4 /m²/d) depending on waste composition, cover materials, soil moisture, temperature and other variables (Bogner et al., 1997a). Results from a limited number of whole landfill CH_4 emissions measurements in Europe, the US and South Africa are in the range of about 0.1–1.0 tCH_4/ha/d (Nozhevnikova et al., 1993; Oonk and Boom, 1995; Borjesson, 1996; Czepiel et al., 1996; Hovde et al., 1995; Mosher et al., 1999; Tregoures et al., 1999; Galle et al., 2001; Morris, 2001; Scharf et al., 2002).

The implementation of an active landfill gas extraction system using vertical wells or horizontal collectors is the single most important mitigation measure to reduce emissions. Intensive field studies of the CH_4 mass balance at cells with a variety of design and management practices have shown that >90% recovery can be achieved at cells with final cover and an efficient gas extraction system (Spokas et al., 2006). Some sites may have less efficient or only partial gas extraction systems and there are fugitive emissions from landfilled waste prior to and after the implementation of active gas extraction; thus estimates of 'lifetime' recovery efficiencies may be as low as 20% (Oonk and Boom, 1995), which argues for early implementation of gas recovery. Some measures that can be implemented to improve overall gas collection are installation of horizontal gas collection systems concurrent with filling, frequent monitoring and remediation of edge and piping leakages, installation of secondary perimeter extraction systems for gas migration and emissions control, and frequent inspection and maintenance of cover materials. Currently, landfill CH_4 is being used to fuel industrial boilers; to generate electricity using internal combustion engines, gas turbines or steam turbines; and to produce a substitute natural gas after removal of CO_2 and trace components. Although electrical output ranges from small 30 kWe microturbines to 50 MWe steam turbine generators, most plants are in the 1–15 MWe range. Significant barriers to increased diffusion of landfill gas utilization, especially where it has not been previously implemented, can be local reluctance from electrical utilities to include small power producers and from gas utilities/pipeline companies to transport small percentages of upgraded landfill gas in natural gas pipelines.

A secondary control on landfill CH_4 emissions is CH_4 oxidation by indigenous methanotrophic microorganisms in cover soils. Landfill soils attain the highest rates of CH_4 oxidation recorded in the literature, with rates many times higher than in wetland settings. CH_4 oxidation rates at landfills can vary over several orders of magnitude and range from negligible to 100% of the CH_4 flux to the cover. Under circumstances of high oxidation potential and low flux of landfill CH_4 from the landfill, it has been demonstrated that atmospheric CH_4 may be oxidized at the landfill surface (Bogner et al., 1995; 1997b; 1999; 2005; Borjesson and Svensson, 1997b). In such cases, the landfill cover soils function as a sink rather than a source of atmospheric CH_4. The thickness, physical properties moisture content, and temperature of cover soils directly affect oxidation, because rates are limited by the transport of CH_4 upward from anaerobic zones and O_2 downward from the atmosphere. Laboratory studies have shown that oxidation rates in landfill cover soils may be as high as 150–250 g $CH_4/m^2/d$ (Kightley et al., 1995; de Visscher et al., 1999). Recent field studies have demonstrated that oxidation rates can be greater than 200 g/m^2/d in thick, compost-amended 'biocovers' engineered to optimize oxidation (Bogner et al., 2005; Huber-Humer, 2004). The prototype biocover design includes an underlying coarse-grained gas distribution layer to provide more uniform fluxes to the biocover above (Huber-Humer, 2004). Furthermore, engineered biocovers have been shown to effectively oxidize CH_4 over multiple annual cycles in northern temperate climates (Humer-Humer, 2004). In addition to biocovers, it is also possible to design passive or active methanotrophic biofilters to reduce landfill CH_4 emissions (Gebert and Gröngröft, 2006; Streese and Stegmann, 2005). In field settings, stable C' isotopic techniques have proven extremely useful to quantify the fraction of CH_4 that is oxidized in landfill cover soils (Chanton and Liptay, 2000; de Visscher et al., 2004; Powelson et al., 2007). A secondary benefit of CH_4 oxidation in cover soils is the co-oxidation of many non-CH_4 organic compounds, especially aromatic and lower chlorinated compounds, thereby reducing their emissions to the atmosphere (Scheutz et al., 2003a).

Other measures to reduce landfill CH_4 emissions include installation of geomembrane composite covers (required in the US as final cover); design and installation of secondary perimeter gas extraction systems for additional gas recovery; and implementation of bioreactor landfill designs so that the period of active gas production is compressed while early gas extraction is implemented.

Landfills are a significant source of CH_4 emissions, but they are also a long-term sink for carbon (Bogner, 1992; Barlaz, 1998. See Figure 10.1 and Box 10.1). Since lignin is recalcitrant and cellulosic fractions decompose slowly, a minimum of 50% of the organic carbon landfilled is not typically converted to biogas carbon but remains in the landfill (See references cited on Figure 10.1). Carbon storage makes landfilling a more competitive alternative from a climate change perspective, especially where landfill gas recovery is combined with energy use (Flugsrud et al. 2001; Micales and Skog, 1997; Pingoud et al. 1996; Pipatti and Savolainen, 1996; Pipatti and Wihersaari, 1998). The fraction of carbon storage in landfills can vary over a wide range, depending on original waste composition and landfill conditions (for example, see Hashimoto and Moriguchi, 2004 for a review addressing harvested wood products).

10.4.3 Incineration and other thermal processes for waste-to-energy

These processes include incineration with and without energy recovery, production of refuse-derived fuel (RDF), and industrial co-combustion (including cement kilns: see Onuma et al., 2004 and Section 7.3.3). Incineration reduces the mass of waste and can offset fossil-fuel use; in addition, GHG emissions are avoided, except for the small contribution from fossil carbon (Consonni et al., 2005). Incineration has been widely applied in many developed countries, especially those with limited space for landfilling such as Japan and many European countries. Globally, about 130 million tonnes of waste are annually combusted in >600 plants in 35 countries (Themelis, 2003).

Waste incinerators have been extensively used for more than 20 years with increasingly stringent emission standards in Japan, the EU, the US and other countries. Mass burning is relatively expensive and, depending on plant scale and flue-gas treatment, currently ranges from about 95–150 €/t waste (87–140 US$/t) (Faaij et al., 1998; EIPPC Bureau, 2006). Waste-to-energy plants can also produce useful heat or electricity, which improves process economics. Japanese incinerators have routinely implemented energy recovery or power generation (Japan Ministry of the Environment, 2006). In northern Europe, urban incinerators have historically supplied fuel for district heating of residential and commercial buildings. Starting in the 1980s, large waste incinerators with stringent emission standards have been widely deployed in Germany, the Netherlands and other European countries. Typically such plants have a capacity of about 1 Mt waste/yr, moving grate boilers (which allow mass burning of waste with diverse properties), low steam pressures and temperatures (to avoid corrosion) and extensive flue gas cleaning to conform with EU Directive 2000/76/EC. In 2002, European incinerators for waste-to-energy generated 41 million GJ electrical energy and 110 million GJ thermal energy (Themelis, 2003). Typical electrical efficiencies are 15% to >20% with more efficient designs becoming available. In recent years, more advanced combustion concepts have penetrated the market, including fluidized bed technology.

10.4.4 Biological treatment including composting, anaerobic digestion, and MBT (Mechanical Biological Treatment)

Many developed and developing countries practise composting and anaerobic digestion of mixed waste or biodegradable waste fractions (kitchen or restaurant wastes, garden waste, sewage sludge). Both processes are best applied to source-separated waste fractions: anaerobic digestion is particularly appropriate for wet wastes, while composting is often appropriate for drier feedstocks. Composting decomposes waste aerobically into CO_2, water and a humic fraction; some carbon storage also occurs in the residual compost (see references on Figure 10.1). Composting can be sustainable at reasonable cost in developing countries; however, choosing more labour-intensive processes over highly mechanized technology at large scale is typically more appropriate and sustainable; Hoornweg et al. (1999) give examples from India and other countries. Depending on compost quality, there are many potential applications for compost in agriculture, horticulture, soil stabilization and soil improvement (increased organic matter, higher water-holding capacity) (Cointreau, 2001). However, CH_4 and N_2O can both be formed during composting by poor management and the initiation of semi-aerobic (N_2O) or anaerobic (CH_4) conditions; recent studies also indicate potential production of CH_4 and N_2O in well-managed systems (Hobson et al., 2005).

Anaerobic digestion produces biogas (CH_4 + CO_2) and biosolids. In particular, Denmark, Germany, Belgium and France have implemented anaerobic digestion systems for waste processing, with the resulting biogas used for process heating, onsite electrical generation and other uses. Minor quantities of CH_4 can be vented from digesters during start-ups, shutdowns and malfunctions. However, the GHG emissions from controlled biological treatment are small in comparison to uncontrolled CH_4 emissions from landfills without gas recovery (e.g. Petersen et al. 1998; Hellebrand 1998; Vesterinen 1996; Beck-Friis, 2001; Detzel et al. 2003). The advantages of biological treatment over landfilling are reduced volume and more rapid waste stabilization. Depending on quality, the residual solids can be recycled as fertilizer or soil amendments, used as a CH_4-oxidizing biocovers on landfills (Barlaz et al., 2004; Huber-Humer, 2004), or landfilled at reduced volumes with lower CH_4 emissions.

Mechanical biological treatment (MBT) of waste is now being widely implemented in Germany, Austria, Italy and other EU countries. In 2004, there were 15 facilities in Austria, 60 in Germany and more than 90 in Italy; the total throughput was approximately 13 million tonnes with larger plants having a capacity of 600–1300 tonnes/day (Diaz et al., 2006). Mixed waste is subjected to a series of mechanical and biological operations to reduce volume and achieve partial stabilization of the organic carbon. Typically, mechanical operations (sorting, shredding, crushing) first produce a series of waste fractions for recycling or for subsequent treatment (including combustion or secondary biological processes). The biological steps consist of either aerobic composting or anaerobic digestion. Composting can occur either in open windrows or in closed buildings with gas collection and treatment. In-vessel anaerobic digestion of selected organic fractions produces biogas for energy use. Compost products and digestion residuals can have potential horticultural or agricultural applications; some MBT residuals are landfilled, or soil-like residuals can be used as landfill cover. Under landfill conditions, residual materials retain some potential for CH_4 generation (Bockreis and Steinberg, 2005). Reductions of as much as 40–60% of the original organic carbon are possible with MBT (Kaartinen, 2004). Compared with landfilling, MBT can theoretically reduce CH_4 generation by as much as 90% (Kuehle-Weidemeier and Doedens, 2003). In practice, reductions are smaller and dependent on the specific MBT processes employed (see Binner, 2002).

10.4.5 Waste reduction, re-use and recycling

Quantifying the GHG-reduction benefits of waste minimization, recycling and re-use requires the application of LCA tools (Smith et al., 2001). Recycling reduces GHG emissions through lower energy demand for production (avoided fossil fuel) and by substitution of recycled feedstocks for virgin materials. Efficient use of materials also reduces waste. Material efficiency can be defined as a reduction in primary materials for a particular purpose, such as packaging or construction, with no negative impact on existing human activities. At several stages in the life cycle of a product, material efficiency can be increased by more efficient design, material substitution, product recycling, material recycling and quality cascading (use of recycled material for a secondary product with lower quality demands). Both material recycling and quality cascading occur in many countries at large scale for metals recovery (steel, aluminium) and recycling of paper, plastics and wood. All these measures lead to indirect energy savings, reductions in GHG emissions, and avoidance of GHG generation. This is especially true for products resulting from energy-intensive production processes such as metals, glass, plastic and paper (Tuhkanen et al., 2001).

The magnitude of avoided GHG-emissions benefits from recycling is highly dependent on the specific materials involved, the recovery rates for those materials, the local options for managing materials, and (for energy offsets) the specific fossil fuel avoided (Smith et al., 2001). Therefore, existing studies are often not comparable with respect to the assumptions and calculations employed. Nevertheless, virtually all developed countries have implemented comprehensive national, regional or local recycling programmes. For example, Smith et al. (2001) thoroughly addressed the GHG-emission benefits from recycling across the EU, and Pimenteira et al. (2004) quantified GHG emission reductions from recycling in Brazil.

10.4.6 Wastewater and sludge treatment

There are many available technologies for wastewater management, collection, treatment, re-use and disposal, ranging from natural purification processes to energy-intensive advanced technologies. Although decision-making tools are available that include environmental trade-offs and costs (Ho, 2000), systematic global studies of GHG-reduction potentials and costs for wastewater are still needed. When efficiently applied, wastewater transport and treatment technologies reduce or eliminate GHG generation and emissions; in addition, wastewater management promotes water conservation by preventing pollution, reducing the volume of pollutants, and requiring a smaller volume of water to be treated. Because the size of treatment systems is primarily governed by the volume of water to be treated rather than the mass loading of nitrogen and other pollutants, smaller volumes mean that smaller treatment plants with lower capital costs can be more extensively deployed. Wastewater collection and transport includes conventional (deep) sewerage and simplified (shallow) sewerage. Deep sewerage in developed countries has high capital and operational costs. Simplified (shallow) sewerage in both developing and developed countries uses smaller-diameter piping and shallower excavations, resulting in lower capital costs (30–50%) than deep systems.

Wastewater treatment removes pollutants using a variety of technologies. Small wastewater treatment systems include pit latrines, composting toilets and septic tanks. Septic tanks are inexpensive and widely used in both developed and developing countries. Improved on-site treatment systems used in developing countries include inverted trench systems and aerated treatment units. More advanced treatment systems include activated sludge treatment, trickling filters, anaerobic or facultative lagoons, anaerobic digestion and constructed wetlands. Depending on scale, many of these systems have been used in both developed and developing countries. Activated sludge treatment is considered the conventional method for large-scale treatment of sewage. In addition, separation of black water and grey water can reduce the overall energy requirements for treatment (UNEP/GPA-UNESCO/IHE, 2004). Pretreatment or limitation of industrial wastes is often necessary to limit excessive pollutant loads to municipal systems, especially when wastewaters are contaminated with heavy metals. Sludges (or biosolids) are the product of most wastewater treatment systems. Options for sludge treatment include stabilization, thickening, dewatering, anaerobic digestion, agricultural re-use, drying and incineration. The use of composted sludge as a soil conditioner in agriculture and horticulture recycles carbon, nitrogen and phosphorus (and other elements essential for plant growth). Heavy metals and some toxic chemicals are difficult to remove from sludge; either the limitation of industrial inputs or wastewater pretreatment is needed for agricultural use of sludges. Lower quality uses for sludge may include mine site rehabilitation, highway landscaping, or landfill cover (including biocovers). Some sludges are landfilled, but this practice may result in increased volatile siloxanes and H_2S in the landfill gas. Treated wastewater can either be re-used or discharged, but re-use is the most desirable option for agricultural and horticultural irrigation, fish aquaculture, artificial recharge of aquifers, or industrial applications.

10.4.7 Waste management and mitigation costs and potentials

In the waste sector, it is often not possible to clearly separate costs for GHG mitigation from costs for waste management. In addition, waste management costs can exhibit high variability depending on local conditions. Therefore the baseline and cost assumptions, local availability of technologies, and economic and social development issues for alternative waste management strategies need to be carefully defined. An older study by de Jager and Blok (1996) assumed a 20-year project life to compare the cost-effectiveness of various options for mitigating CH_4 emissions from waste in the Netherlands, with costs ranging from –2 US\$/tCO$_2$-eq for landfilling with gas recovery and on-site electrical generation to >370 US\$/tCO$_2$-eq for incineration. In general, for landfill CH_4 recovery and utilization, project economics are highly site-specific and dependent on the financial arrangements as well as the distribution of benefits, risks and responsibilities among multiple partners. Some representative unit costs for landfill-gas recovery and utilization (all in 2003 US\$/kW installed power) are: 200–400 for gas collection; 200–300 for gas conditioning (blower/compressor, dehydration, flare); 850–1200 for internal combustion engine/generator; and 250–350 for planning and design (Willumsen, 2003).

Smith et al. (2001) highlighted major cost differences between EU member states for mitigating GHG emissions from waste. Based on fees (including taxes) for countries with data, this study compared emissions and costs for various waste management practices with respect to direct GHG emissions, carbon sequestration, transport emissions, avoided emissions from recycling due to material and energy savings, and avoided emissions from fossil-fuel substitution via thermal processes and biogas (including landfill gas). Recycling costs are highly dependent on the waste material recycled. Overall, the financial success of any recycling venture is dependent on the current market value of the recycled products. The price obtained for recovered materials is typically lower than separation/reprocessing costs, which can be, in turn, higher than the cost of virgin materials – thus recycling activities usually require subsidies (except for aluminium and paper recycling). Recycling, composting and anaerobic digestion can provide large potential emission reductions, but further implementation is dependent on reducing the cost of separate collection (10–400 €/t waste (9–380 US\$/t)) and, for composting, establishing local markets for the compost product. Costs for composting can range from 20–170 €/t waste (18–156 US\$/t) and are typically 35 €/t waste (32 US\$/t) for open-windrow operations and 50 €/t waste (46 US\$/t) for in-vessel processes. When the replaced fossil fuel is coal, both mass incineration and co-combustion offer comparable and less expensive GHG-emission reductions compared to recycling (averaging 64 €/t waste (59 US\$/t), with a range of 30–150 €/t (28–140 US\$/t)). Landfill disposal is the most inexpensive waste management option in the EU (averaging 56 €/t waste (52 US\$/t), ranging from 10–160 €/t waste (9–147 US\$/t), including taxes), but it is also the largest source of GHG emissions. With improved gas management, landfill emissions can be significantly reduced at low cost. However, landfilling costs in the EU are increasing due to increasingly stringent regulations, taxes and declining capacity. Although there is only sparse information regarding MBT costs, German costs are about 90 €/t waste (83 US$/t, including landfill disposal fees); recent data suggest that, in the future, MBT may become more cost-competitive with landfilling and incineration.

Costs and potentials for reducing GHG emissions from waste are usually based on landfill CH_4 as the baseline (Bates and Haworth, 2001; Delhotal et al. 2006; Monni et al. 2006; Nakicenovic et al., 2000; Pipatti and Wihersaari 1998). When reporting to the UNFCCC, most developed countries take the dynamics of landfill gas generation into account; however, most developing countries and non-reporting countries do not. Basing their study on reported emissions and projections, Delhotal et al. (2006) estimated break-even costs for GHG abatement from landfill gas utilization that ranged from about –20 to +70 US$/$tCO_2$-eq, with the lower value for direct use in industrial boilers and the higher value for on-site electrical generation. From the same study, break-even costs (all in US$/$tCO_2$-eq) were approximately 25 for landfill-gas flaring; 240–270 for composting; 40–430 for anaerobic digestion; 360 for MBT and 270 for incineration. These costs were based on the EMF-21 study (US EPA, 2003), which assumed a 15-year technology lifetime, 10% discount rate and 40% tax rate.

Compared to thermal and biological processes which only affect future emissions, landfill CH_4 is generated from waste landfilled in previous decades, and gas recovery, in turn, reduces emissions from waste landfilled in previous years. Most existing studies for the waste sector do not consider these temporal issues. Monni et al. (2006) developed baseline and mitigation scenarios for solid waste management using the first order decay (FOD) methodology in the 2006 IPCC Guidelines, which takes into account the timing of emissions. The baseline scenario by Monni et al. (2006) assumed that: 1) waste generation will increase with growing population and GDP (using the same population and GDP data as SRES scenario A1b); 2) waste management strategies will not change significantly, and 3) landfill gas recovery and utilization will continue to increase at the historical rate of 5% per year in developed countries (Bogner and Matthews, 2003; Willumsen, 2003). Mitigation scenarios were developed for 2030 and 2050 which focus on increased landfill gas recovery, increased recycling, and increased incineration. In the increased landfill gas recovery scenario, recovery was estimated to increase 15% per year, with most of the increase in developing countries because of CDM or similar incentives (above baseline of current CDM projects). This growth rate is about triple the current rate and corresponds to a reasonable upper limit, taking into account the fact that recovery in developed countries has already reached high levels, so that increases would come mainly from developing countries, where current lack of funding is a barrier to deployment. Landfill gas recovery was capped at 75% of estimated annual CH_4 generation for developed countries and 50% for developing countries in both the baseline and increased landfill gas recovery scenarios. In the increased incineration scenario, incineration grew 5% each year in the countries where waste incineration occurred in 2000. For OECD countries where no incineration took place in 2000, 1% of the waste generated was assumed to be incinerated in 2012. In non-OECD countries, 1% waste incineration was assumed to be reached only in 2030. The maximum rate of incineration that could be implemented was 85% of the waste generated. The increased recycling scenario assumed a growth in paper and cardboard recycling in all parts of the world using a technical maximum of 60% recycling (CEPI, 2003). This maximum was assumed to be reached in 2050. In the mitigation scenarios, only direct emission reductions compared to the baseline CH_4 emissions from landfills were estimated – thus avoided emissions from recycled materials, reduced energy use, or fossil fuel offsets were not included. In the baseline scenario (Figure 10.8), emissions increase threefold during the period from 1990 to 2030 and more than fivefold by 2050. These growth rates do not include current or planned legislation relating to either waste minimization or landfilling – thus future emissions may be overestimated. Most of the increase comes from non-OECD countries whose current emissions are smaller because of lower waste generation and a higher percentage of waste degrading aerobically. The mitigation scenarios show that reductions by individual measures in 2030 range from 5–20% of total emissions and increase proportionally with time. In 2050, the corresponding range is approximately 10–30%. As the measures in the scenarios are largely additive, total mitigation potentials of approximately 30% in 2030 and 50% in 2050 are projected relative to the baseline. Nevertheless, the estimated abatement potential is not capable of mitigating the growth in emissions.

The baseline emission estimates in the Delhotal et al. (2006) study are based on similar assumptions to the Monni et al. (2006) study: population and GDP growth with increasing amounts of landfilled waste in developing countries. Baselines also include documented or expected changes in disposal rates due to composting and recycling, as well as the effects of landfill-gas recovery. In Delhotal et al. (2006), emissions increase by about 30% between 2000 and 2020; therefore, the growth in emissions to 2020 is more moderate than in Monni et al. (2006). This more moderate growth can be attributed to the inclusion of current and planned policies and measures to reduce emissions, plus the fact that historical emissions from prior landfilled waste were only partially considered.

Scenario development in both studies was complemented with estimates on maximum mitigation potentials at given marginal cost levels using the baseline scenarios as the starting point. Monni et al. (2006) derived annual regional waste-generation estimates for the Global Times model by using static aggregate emission coefficients calibrated to regional FOD models. Some modifications to the assumptions used in the

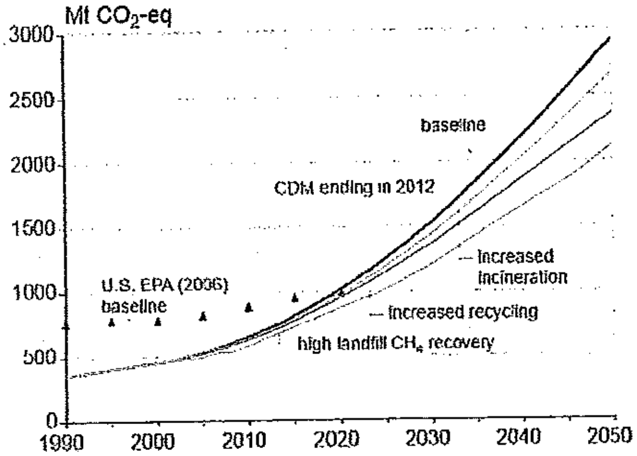


Figure 10.8: Global CH_4 emissions from landfills in baseline scenario compared to the following mitigation scenarios: increased incineration, CDM ending by 2012 (end of the first Kyoto commitment period), increased recycling, and high landfill CH_4 recovery rates including continuation of CDM after 2012 (Monni et al., 2006). The emission reductions estimated in the mitigation scenarios are largely additional to 2050. This figure also includes the US EPA (2006) baseline scenario for landfill CH_4 emissions from Delhotal et al. (2006).

scenario development were also made; for example, recycling was excluded due to its economic complexity, biological treatment was included and the technical efficiency of landfill-gas recovery was assumed the same in all regions (75%). Cost data were taken from various sources (de Feber & Gielen, 2000; OECD, 2004; Hoornweg, 1999).

As in the EMF-21 study (US EPA, 2003), both Delhotal et al. (2006) and Monni et al. (2006) assumed the same capital costs for all regions, but used regionalized labour costs for operations and maintenance.

Delhotal et al. (2006) and Monni et al. (2006) both conclude that substantial emission reductions can be achieved at low or negative costs (see Table 10.4). At higher costs, more significant reductions would be possible (more than 80% of baseline emissions) with most of the additional mitigation potential coming from thermal processes for waste-to-energy. Since combustion of waste results in minor fossil CO_2 emissions, these were considered in the calculations, but Table 10.4 only includes emissions reductions from landfill CH_4. In general, direct GHG emission reductions from implementation of thermal processes are much less than indirect reductions due to fossil fuel replacement, where that occurs. The emission reduction potentials for 2030 shown in Table 10.4 are assessed using a steady-state approach that can overestimate near-term annual reductions but gives more realistic values when integrated over time.

The economic mitigation potentials for the year 2030 in Table 10.5 take the dynamics of landfill gas generation into account. These estimates are derived from the static, long-term mitigation potentials previously shown in Table 10.4 (Monni et al. 2006). The upper limits of the ranges assume that landfill disposal is limited in the coming years so that only 15% of the waste generated globally is landfilled after 2010. This would mean that by 2030 the maximum economic potential would be almost 70% of the global emissions (see Table 10.5). The lower limits of the table have been scaled down to reflect a more realistic timing of implementation in accordance with emissions in the high landfill gas recovery (HR) and increased incineration (II) scenarios (Monni et al., 2006).

It must be emphasized that there are large uncertainties in costs and potentials for mitigation of GHG emissions from waste due to the uncertainty of waste statistics for many countries and emissions methodologies that are relatively unsophisticated. It is also important to point out that the cost estimates are global

Table 10.4: Economic reduction potential for CH_4 emissions from landfilled waste by level of marginal costs for 2020 and 2030 based on steady state models[a].

	US$/t$CO_2$-equivalent				
2020 (Delhotal et al., 2006)	**0**	**15**	**30**	**45**	**60**
OECD	12%	40%	46%	67%	92%
EIT	NA	NA	NA	NA	NA
Non-OECD	NA	NA	NA	NA	NA
Global	12%	41%	50%	57%	88%
2030 (Monni et al., 2006)	**0**	**10**	**20**	**50**	**100**
OECD	48%	86%	89%	94%	95%
EIT	31%	80%	93%	99%	100%
Non-OECD	32%	38%	50%	77%	88%
Global	35%	53%	63%	83%	91%

[a] The steady-state approach tends to overestimate the near-term annual reduction potential but gives more realistic results when integrated over time.

Table 10.5: Economic potential for mitigation of regional landfill CH_4 emissions at various cost categories in 2030 (from estimates by Monni et al., 2006). See notes.

Region	Projected emissions for 2030	Total economic mitigation potential ($MtCO_2$-eq) at <100 US$/$tCO_2$-eq	Economic mitigation potential ($MtCO_2$-eq) at various cost categories (US$/$tCO_2$-eq)			
			<0	0-20	20-50	50-100
OECD	360	100-200	100-120	20-100	0-7	1
EIT	180	100	30-60	20-80	5	1-10
Non-OECD	960	200-700	200-300	30-100	0-200	0-70
Global	1500	400-1000	300-500	70-300	5-200	10-70

Notes:

1. Costs and potentials for wastewater mitigation are not available.
2. Regional numbers are rounded to reflect the uncertainty in the estimates and may not equal global totals.
3. Landfill carbon sequestration is not considered.
4. The timing of measures limiting landfill disposal affect the annual mitigation potential in 2030. The upper limits of the ranges given assume that landfill disposal is limited in the coming years to 15% of the waste generated globally. The lower limits correspond to the sum of the mitigation potential in the high recycling and increased incineration scenarios in the Monni et al. 2006 study.

averages and therefore not necessarily applicable to local conditions.

10.4.8 Fluorinated gases: end-of-life issues, data and trends in the waste sector

The CFCs and HCFCs regulated as ozone-depleting substances (ODS) under the Montreal Protocol can persist for many decades in post-consumer waste and occur as trace components in landfill gas (Scheutz et al., 2003). The HFCs regulated under the Kyoto Protocol are promoted as substitutions for the ODS. High global-warming potential (GWP) fluorinated gases have been used for more than 70 years: the most important are the chlorofluorocarbons (CFCs), hydrochlorofluorocarbons (HCFCs) and the hydrofluorocarbons (HFCs) with the existing bank of CFCs and HCFCs estimated to be >1.5 Mt and 0.75 Mt, respectively (TFFEoL, 2005; IPCC, 2005). These gases have been used as refrigerants, solvents, blowing agents for foams and as chemical intermediates. End-of-life issues in the waste sector are mainly relevant for the foams; for other products, release will occur during use or just after end-of-life. For the rigid foams, releases during use are small (Kjeldsen and Jensen, 2001, Kjeldsen and Scheutz, 2003, Scheutz et al. 2003b), so most of the original content is still present at the end of their useful life. The rigid foams include polyurethane and polystyrene used as insulation in appliances and buildings: in these, CFC-11 and CFC-12 were the main blowing agents until the mid-1990s. After the mid-1990s, HCFC-22, HCFC-141b and HCFC-142b with HFC-134a have been used (CALEB, 2000). Considering that home appliances are the foam-containing product with the lowest lifetime (average maximum lifetime 15 years, TFFEoL, 2005), a significant fraction of the CFC-11 in appliances has already entered waste management systems. Building insulation has a much longer lifetime (estimated to 30-80 years, Gamlen et al., 1986) and most of the fluorinated gases in building insulation have not yet reached the end of their useful life (TFFEoL, 2005). Daniel et al. (2007) discuss the uncertainties and some possible temporal trends for depletion of CFC-11 and CFC-12 banks.

Consumer products containing fluorinated gases are managed in different ways. After 2001, landfill disposal of appliances was prohibited in the EU (IPCC, 2005), resulting in appliance-recycling facilities. A similar system was established in Japan in 2001 (IPCC, 2005). For other developed countries, appliance foams are often buried in landfills, either directly or following shredding and metals recycling. For rigid foams, shredding results in an instantaneous release with the fraction released related to the final particle size (Kjeldsen and Scheutz, 2003). A recent study estimating CFC-11 releases after shredding at three American facilities showed that 60–90% of the CFC remains and is slowly released following landfill disposal (Scheutz et al., 2005a). In the US and other countries, appliances typically undergo mechanical recovery of ferrous metals with landfill disposal of residuals. A study has shown that 8–40% of the CFC-11 is lost during segregation (Scheutz et al., 2002; Fredenslund et al., 2005). Then, during landfilling, the compactors shred residual foam materials and further enhance instantaneous gaseous releases.

In the anaerobic landfill environment, some fluorinated gases may be biodegraded because CFCs and, to some extent, HCFCs can undergo dechlorination (Scheutz et al., 2003b). Potentially this may result in the production of more toxic intermediate degradation products (e.g., for CFC-11, the degradation products can be HCFC-21 and HCFC-31). However, recent laboratory experiments have indicated rapid CFC-11 degradation with only minor production of toxic intermediates (Scheutz et al., 2005b). HFCs have not been shown to undergo either anaerobic or aerobic degradation. Thus, landfill attenuation processes may decrease emissions of some fluorinated gases, but not of others. However, data are entirely lacking for PFCs, and field studies are needed to verify that CFCs and HCFCs are being attenuated in situ in order to guide future policy decisions.

10.4.9 Air quality issues: NMVOCs and combustion emissions

Landfill gas contains trace concentrations of aromatic, chlorinated and fluorinated hydrocarbons, reduced sulphur gases and other species. High hydrocarbon destruction efficiencies are typically achieved in enclosed flares (>99%), which are recommended over lower-efficiency open flares. Hydrogen sulphide is mainly a problem at landfills which co-dispose large quantities of construction and demolition debris containing gypsum board. Emissions of NO_x can sometimes be a problem for permitting landfill gas engines in strict air quality regions.

At landfill sites, recent field studies have indicated that NMVOC fluxes through final cover materials are very small with both positive and negative fluxes ranging from approximately 10^{-8} to 10^{-4} g/m/d for individual species (Scheutz et al., 2003a; Boguer et al., 2003; Barlaz et al., 2004). In general, the emitted compounds consist of species recalcitrant to aerobic degradation (especially higher chlorinated compounds), while low to negative emissions (uptake from the atmosphere) are observed for species which are readily degradable in aerobic cover soils, such as the aromatics and vinyl chloride (Scheutz et al., 2003a).

Uncontrolled emissions resulting from waste incineration are not permitted in developed countries, and incinerators are equipped with advanced emission controls. Modern incinerators must meet stringent emission-control standards in Japan, the EU, the US and other developed countries (EIPPC Bureau, 2006). For reducing incinerator emissions of volatile heavy metals and dioxins/dibenzofurans, the removal of batteries, other electronic waste and polyvinyl chloride (PVC) plastics is recommended prior to combustion (EIPPC Bureau, 2006).

10.5 Policies and measures: waste management and climate

GHG emissions from waste are directly affected by numerous policy and regulatory strategies that encourage energy recovery from waste, restrict choices for ultimate waste disposal, promote waste recycling and re-use, and encourage waste minimization. In many developed countries, especially Japan and the EU, waste-management policies are closely related to and integrated with climate policies. Although policy instruments within the waste sector consist mainly of regulations, there are also economic measures to promote recycling, waste minimization and selected waste management technologies. In industrialized countries, waste minimization and recycling are encouraged through both policy and regulatory drivers. In developing countries, major policies are aimed at restricting the uncontrolled dumping of waste. Table 10.6 provides an overview of policies and measures, some of which are discussed below.

10.5.1 Reducing landfill CH_4 emissions

There are two major strategies to reduce landfill CH_4 emissions: implementation of standards that require or encourage landfill CH_4 recovery and a reduction in the quantity of biodegradable waste that is landfilled. In the US, landfill CH_4 emissions are regulated indirectly under the Clean Air Act (CAA) Amendments/New Source Performance Standards (NSPS) by applying a landfill-gas generation model, either measured or default mixing ratios for total non-methane organic compounds (NMOCs), and restricting the emissions of NMOCs. Larger quantities of landfill CH_4 are also being annually recovered to both comply with air-quality regulations and provide energy, assisted by national tax credits and local renewable-energy/green-power initiatives. As discussed above, the EU landfill directive (1999/31/EC) requires a phased reduction in landfilled biodegradable waste to 50% of 1995 levels by 2009 and 35% by 2016, as well as the collection and flaring of landfill gas at existing sites (Commission of the European Community, 2001). However, increases in the availability of landfill alternatives (recycling, composting, incineration, anaerobic digestion and MBT) are required to achieve these regulatory goals (Price, 2001).

Landfill CH_4 recovery has also been encouraged by economic and regulatory incentives. In the UK, for example, the Non Fossil Fuel Obligation, requiring a portion of electrical generation capacity from non-fossil sources, provided a major incentive for landfill gas-to-electricity projects during the 1980s and 1990s. It has now been replaced by the Renewables Obligation. In the US, as mentioned above, the implementation of CAA regulations in the early 1990s provided a regulatory driver for gas recovery at large landfills; in parallel, the US EPA Landfill Methane Outreach Program provides technical support, tools and resources to facilitate landfill gas utilization projects in the US and abroad. Also, periodic tax credits in the US have provided an economic incentive for landfill gas utilization – for example, almost 50 of the 400+ commercial projects in the US started up in 1998, just before the expiration of federal tax credits. A small US tax credit has again become available for landfill gas and other renewable energy sources; in addition, some states also provide economic incentives through tax structures or renewable energy credits and bonds. Other drivers include state requirements that a portion of electrical energy be derived from renewables, green-power programmes (which allow consumers to select renewable providers), regional programmes to reduce GHG emissions (the RGGI/ Regional GHG Initiative in the northeastern states; a state programme in California) and voluntary markets (such as the Chicago Climate Exchange with binding commitments by members to reduce GHG emissions).

In non-Annex I countries, it is anticipated that landfill CH_4 recovery will increase significantly in the developing countries of Asia, South America and Africa during the next two decades as controlled landfilling is phased in as a major waste-disposal

Table 10.6: Examples of policies and measures for the waste management sector.

Policies and measures	Activity affected	GHG affected	Type of instruments
Reducing landfill CH_4 emissions			
Standards for landfill performance to reduce landfill CH_4 emissions by capture and combustion of landfill gas with or without energy recovery	Management of landfill sites	CH_4	Regulation Economic Incentive
Reduction in biodegradable waste that is landfilled.	Disposal of biodegradable waste	CH_4	Regulation
Promoting incineration and other thermal processes for waste-to-energy			
Subsidies for construction of incinerator combined with standards for energy efficiency	Perfomance standards for incinerators	CO_2 CH_4	Regulation
Tax exemption for electricity generated by waste incineration with energy recovery	Energy recovery from incineration of waste	CO_2 CH_4	Economic Incentive
Promoting waste minimization, re-use and recovery			
Extended Producer Responsibility (EPR)	Manufacture of products Recovery of used products Disposal of waste	CO_2 CH_4 Fluorinated gases	Regulation Voluntary
Unit pricing / Variable rate pricing / Pay-as-you-throw (PAYT)	Recovery of used products Disposal of waste	CO_2 CH_4	Economic incentive
Landfill tax	Recovery of used products Disposal of waste	CO_2 CH_4	Regulation
Separate collection and recovery of specific waste fractions	Recovery of used products Disposal of waste	CO_2 CH_4	Subsidy
Promotion of the use of recycled products	Manufacturing of products	CO_2 CH_4	Regulation Voluntary
Wastewater and sludge treatment			
Collection of CH_4 from wastewater treatment system	Management of wastewater treatment system	CH_4	Regulation Voluntary
Post-consumer management of fluorinated gases			
Substitutes for gases used commercially	Production of fluorinated gases	Fluorinated gases	Regulation Economic Incentive Voluntary
Collection of fluorinated gases from end-of-life products	Management of end-of-life products	Fluorinated gases	Regulation Voluntary
JI and CDM in waste management sector			
JI and CDM	Landfill gas and biogas recovery	CO_2 CH_4	Kyoto mechanism

strategy. Where this occurs in parallel with deregulated electrical markets and more decentralized electrical generation, it can provide a strong driver for increased landfill CH_4 recovery with energy use. Significantly, both JI in the EIT countries and the recent availability of the Clean Development Mechanism (CDM) in developing countries are providing strong economic incentives for improved landfilling practices (to permit gas extraction) and landfill CH_4 recovery. Box 10.2 summarizes the important role of landfill CH_4 recovery within CDM and gives an example of a successful project in Brazil.

10.5.2 Incineration and other thermal processes for waste-to-energy

Thermal processes can efficiently exploit the energy value of post-consumer waste, but the high cost of incineration with emission controls restricts its sustainable application in many developing countries. Subsidies for construction of incinerators have been implemented in several countries, usually combined with standards for energy efficiency (Austrian Federal Government, 2001; Government of Japan, 1997). Tax exemptions for electricity generated by waste incinerators (Government of the Netherlands, 2001) and for waste disposal with energy recovery (Government of Norway, 2002) have been adopted. In Sweden, it has been illegal to landfill pre-sorted combustible waste since 2002 (Swedish Environmental Protection Agency, 2005). Landfill taxes have also been implemented in a number of EU countries to elevate the cost of landfilling to encourage more costly alternatives (incineration, industrial co-combustion, MBT). In the UK, the landfill tax has also been used as a funding mechanism for environmental and community projects, as discussed by Morris et al. (2000) and Grigg and Read (2001).

10.5.3 Waste minimization, re-use and recycling

Widely implemented policies include Extended Producer Responsibility (EPR), unit pricing (or PAYT/Pay As You Throw) and landfill taxes. Waste reduction can also be promoted by recycling programmes, waste minimization and other measures (Miranda et al., 1994; Fullerton and Kinnaman, 1996). The EPR regulations extend producer responsibility to the post-consumer period, thus providing a strong incentive to redesign products using fewer materials as well as those with increased recycling potential (OECD, 2001). Initially, EPR programmes were reported to be expensive (Hanisch, 2000), but the EPR concept is very broad: a number of successful schemes have been implemented in various countries for diverse waste fractions such as packaging waste, old vehicles and electronic equipment. EPR programmes range in complexity and cost, but waste reductions have been reported in many countries and regions. In Germany, the 1994 Closed Substance Cycle and Waste Management Act, other laws and voluntary agreements have restructured waste management over the past 15 years (Giegrich and Vogt, 2005).

Unit pricing has been widely adopted to decrease landfilled waste and increase recycling (Miranda et al., 1996). Some municipalities have reported a secondary increase in waste generation after an initial decrease following implementation of unit pricing, but the ten-year sustainability of these programmes has been demonstrated (Yamakawa and Ueta, 2002).

Separate and efficient collection of recyclable materials is needed with both PAYT and landfill tax systems. For kerbside programmes, the percentage recycled is related to the efficiency of kerbside collection and the duration of the programme (Jenkins et al., 2003). Other policies and measures include local subsidies and educational programmes for collection of recyclables, domestic composting of biodegradable waste and procurement of recycled products (green procurement). In the US, for example, 21 states have requirements for separate collection of garden (green) waste, which is diverted to composting or used as an alternative daily cover on landfills.

10.5.4 Policies and measures on fluorinated gases

The HFCs regulated under the Kyoto Protocol substitute for the ODS. A number of countries have adopted collection systems for products still in use based on voluntary agreements (Austrian Federal Government, 2001) or EPR regulations for appliances (Government of Japan, 2002). Both the EU and Japan have successfully prohibited landfill disposal of appliances containing ODS foams after 2001 (TFFEoL, 2005).

10.5.5 Clean Development Mechanism/Joint Implementation

Because lack of financing is a major impediment to improved waste and wastewater management in EIT and developing countries, the JI and CDM have been useful mechanisms for obtaining external investment from industrialized countries. As described in Section 10.3, open dumping and burning are common waste disposal methods in many developing countries, where GHG emissions occur concurrently with odours, public health and safety problems, and environmental degradation. In addition, developing countries often do not have existing infrastructure for collection and treatment of municipal wastewaters. Thus, the benefits from JI and CDM are twofold: improving waste management practices and reducing GHG emissions. To date, CDM has assisted many landfill gas recovery projects (see Box 10.2) while improving landfill operations, because adequate cover materials are required to minimize air intrusion during gas extraction (to prevent internal landfill fires). The validation of CDM projects requires attention to baselines, additionality and other criteria contained in approved methodologies (Hiramatsu et al., 2003); however, for landfill gas CDM projects, certified emission reductions (CERs, with units of tCO2-eq) are determined directly from quantification of the CH_4 captured and combusted. In many countries, the anaerobic digestion of wastewaters and sludges could produce a useful biogas for heating use or onsite electrical generation (Government of Japan, 1997; Government of Republic of Poland, 2001); such projects could also be suitable for JI and CDM. In the future, waste sector projects involving municipal wastewater treatment, carbon storage in landfills or compost, and avoided GHG emissions due to recycling, composting, or incineration could potentially be implemented pending the development of approved methodologies.

10.5.6 Non-climate policies affecting GHG emissions from waste

The EIT and many developing countries have implemented market-oriented structural reforms that affect GHG emissions. As GDP is a key parameter to predict waste generation (Daskalopoulos et al., 1998), economic growth affects the consumption of materials, the production of waste, and hence GHG emissions from the waste sector. Decoupling waste generation from economic and demographic drivers, or dematerialization, is often discussed in the context of sustainable development. Many developed countries have reported recent decoupling trends (OECD, 2002a), but the literature shows no absolute decline in material consumption in developed countries (Bringezu et al., 2004). In other words, solid waste generation does not support an environmental Kuznets curve (Dinda, 2004), because environmental problems related to waste are not fully internalized. In Asia, Japan and China are both encouraging 'circular economy' or 'sound material-cycle society' as a new development strategy, whose core concept is the circular (closed) flow of materials and the use of raw materials and energy through multiple phases (Japan Ministry of the Environment, 2003; Yuan et al., 2006). This approach is expected to achieve efficient economic growth while discharging fewer pollutants.

Box 10.2: Significant role of landfill gas recovery for CDM projects: overview and example

As of late October 2006, 376 CDM projects had achieved registration. These include 33 landfill gas projects, which collectively total 12% of the annual average CERs (12 million of approximately 91 million CERs per year). (http://cdm.unfccc.int/Projects/registered.html). The pie chart shows the distribution of landfill gas CERs by country. Most of these projects are located in Latin America and the Carribean region (72% of landfill gas CERs), dominated by Brazil (nine projects; 48% of CERs). Some projects are flaring gas, while others are using the gas for on-site electrical generation or direct-use projects (including leachate evaporation). Although eventual landfill gas utilization is desirable, an initial flaring project under CDM can simplify the CDM process (fewer participants, lower capital cost) and permit definition of composite gas quantity and quality prior to capital investment in engines or other utilization hardware.

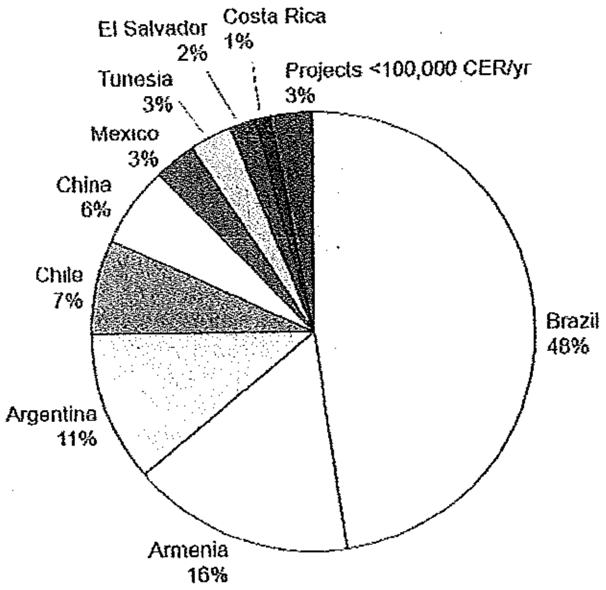


Figure 10.9: Distribution of landfill gas CDM projects based on average annual CERs for registered projects late October 2006 (unfccc.org). Includes 10.9 Mt CERs for landfill CH_4 of 91 Mt total CERs. Projects <100,000 CERs/yr are located in Israel, Bolivia, Bangladesh and Malaysia

An example of a successful Brazilian project is the ONYX SASA Landfill Gas Recovery Project at the VES landfill, Trémembé, Sao Paulo State (Figure 10.10). The recovered landfill gas is flared and used to evaporate leachate. As of December, 2005, approximately 93,600 CERs had been delivered (Veolia Environmental Services, 2005).

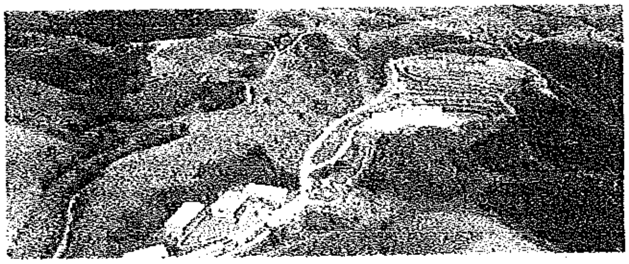


Figure 10.10: ONYX SASA Landfill Gas Recovery Project, VES landfill, Trémembé, Sao Paulo State

In 2002, the Johannesburg Summit adopted the Millennium Development Goals to reduce the number of people without access to sanitation services by 50% via the financial, technical and capacity-building expertise of the international community. If achieved, the Johannesburg Summit goals would significantly reduce GHG emissions from wastewater.

10.5.7 Co-benefits of GHG mitigation policies

Most policies and measures in the waste sector address broad environmental objectives, such as preventing pollution, mitigating odours, preserving open space and maintaining air, soil and water quality (Burnley, 2001). Thus, reductions in GHG emissions frequently occur as a co-benefit of regulations and policies not undertaken primarily for the purpose of climate-change mitigation (Austrian Federal Government, 2001). For example, the EU Landfill Directive is primarily concerned with preventing pollution of water, soil and air (Burnley, 2001).

10.6 Long-term considerations and sustainable development

10.6.1 Municipal solid waste management

GHG emissions from waste can be effectively mitigated by current technologies. Many existing technologies are also cost effective: for example, landfill gas recovery for energy use can be profitable in many developed countries. However, in developing countries, a major barrier to the diffusion of technologies is lack of capital – thus the CDM, which is increasingly being implemented for landfill gas recovery projects, provides a major incentive for both improved waste management and GHG emission reductions. For the long term, more profound changes in waste management strategy are expected in both developed and developing countries, including more emphasis on waste minimization, recycling, re-use and energy recovery. Huhtala (1997) studied optimal recycling rates for municipal solid waste using a model that included recycling costs and consumer preferences; results suggested that a recycling rate of 50% was achievable, economically justified and environmentally preferable. This rate has already been achieved in many countries for the more valuable waste fractions such as metals and paper (OECD, 2002b).

Decisions for alternative waste management strategies are often made locally; however, there are also regional drivers based on national regulatory and policy decisions. Selected waste management options also determine GHG mitigation options. For the many countries which continue to rely on landfilling, increased utilization of landfill CH_4 can provide a cost-effective mitigation strategy. The combination of gas utilization for energy with biocover landfill cover designs to increase CH_4 oxidation can largely mitigate site-specific CH_4 emissions (Huber-Humer, 2004; Barlaz et al., 2004). These technologies are simple ('low technology') and can be readily deployed at any site. Moreover, R&D to improve gas-collection efficiency, design biogas engines and turbines with higher efficiency, and develop more cost-effective gas purification technologies are underway. These improvements will be largely incremental but will increase options, decrease costs, and remove existing barriers for expanded applications of these technologies.

Advances in waste-to-energy have benefited from general advances in biomass combustion; thus the more advanced technologies such as fluidized bed combustion with emissions control can provide significant future mitigation potential for the waste sector. When the fossil fuel offset is also taken into account, the positive impact on GHG reduction can be even greater (e.g., Lohiniva et al. 2002; Pipatti and Savolainen 1996; Consonni et al. 2005). High cost, however, is a major barrier to the increased implementation of waste-to-energy. Incineration has often proven to be unsustainable in developing countries – thus thermal processes are expected to be primarily (but not exclusively) deployed in developed countries. Advanced combustion technologies are expected to become more competitive as energy prices increase and renewable energy sources gain larger market share.

Anaerobic digestion as part of MBT, or as a stand-alone process for either wastewater or selected wastes (high moisture), is expected to continue in the future as part of the mix of mature waste management technologies. In general, anaerobic digestion technologies incur lower capital costs than incineration; however, in terms of national GHG mitigation potential and energy offsets, their potential is more limited than landfill CH_4 recovery and incineration. When compared to composting, anaerobic digestion has advantages with respect to energy benefits (biogas), reduced process times and reduced volume of residuals; however, as applied in developed countries, it typically incurs higher capital costs. Projects where mixed municipal waste was anaerobically digested (e.g., the Valorga project) have been largely discontinued in favour of projects using specific biodegradable fractions such as food waste. In some developing countries such as China and India, small-scale digestion of biowaste streams with CH_4 recovery and use has been successfully deployed for decades as an inexpensive local waste-to-energy strategy – many other countries could also benefit from similar small-scale projects. For both as a primary wastewater treatment process or for secondary treatment of sludges from aerobic processes, anaerobic digestion under higher temperature using thermophilic regimes or two-stage processes can provide shorter retention times with higher rates of biogas production.

Regarding the future of up-front recycling and separation technologies, it is expected that wider implementation of incrementally-improving technologies will provide more rigorous process control for recycled waste streams transported to secondary markets or secondary processes, including paper and aluminium recycling, composting and incineration. If analysed within an LCA perspective, waste can be considered a resource, and these improvements should result in more advantageous material and energy balances for both individual components and urban waste streams as a whole. For developing countries, provided sufficient measures are in place to protect workers and the local environment, more labour-intensive recycling practices can be introduced and sustained to conserve materials, gain energy benefits and reduce GHG emissions. In general, existing studies on the mitigation potential for recycling yield variable results because of the differing assumptions and methodologies applied; however, recent studies (i.e., Myllymaa et al., 2005) are beginning to quantitatively examine the environmental benefits of alternative waste strategies, including recycling.

10.6.2 Wastewater management

Although current GHG emissions from wastewater are lower than emissions from waste, it is recognized that there are substantial emissions which are not quantified by current estimates, especially from septic tanks, latrines and uncontrolled discharges in developing countries. Nevertheless, the quantity of wastewater collected and treated is increasing in many countries in order to maintain and improve potable water quality, as well for other public health and environmental protection benefits. Concurrently, GHG emissions from wastewater will decrease relative to future increases in wastewater collection and treatment.

For developing countries, it is a significant challenge to develop and implement innovative, low-cost but effective and sustainable measures to achieve a basic level of improved sanitation (Moe and Reingans, 2006). Historically, sanitation

Table 10.7: Summary of adaptation, mitigation and sustainable development issues for the waste sector.

Technologies and practices	Vulnerability to climate change	Adaptation implications & strategies to minimize emissions	Sustainable development dimensions			Comments
			Social	Economic	Environmental	
Recycling, reuse & waste minimization	Indirect low vulnerability or no vulnerability	Minimal implications	Usually positive Negative for waste scavenging without public health or safety controls	Positive Job creation	Positive Negative for waste scavenging from open dumpsites with air and water pollution	Indirect benefits for reducing GHG emissions from waste Reduces use of energy and raw materials. Requires implementation of health and safety provisions for workers
Controlled landfilling with landfill gas recovery and utilization	Indirect low vulnerability or positive effects: Higher temperatures increase rates of microbial methane oxidation rates in cover materials	Minimal implications May be regulatory mandates or economic incentives Replaces fossil fuels for process heat or electrical generation	Positive Odour reduction (non-CH_4 gases)	Positive Job creation Energy recovery potential	Positive Negative for improperly managed sites with air and water pollution	Primary control on landfill CH_4 emissions with >1200 commercial projects Important local source of renewable energy: replaces fossil fuels Landfill gas projects comprise 12% of annual registered CERs under CDM[a] Oxidation of CH_4 and NMVOCs in cover soils is a smaller secondary control on emissions
Controlled landfilling without landfill gas recovery	Indirect low vulnerability or positive effects: Higher temperatures increase rates of microbial methane oxidation rates in cover materials	Minimal implications Gas monitoring and control still required	Positive Odour reduction (non-CH_4 gases)	Positive Job creation	Positive Negative for improperly managed sites with air and water pollution	Use of cover soils and oxidation in cover soils reduce rate of CH_4 and NMVOC emissions
Optimizing microbial methane oxidation in landfill cover soils ('biocovers')	Indirect low vulnerability or positive effects: Increased rates at higher temperatures	Minimal implications or positive effects	Positive Odour reduction (non-CH_4 gases)	Positive Job creation	Positive Negative for improperly designed or managed biocovers with GHG emissions and NMVOC emissions	Important secondary control on landfill CH_4 emissions and emissions of NMVOCs Utilizes other secondary materials (compost, composted sludges) Low-cost low-technology strategy for developing countries
Uncontrolled disposal (open dumping & burning)	Highly vulnerable Detrimental effects: warmer temp. promote pathogen growth and disease vectors	Exacerbates adaptation problems Recommend implementation of more controlled disposal and recycling practices	Negative	Negative	Negative	Consider alternative lower-cost medium technology solutions (e.g., landfill with controlled waste placement, compaction, and daily cover materials)
Thermal processes including incineration, industrial co-combustion, and more advanced processes for waste-to-energy (e.g., fluidized bed technology with advanced flue gas cleaning)	Low vulnerability	Minimal implications Requires source control and emission controls to prevent emissions of heavy metals, acid gases, dioxins and other air toxics	Positive Odour reduction (non-CH_4 gases)	Positive Job creation Energy recovery potential	Positive Negative for improperly designed or managed facilities without air pollution controls	Reduces GHG emissions relative to landfilling Costly, but can provide significant mitigation potential for the waste sector, especially in the short term Replaces fossil fuels
Aerobic biological treatment (composting) Also a component of mechanical biological treatment (MBT)	Indirect low vulnerability or positive effects: Higher temperatures increase rates of biological processes (Q_{10})	Minimal implications or positive effects Produces CO_2 (biomass) and compost Reduces volume, stabilizes organic C, and destroys pathogens	Positive Odour reduction (non-CH_4 gases)	Positive Job creation Use of compost products	Positive Negative for improperly designed or managed facilities with odours, air and water pollution	Reduces GHG emissions Can produce useful secondary materials (compost) provided there is quality control on material inputs and operations Can emit N_2O and CH_4 under reduced aeration or anaerobic conditions
Anaerobic biological treatment (anaerobic digestion) Also a component of mechanical-biological treatment (MBT)	Indirect low vulnerability or positive effects: Higher temperatures increase rates of biological processes	Minimal implications Produces CH_4, CO_2, and biosolids under highly controlled conditions Biosolids require management	Positive Odour reduction (non-CH_4 gases)	Positive Job creation Energy recovery potential Use of residual biosolids	Positive Negative for improperly designed or managed facilities with, odours, air and water pollution	Reduces GHG emissions CH_4 in biogas can replace fossil fuels for process heat or electrical generation Can emit minor quantities of CH_4 during start-ups, shutdowns and malfunctions
Wastewater control and treatment (aerobic or anaerobic)	Highly vulnerable Detrimental effects in absence of wastewater control and treatment: Warmer temperatures promote pathogen growth and poor public health	Large adaptation implications High potential for reducing uncontrolled GHG emissions Residuals (biosolids) from aerobic treatment may be anaerobically digested	Positive Odour reduction (non-CH_4 gases)	Positive Job creation Energy recovery potential from anaerobic processes Use of sludges and other residual biosolids	Positive Negative for improperly designed or managed facilities with odours, air and water pollution and GHG emissions	Wide range of available technologies to collect, treat, recycle and re-use wastewater Wide range of costs CH_4 from anaerobic processes replaces fossil fuels for process heat or electrical generation Need to design and operate to minimize N_2O and CH_4 emissions during transport and treatment

a http://cdm.unfccc.int/Projects/registered.html, October 2006 in developed countries has included costly centralized sewerage and wastewater treatment plants, which do not offer appropriate sustainable solutions for either rural areas in developing countries with low population density or unplanned, rapidly growing, peri-urban areas with high population density (Montgomery and Elimelech, 2007). It has been demonstrated that a combination of low-cost technology with concentrated efforts for community acceptance, participation and management can successfully expand sanitation coverage; for example, in India more than one million pit latrines have been built and maintained since 1970 (Lenton et al., 2005). The combination of household water treatment and 'point-of-use' low-technology improved sanitation in the form of pit latrines or septic systems has been shown to lower diarrhoeal diseases by >30% (Fewtrell et al., 2005).

Wastewater is also a secondary water resource in countries with water shortages. Future trends in wastewater technology include buildings where black water and grey water are separated, recycling the former for fertilizer and the latter for toilets. In addition, low-water use toilets (3–5 L) and ecological sanitation approaches (including ecological toilets), where nutrients are safely recycled into productive agriculture and the environment, are being used in Mexico, Zimbabwe, China, and Sweden (Esrey et al., 2003). These could also be applied in many developing and developed countries, especially where there are water shortages, irregular water supplies, or where additional measures for conservation of water resources are needed. All of these measures also encourage smaller wastewater treatment plants with reduced nutrient loads and proportionally lower GHG emissions.

10.6.3 Adaptation, mitigation and sustainable development in the waste sector

In addition to providing mitigation of GHG emissions, improved public health, and environmental benefits, solid waste and wastewater technologies confer significant co-benefits for adaptation, mitigation and sustainable development (Table 10.7; see also Section 12.3.4). In developing countries, improved waste and wastewater management using low- or medium-technology strategies are recommended to provide significant GHG mitigation and public health benefits at lower cost. Some of these strategies include small-scale wastewater management such as septic tanks and recycling of grey water, construction of medium-technology landfills with controlled waste placement and use of daily cover (perhaps including a final biocover to optimize CH_4 oxidation), and controlled composting of organic waste.

The major impediment in developing countries is the lack of capital, which jeopardizes improvements in waste and wastewater management. Developing countries may also lack access to advanced technologies. However, technologies must be sustainable in the long term, and there are many examples of advanced, but unsustainable, technologies for waste management that have been implemented in developing countries. Therefore, the selection of truly sustainable waste and wastewater strategies is very important for both the mitigation of GHG emissions and for improved urban infrastructure.

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Policy Analysis

Is It Better To Burn or Bury Waste for Clean Electricity Generation?

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Is It Better To Burn or Bury Waste for Clean Electricity Generation?

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The use of municipal solid waste (MSW) to generate electricity through landfill-gas-to-energy (LFGTE) and waste-to-energy (WTE) projects represents roughly 14% of U.S. nonhydro renewable electricity generation. Although various aspects of LFGTE and WTE have been analyzed in the literature, this paper is the first to present a comprehensive set of life-cycle emission factors per unit of electricity generated for these energy recovery options. In addition, sensitivity analysis is conducted on key inputs (e.g., efficiency of the WTE plant, landfill gas management schedules, oxidation rate, and waste composition) to quantify the variability in the resultant life-cycle emissions estimates. While methane from landfills results from the anaerobic breakdown of biogenic materials, the energy derived from WTE results from the combustion of both biogenic and fossil materials. The greenhouse gas emissions for WTE ranges from 0.4 to 1.5 $MTCO_2e/MWh$, whereas the most agressive LFGTE scenario results in 2.3 $MTCO_2e/MWh$. WTE also produces lower NO_x emissions than LFGTE, whereas SO_x emissions depend on the specific configurations of WTE and LFGTE.

Introduction

In response to increasing public concern over air pollution and climate change, the use of renewable energy for electricity generation has grown steadily over the past few decades. Between 2002 and 2006, U.S. renewable electricity generation—as a percent of total generation—grew an average of 5% annually (*1*), while total electricity supply grew by only 1% on average (*2*). Support mechanisms contributing to the growth of renewables in the United States include corporate partnership programs, investment tax credits, renewable portfolio standards, and green power markets. These mechanisms provide electric utilities, investment firms, corporations, governments, and private citizens with a variety of ways to support renewable energy development. With several competing renewable alternatives, investment and purchasing decisions should be informed, at least in part, by rigorous life-cycle assessment (LCA).

In 2005, a total of 245 million tons of MSW was generated in the United States, with 166 million tons discarded to landfills (*3*). Despite the increase in recycling and composting rates, the quantity of waste disposed to landfills is still significant and expected to increase. How to best manage the discarded portion of the waste remains an important consideration, particularly given the electricity generation options. Although less prominent than solar and wind, the use of municipal solid waste (MSW) to generate electricity represents roughly 14% of U.S. nonhydro renewable electricity generation (*1*). In this paper we compare two options for generating electricity from MSW. One method, referred to as landfill-gas-to-energy (LFGTE), involves the collection of landfill gas (LFG) (50% CH_4 and 50% CO_2), which is generated through the anaerobic decomposition of MSW in landfills. The collected LFG is then combusted in an engine or a turbine to generate electricity. A second method, referred to as waste-to-energy (WTE) involves the direct combustion of MSW, where the resultant steam is used to run a turbine and electric generator.

Clean Air Act (CAA) regulations require capture and control of LFG from large landfills by installing a gas collection system within 5 years of waste placement (*4*). The gas collection system is expanded to newer areas of the landfill as more waste is buried. Not all LFG is collected due to delays in gas collection from initial waste placement and leaks in the header pipes, extraction wells, and cover material. Collected gas can be either flared or utilized for energy recovery. As of 2005, there were 427 landfills out of 1654 municipal landfills in the United States with LFGTE projects for a total capacity of 1260 MW. It is difficult to quantify emissions with a high degree of certainty since emissions result from biological processes that can be difficult to predict, occur over multiple decades, and are distributed over a relatively large area covered by the landfill.

CAA regulations require that all WTE facilities have the latest in air pollution control equipment (*5*). Performance data including annual stack tests and continuous emission monitoring are available for all 87 WTE plants operating in 25 states. Since the early development of this technology, there have been major improvements in stack gas emissions controls for both criteria and metal emissions. The performance data indicate that actual emissions are less than regulatory requirements. Mass burn is the most common and established technology in use, though various MSW combustion technologies are described in ref *6*. All WTE facilities in the United States recover heat from the combustion process to run a steam turbine and electricity generator.

Policy-makers appear hesitant to support new WTE through new incentives and regulation. Of the 30 states that have state-wide renewable portfolio standards, all include landfill gas as an eligible resource, but only 19 include waste-to-energy (*7*). While subjective judgments almost certainly play a role in the preference for LFGTE over WTE, there is a legitimate concern about the renewability of waste-to-energy. While the production of methane in landfills is the result of the anaerobic breakdown of biogenic materials, a significant fraction of the energy derived from WTE results from combusting fossil-fuel-derived materials, such as plastics. Countering this effect, however, is significant methane leakage—ranging from 60% to 85%—from landfills (*8*). Since methane has a global warming potential of 21 times that of CO_2, the CO_2e emissions from LFGTE may be larger than those from WTE despite the difference in biogenic composition.

Although WTE and LFGTE are widely deployed and analyzed in the literature (*9*–*13*), side-by-side comparison of the life-cycle inventory (LCI) emission estimates on a mass

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per unit energy basis is unavailable. LCI-based methods have been used to evaluate and compare solid waste management (SWM) unit operations and systems holistically to quantify either the environmental impacts or energy use associated with SWM options in the broad context of MSW management (*14–16*).

The purpose of this paper is to present a comprehensive set of life-cycle emission factors—per unit of electricity generated—for LFGTE and WTE. In addition, these emission factors are referenced to baseline scenarios without energy recovery to enable comparison of the emissions of LFGTE and WTE to those of other energy sources. While the methodology presented here is applicable to any country, this analysis is based on U.S. waste composition, handling, and disposal, with which the authors are most familiar. In addition, parametric sensitivity analysis is applied to key input parameters to draw robust conclusions regarding the emissions from LFGTE and WTE. The resultant emission factors provide critical data that can inform the development of renewable energy policies as well as purchasing and investment decisions for renewable energy projects in the prevailing marketplace.

Modeling Framework

The LFGTE and WTE emission factors are based on the composition and quantity of MSW discarded in the United States in 2005 (Table S1 of Supporting Information (SI)). We excluded the estimated quantity and composition of recycled and composted waste.

The emission factors are generated using the life-cycle-based process models for WTE (*17*) and LF/LFGTE (*18*) embedded in the municipal solid waste decision support tool (MSW-DST). The MSW-DST was developed through a competed cooperative agreement between EPA's Office of Research and Development and RTI International (*19–22*). The research team included North Carolina State University, which had a major role in the development of the LCI database, process, and cost models as well as the prototype MSW-DST. While a summary is provided here, Table S2 (SI) provides a comprehensive set of references for those interested in particular model details. The MSW-DST includes a number of process models that represent the operation of each SWM unit and all associated processes for collection, sorting, processing, transport, and disposal of waste. In addition, there are process models to account for the emissions associated with the production and consumption of gasoline and electricity. The objective of each process model is to relate the quantity and composition of waste entering a process to the cost and LCI of emissions for that process. The LCI emissions are calculated on the basis of a combination of default LCI data and user-input data to enable the user to model a site-specific system. For example, in the landfill process model, one key exogenous input is the efficiency of the LFG collection system. The functional unit in each process model is 1 ton of MSW set out for collection. The MSW includes the nonhazardous solid waste generated in residential, commercial, institutional, and industrial sectors (*3*).

Each process model can track 32 life-cycle parameters, including energy consumption, CO_2, CO, NO_x, SO_x, total greenhouse gases (CO_2e), particulate matter (PM), CH_4, water pollutants, and solid wastes. CO_2 emissions are represented in two forms: fossil and biogenic. CO_2 released from anthropogenic activities such as burning fossil fuels or fossil-fuel-derived products (e.g., plastics) for electricity generation and transportation are categorized as CO_2-fossil. Likewise, CO_2 released during natural processes such as the decay of paper in landfills is categorized as CO_2-biogenic.

The management of MSW will always result in additional emissions due to collection, transportation, and separation of waste. However, for this analysis, the configuration of the SWM system up through the delivery of the waste to either a landfill or WTE facility is assumed to be same.

TABLE 1. Inputs to the Landfill Process Model

	LFG collection system efficiency [a] (%)	oxidation rate (%)
during venting	0	15
during first year of gas collection	50	15
during second year of gas collection	70	15
during third year and on of gas collection	80	15

[a] We assumed efficiency of the collection system based on the year of the operation and the ranges stated in U.S. EPA's AP-42 (*8*).

Electricity Grids. While LFGTE and WTE provide emissions reductions relative to landfill scenarios without energy recovery, the generation of electricity from these sources also displaces conventional generating units on the electricity grid. The process models in MSW-DST can calculate total electricity generated and apply an offset analysis on the grid mix of fuels specific to each of the North American Electric Reliability Council (NERC) regions, an average national grid mix, or a user-defined grid mix. Because our focus is on the emissions differences between WTE and LFGTE technologies, the emissions factors reported here exclude the displaced grid emissions.

For reference purposes, emission factors for conventional electricity-generating technologies are reported along with the emission factors for WTE and LFGTE (*25*). These emission factors on a per megawatt hour basis include both the operating emissions from power plants with postcombustion air pollution control equipment and precombustion emissions due to extraction, processing, and transportation of fuel. The background LCI data are collected on a unit mass of fuel (*23*); when converted on a per unit of electricity generated basis, the magnitude of resultant emissions depends on the efficiency of the power plant. A sensitivity analysis was conducted on plant efficiencies to provide ranges for emission factors.

Estimating Emission Factors for Landfill Gas-to-Energy. The total LCI emissions from landfills are the summation of the emissions resulting from (1) the site preparation, operation, and postclosure operation of a landfill, (2) the decay of the waste under anaerobic conditions, (3) the equipment utilized during landfill operations and landfill gas management operations, (4) the production of diesel required to operate the vehicles at the site, and (5) the treatment of leachate (*18*). The production of LFG was calculated using a first-order decay equation for a given time horizon of 100 years and the empirical methane yield from each individual waste component (*18, 24*). Other model inputs include the quantity and the composition of waste disposed (Table S1, SI), LFG collection efficiency (Table 1), annual LFG management schedule (Figure 1), oxidation rate (Table 1), emission factors for combustion byproduct from LFG control devices (Table S3, SI), and emission factors for equipment used on site during the site preparation and operation of a landfill. While there are hundreds of inputs to the process models, we have modified and conducted sensitivity analysis on the input parameters that will affect the emission factors most significantly.

The emission factors are calculated under the following scenario assumptions: (1) A regional landfill subject to CAA is considered. (2) A single cell in the regional landfill is modeled. (3) Waste is initially placed in the new cell in year 0. (4) The landfill already has an LFG collection network in place. (5) An internal combustion engine (ICE) is utilized to generate electricity. (6) The offline time that is required for

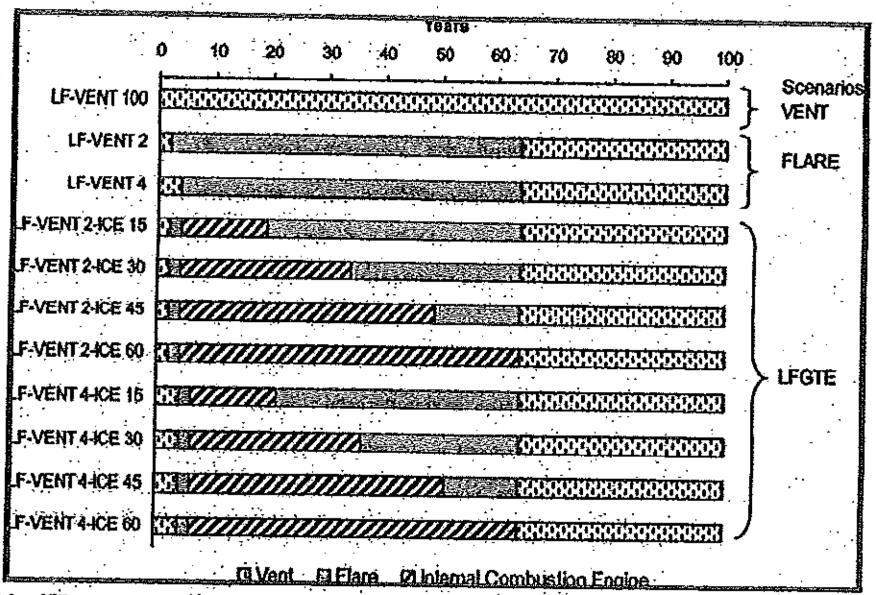

FIGURE 1. Annual landfill gas management schedule assumed for alternative scenarios.

the routine maintenance of the ICE is not considered. (7) The LFG control devices are assumed to have a lifetime of 15 years. (8) The LFG will be collected and controlled until year 65. This assumption is based on a typical landfill with an average operating lifetime of 20 years in which LFG production decreases significantly after about 60 years from initial waste placement. This is based on the use of a first-order decay equation utilizing empirical data from about 50 U.S. LFG collection systems.

The timing of LFG-related operations has significant variation and uncertainty that will influence the total emissions from landfills as well as the emission factors per unit of electricity generated. To capture these uncertainties and variation, several different management schemes were tested. Figure 1 presents the different cases considered for LFGTE projects. Each case differs according to the management timeline of the LFG. For instance, LF-VENT 2-ICE 15 corresponds to no controls on LFG for the first two years, after which the LFG is collected and flared in the third and fourth years. From year 5 until year 19, for a period of 15 years, the LFG is processed through an ICE to generate electricity, after which the collected gas is flared until year 65. Finally from year 65 on, the LFG is released to the atmosphere without controls.

To quantify the emissions benefit from LFGTE and WTE, landfill emissions occurring in the absence of an energy recovery unit can serve as a useful comparison. Thus, three baseline scenarios without electricity generation were defined for comparison to the energy recovery scenarios: LF-VENT 100 (LFG is uncontrolled for the entire lifetime of the LF), LF-VENT 2 (LFG is uncontrolled for the first two years, and then the LFG is collected and flared until year 65), LF-VENT 4 (LFG is uncontrolled for the first four years, and then the LFG is collected and flared until year 65). Since emissions are normalized by the amount of electricity generated (MW h) to obtain the emission rates, an estimate of hypothetical electricity generation for the baseline scenarios must be defined. The average electricity generation from a subset of the energy recovery scenarios is used to calculate the baseline emission rates. For example, emission factors [g/(MW h)] for LF-VENT 2 are based on the average of electricity generated in LF-VENT 2-ICE 15, LF-VENT 2-ICE 30, LF-VENT 2-ICE 45, and LF-VENT 2-ICE 60. Additional sensitivity analysis was conducted on oxidation rates where scenarios were tested for a range of 10–35%.

Estimating Emission Factors for Waste-to-Energy. The total LCI emissions are the summation of the emissions associated with (1) the combustion of waste (i.e., the stack gas (accounting for controls)), (2) the production and use of limestone in the control technologies (i.e., scrubbers), and (3) the disposal of ash in a landfill (*17*).

Emissions associated with the manufacture of equipment such as turbines and boilers for the WTE facility are found to be insignificant (<5% of the overall LCI burdens) and, as a result, were excluded from this analysis (*25*). In addition, WTE facilities have the capability to recover ferrous material from the incoming waste stream and also from bottom ash with up to a 90% recovery rate. The recovered metal displaces the virgin ferrous material used in the manufacturing of steel. The emission offsets from this activity could be significant depending on the amount of ferrous material recovered. Total LCI emissions for WTE were presented without the ferrous offsets; however, sensitivity analysis was conducted to investigate the significance.

In the United States, federal regulations set limits on the maximum allowable concentration of criteria pollutants and some metals from MSW combustors (*5*). The LCI model calculates the controlled stack emissions using either the average concentration values at current WTE facilities based on field data or mass emission limits based on regulatory requirements as upper bound constraints. Two sets of concentration values (Table S4, SI) are used in calculations to report two sets of emission factors for WTE (i.e., WTE-Reg and WTE-Avg). The emission factors for WTE-Reg were based on the regulatory concentration limits (*5*), whereas the emission factors for WTE-Avg were based on the average concentrations at current WTE facilities.

The CO_2 emissions were calculated using basic carbon stoichiometry given the quantity, moisture, and ultimate analysis of individual waste items in the waste stream. The LCI model outputs the total megawatt hour of electricity production and emissions that are generated per unit mass of each waste item. The amount of electricity output is a function of the quantity, energy, and moisture content of the individual waste items in the stream (Table S1, Supporting Information), and the system efficiency. A lifetime of 20 years and a system efficiency of 19% [18000 Btu/(kW h)] were assumed for the WTE scenarios. For each pollutant, the following equation was computed:

$$LCI\_WTE_i = \sum_j \{(LCI\_Stack_{ij} + LCI\_Limestone_{ij} + LCI\_Ash_{ij}) \times Mass_j\}/Elec \quad \text{for all } i \quad (1)$$

where LCI_WTE_i is the LCI emission factor for pollutant i [g/(MW h)], LCI_Stack_{ij} is the controlled stack gas emissions for pollutant i (g/ton of waste item j), $LCI\_Limestone_{ij}$ is the allocated emissions of pollutant i from the production and use of limestone in the scrubbers (g/ton of waste item j), LCI_Ash_{ij} is the allocated emissions of pollutant i from the disposal of ash (g/ton of waste item j), $Mass_j$ is the amount of each waste item j processed in the facility (ton), and Elec is the total electricity generated from MSW processed in the facility (MWh). In addition, the sensitivity of emission factors to the system efficiency, the fossil and biogenic fractions of MSW, and the remanufacturing offsets from steel recovery was quantified.

Results and Discussion

The LCI emissions resulting from the generation of 1 MW h of electricity through LFGTE and WTE as well as coal, natural gas, oil, and nuclear power (for comparative purposes) were calculated. The sensitivity of emission factors to various inputs was analyzed and is reported. Figures 2–4 summarize the emission factors for total CO_2e, SO_x, and NO_x, respectively.

Landfills are a major source of CH_4 emissions, whereas WTE, coal, natural gas, and oil are major sources of CO_2-fossil emissions (Table S5, SI). The magnitude of CH_4 emissions strongly depends on when the LFG collection system is installed and how long the ICE is used. For example, LF-VENT 2-ICE 60 has the least methane emissions among LFGTE alternatives because the ICE is operated the longest (Table S5, SI). CO_2e emissions from landfills were significantly higher than the emissions for other alternatives because of the relatively high methane emissions (Figure 2, Table S5).

The use of LFG control during operation, closure, and postclosure of the landfill as well as the treatment of leachate contributes to the SO_x emissions from landfills. SO_x emissions from WTE facilities occur during the combustion process and are controlled via wet or dry scrubbers. Overall, the SO_x emissions resulting from the LFGTE and WTE alternatives are approximately 10 times lower than the SO_x emissions resulting from coal- and oil-fired power plants with flue gas controls (Figure 3). The SO_x emissions for WTE ranged from 140 to 730 g/(MW h), and for LFGTE they ranged from 430 to 900 g/(MW h) (Table 2, Table S5). In a coal-fired power plant, average SO_x emissions were 6900 g/(MW h) (Table S6 and S7, SI). Another important observation is that the majority of the SO_x emissions from natural gas are attributed to processing of natural gas rather than the combustion of the natural gas for electricity-generating purposes.

The NO_x emissions for WTE alternatives ranged from 810 to 1800 g/(MW h), and for LFGTE they ranged from 2100 to 3000 g/(MW h) (Figure 4, Table 2, Table S5). In a coal-fired power plant, average NO_x emissions are 3700 g/(MW h) (Tables S6 and S7, Supporting Information). The emission factors for other criteria pollutants were also calculated. Besides CO and HCl emissions, the emission factors for all LFGTE and WTE cases are lower than those for the coal-fired generators (Tables S5–S8, SI).

While we have provided a detailed, side-by-side comparison of life-cycle emissions from LFGTE and WTE, there is an important remaining question about scale: How big an impact can energy recovery from MSW make if all of the discarded MSW (166 million tons/year) is utilized? Hypothetically, if 166 million tons of MSW is discarded in regional landfills, energy recovery on average of ~10 TW h or ~65 (kW h)/ton of MSW of electricity can be generated, whereas a WTE facility can generate on average ~100 TW h or ~600 (kW h)/ton of MSW of electricity with the same amount of MSW (Table 3). WTE can generate an order of magnitude more electricity than LFGTE given the same amount of waste. LFGTE projects would result in significantly lower electricity generation because only the biodegradable portion of the MSW contributes to LFG generation, and there are significant inefficiencies in the gas collection system that affect the quantity and quality of the LFG.

Moreover, if all MSW (excluding the recycled and composted portion) is utilized for electricity generation, the WTE alternative could have a generation capacity of 14000 MW, which could potentially replace ~4.5% of the 313000 MW of current coal-fired generation capacity (*26*).

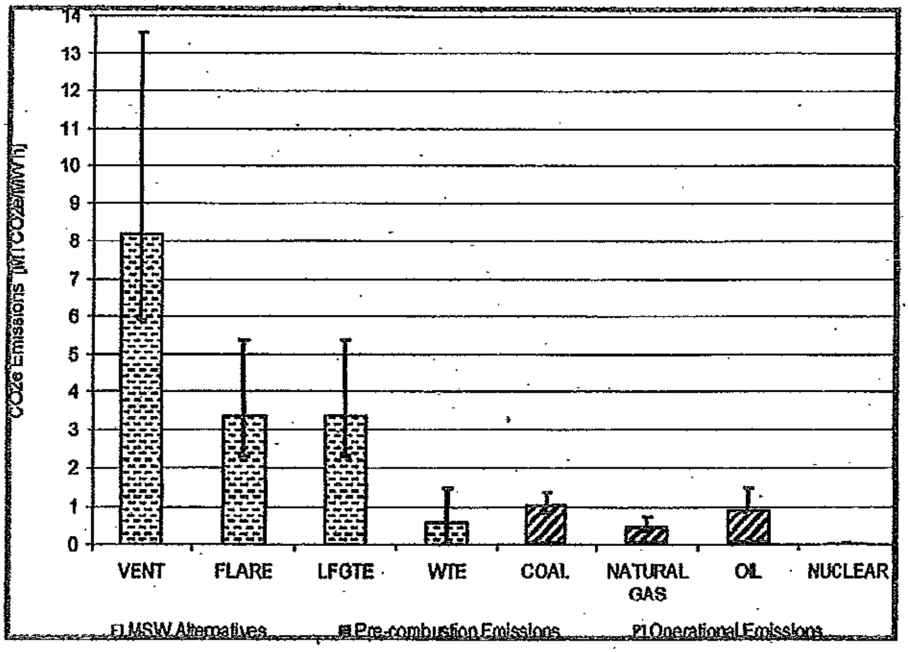

FIGURE 2. Comparison of carbon dioxide equivalents for LFGTE, WTE, and conventional electricity-generating technologies (Tables S5–S8, Supporting Information, include the full data set).

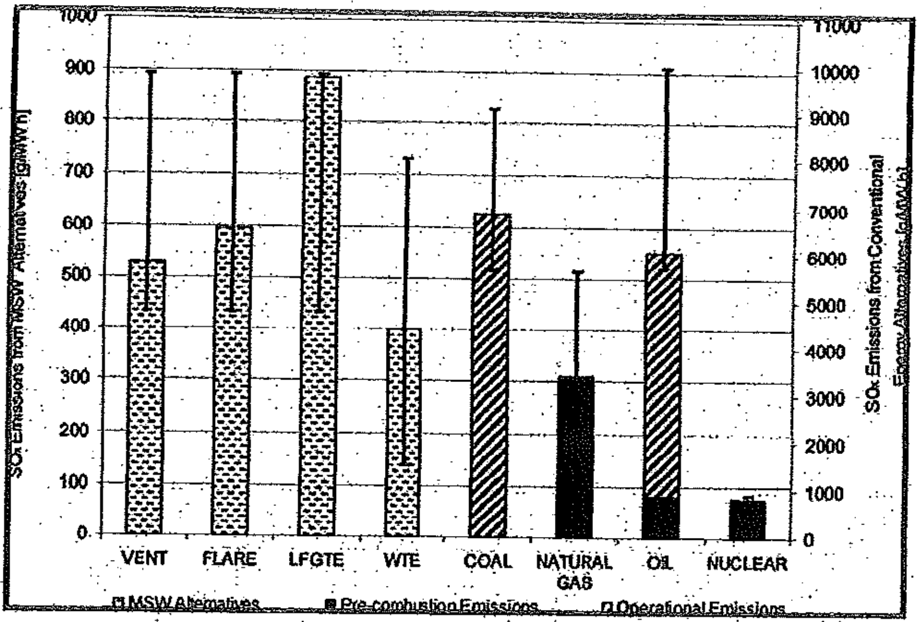

FIGURE 3. Comparison of sulfur oxide emissions for LFGTE, WTE, and conventional electricity-generating technologies (Tables S5–S8, Supporting Information, include the full data set).

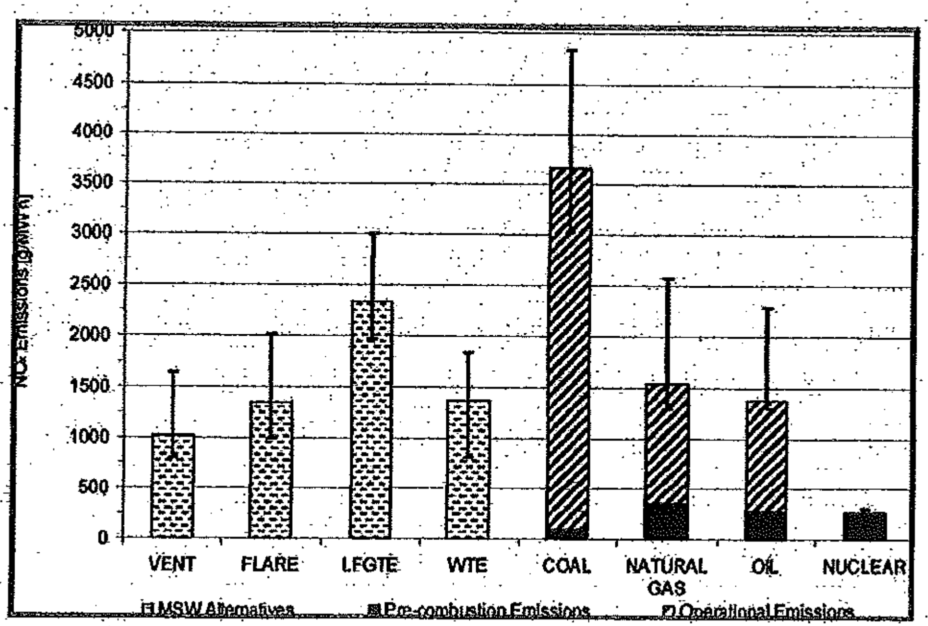

FIGURE 4. Comparison of nitrogen oxide emissions for LFGTE, WTE, and conventional electricity-generating technologies (Tables S5–S8, Supporting Information, include the full data set).

A significant portion of this capacity could be achieved through centralized facilities where waste is transported from greater distances. The transportation of waste could result in additional environmental burdens, and there are clearly limitations in accessing all discarded MSW in the nation. Wanichpongpan studied the LFGTE option for Thailand and found that large centralized landfills with energy recovery performed much better in terms of cost and GHG emissions than small, localized landfills despite the increased burdens associated with transportation (*13*). To quantify these burdens for the United States, emission factors were also calculated for long hauling of the waste via freight or rail. Table S9 (SI) summarizes the emission factors for transporting 1 ton of MSW to a facility by heavy-duty trucks and rail.

Sensitivity analysis was also conducted on key inputs. With incremental improvements, WTE facilities could achieve efficiencies that are closer to those of conventional power plants. Thus, the system efficiency was varied from 15% to 30%, and Table 2 summarizes the resulting LCI emissions. The variation in efficiencies results in a range of 470–930 kWh of electricity/ton of MSW, while with the default heat rate; only 600 (kW h)/ton of MSW can be generated. The efficiency also affects the emission factors; for example, CO_2-fossil emissions vary from 0.36 to 0.71 Mg/(MW h).

The emission savings associated with ferrous recovery decreased the CO_2e emissions of the WTE-Reg case from 0.56 to 0.49 $MTCO_2e/(MW\ h)$. Significant reductions were observed for CO and PM emissions (Table 2).

TABLE 2. Sensitivity of Emission Factors for WTE to Plant Efficiency, Waste Composition, and Remanufacturing Benefits of Steel Recovery

	baseline factors		Sensitivity on: system efficiency	waste composition		steel recovery	
Input Parameters Varied[a]							
heat rate [Btu/(kW h)]	18000	18000	*[11000, 23000]*	18000	18000	18000	18000
efficiency (%)	19	19	*[15, 30]*	19	19	19	19
composition	default	default	default	*all biogenic*	*all fossil*	default	default
stack gas limits	reg	avg	*reg/avg*	reg	reg	*reg*	*avg*
steel recovery	excludes	excludes	excludes	excludes	excludes	*includes*	*includes*
Results: Criteria Pollutants							
CO [g/(MW h)]	790	790	[500,1000]	740	880	−110	−110
NO_x [g/(MW h)]	1300	1500	[810, 1800]	1200	1400	1200	1400
SO_x [g/(MW h)]	578	221	[140, 730]	550	620	450	90
PM [g/(MW h)]	181	60	[38, 230]	180	190	−190	−310
Results: Greenhouse Gases							
CO_2-biogenic [Mg/(MW h)]	0.91	0.91	[0.58, 1.2]	1.5	0.03	0.91	0.91
CO_2-fossil [Mg/(MW h)]	0.56	0.56	[0.36, 0.71]	0.02	1.5	0.49	0.49
CH_4 [Mg/(MW h)]	1.3E−05	1.3E−05	[8.1E−06, 1.6E−05]	1.6E−05	7.9E−06	−5.0E−05	−5.0E−05
CO_2e [$MTCO_2e$/(MW h)]	0.56	0.56	[0.36, 0.71]	0.02	1.45	0.49	0.49
Results: Electricity Generation							
TW h [b]	98	98	[78, 160]	61	37	98	98
(kW h)/ton	590	590	[470, 930]	470	970	590	590
GW [c]	12	12	[9.7, 20]	7.6	4.7	12	12

[a] For each sensitivity analysis scenario, the input parameters in italics were modified and resultant emission factors were calculated and are reported. [b] The values represent the TWh of electricity that could be generated from all MSW disposed into landfills. [c] 1 TWh/8000 h = TW; a capacity factor of approximately 0.91 was utilized.

TABLE 3. Comparison of Total Power Generated

	total electricity generated from 166 million tons of MSW, TW h	total power [a], GW	electricity generated from 1 ton of MSW, (kW h)/ton
waste-to-energy	78–160	9.7–19	470–930
landfill-gas-to-energy	7–14	0.85–1.8	41–84

[a] 1 TW h/8000 h = TW; a capacity factor of approximately 0.91 was utilized.

The composition of MSW also has an effect on the emission factors. One of the controversial aspects of WTE is the fossil-based content of MSW, which contributes to the combustion emissions. The average composition of MSW as discarded by weight was calculated to be 77% biogenic- and 23% fossil-based (Table S1, SI). The sensitivity of emission factors to the biogenic- vs fossil-based waste fraction was also determined. Two compositions (one with 100% biogenic-based waste and another with 100% fossil-based waste) were used to generate the emission factors (Table 2). The CO_2e emissions from WTE increased from 0.56 $MTCO_2e$/(MW h) (WTE-Reg) to 1.5 $MTCO_2e$/(MW h) when the 100% fossil-based composition was used (Table 2, Figure 2). However, the CO_2e emissions from WTE based on 100% fossil-based waste were still lower than the most aggressive LFGTE scenario (i.e., LF-VENT2-ICE60) whose CO_2e emissions were 2.3 $MTCO_2e$/(MW h).

The landfill emission factors include the decay of MSW over 100 years, whereas emissions from WTE and conventional electricity-generating technologies are instantaneous. The operation and decomposition of waste in landfills continue even beyond the monitoring phases for an indefinite period of time. Reliably quantifying the landfill gas collection efficiency is difficult due to the ever-changing nature of landfills, number of decades that emissions are generated, and changes over time in landfill design and operation including waste quantity and composition. Landfills are an area source, which makes emissions more difficult to monitor. In a recent release of updated emission factors for landfill gas emissions, data were available for less than 5% of active municipal landfills (27). Across the United States, there are major differences in how landfills are designed and operated, which further complicates the development of reliable emission factors. This is why a range of alternative scenarios are evaluated with plausible yet optimistic assumptions for LFG control. For WTE facilities, there is less variability in the design and operation. In addition, the U.S. EPA has data for all the operating WTE facilities as a result of CAA requirements for annual stack testing of pollutants of concern, including dioxin/furan, Cd, Pb, Hg, PM, and HCl. In addition, data are available for SO_2, NO_x, and CO from continuous emissions monitoring. As a result, the quality and availability of data for WTE versus LFGTE results in a greater degree of certainty for estimating emission factors for WTE facilities.

The methane potential of biogenic waste components such as paper, food, and yard waste is measured under optimum anaerobic decay conditions in a laboratory study (24), whose other observations reveal that some portion of the carbon in the waste does not biodegrade and thus this quantity gets sequestered in landfills (*28*). However, there is still a debate on how to account for any biogenic "sequestered" carbon. Issues include the choice of appropriate time frame for sequestration and who should be entitled to potential sequestration credits. While important, this analysis does not assign any credits for carbon sequestered in landfills.

Despite increased recycling efforts, U.S. population growth will ensure that the portion of MSW discarded in landfills will remain significant and growing. Discarded MSW is a viable energy source for electricity generation in a carbon-constrained world. One notable difference between LFGTE and WTE is that the latter is capable of producing an order of magnitude more electricity from the same mass of waste. In addition, as demonstrated in this paper, there are significant differences in emissions on a mass per unit energy basis from LFGTE and WTE. On the basis of the assumptions in this paper, WTE appears to be a better option than LFGTE. If the goal is greenhouse gas reduction, then WTE should be considered as an option under U.S. renewable energy policies. In addition, all LFTGE scenarios tested had on the average higher NO_x, SO_x, and PM emissions than WTE. However, HCl emissions from WTE are significantly higher than the LFGTE scenarios.

Supporting Information Available

MSW composition, physical and chemical characteristics of waste items, detailed LCI tables and sensitivity results, and emission factors for long haul of MSW. This material is available free of charge via the Internet at http://pubs.acs.org.

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CENTER FOR A COMPETITIVE WASTE INDUSTRY

COMMENTS to the CALIFORNIA AIR RESOURCES BOARD on LANDFILLS' RESPONSIBILITY for ANTHROPOGENIC GREENHOUSE GASES and the APPROPRIATE RESPONSE TO THOSE FACTS

by

Peter N. Anderson*

INTRODUCTION

This is to provide comment to the Air Resources Board and its staff in order to correct significant misunderstandings concerning the relationship of methane gas generated in landfills to climate change. What follows summarizes our upcoming 150-page report on the subject of landfills' responsibility for anthropogenic greenhouse gas emissions, with particular reference to California.

EXECUTIVE SUMMARY

Conventional wisdom, based upon statements by the Environmental Protection Agency (EPA), assumes landfill operators capture 75% or more of the methane gas (CH_4) that is generated at their facilities. Because of that assumption of high collection efficiency, landfills have been thought to be responsible for only 2% - 3% of anthropogenic, or manmade, greenhouse gases (GHG). This comment explains why the EPA assumption is demonstrably wrong, why the best available evidence does not support a value greater than 20%, and why the appropriate remedies that follow from this correction involve more diversion rather than better landfilling. Specifically–

- There are no field measurements of the efficiency of landfill gas collection systems.
- EPA's assumed 75% gas collection efficiency has no factual basis, is based upon fundamentally incorrect definitions, and uses biased selection from unsupported, and self-serving, guesses as the basis for its assumption.
- The best evidence of typical lifetime capture rates based upon correct definitions does not support a value greater than 20%, as further attested to by the International Panel on Climate Change.
- Correcting the capture rate from 75% to 20% increases landfills' responsibility for anthropogenic greenhouse gas emissions from approximately 2%-3% to 8%-9% or more.
- Because gas collection is actually very poor, the case for diverting decomposable discards from the landfill becomes clear.

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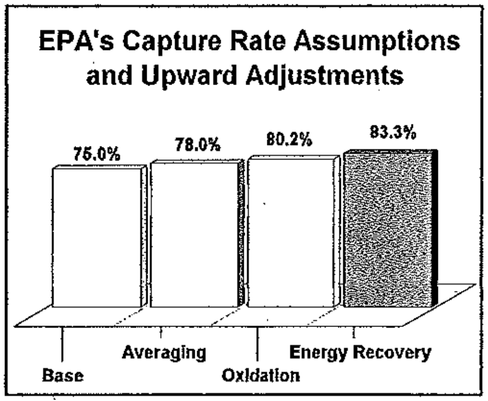
NO FIELD DATA

EPA states that landfills capture 75% of the gases generated, and then it makes several adjustments that improperly increase the value that the agency uses in calculating landfills' responsibility for GHGs to as much as 83%[1] (see CHART).


EPA's Capture Rate Assumptions and Upward Adjustments

The predicate for entering this evaluation of that assumption is to understand that there is virtually no field data on the amount of fugitive gas emissions from landfills. For that reason, EPA's claims that landfills achieve high gas collection efficiencies must be recognized as essentially an arbitrary assumption without any factual basis.

On the other hand, fault does not lie with the agency for the inherent difficulty in developing any factual data on collection efficiency, for there is no smokestack or outfall in which to install devices to measure emissions. Today's mega-sized landfills occupy a space greater than 100 football stadiums, extending over hundreds of acres. Most of a modern landfill, other than a base that is set in approximately 50-foot below grade, will be in the configuration of a four-sided pyramid hundreds of feet high, dwarfing 40 Great Pyramids at Giza.

Gas that is generated inside the waste mass is not stored, and instead seeks the path of least resistance to release the resultant build up of pressure. Through ruptures in the final cover, or before the cap is installed, gas can escape directly into the atmosphere from the top and sides. Or, gas can migrate indirectly through subsurface routes, including via the landfills' own leachate collection system, and through ruptures in the bottom liner and its seals, sometimes reaching into adjoining structures through underground utility lines. These confounding conditions defy measurement, notwithstanding efforts at near infrared scanning that are being attempted.[2]

In addition to the lack of any factual support, EPA's claim has arisen out of a patently biased process that was derived from the wholly inappropriate selection of only the highest self-reporting and self-serving guesses by the private landfill industry. Inexplicably ignored were the many other low-end assumptions in technical reports and industry admissions, even when those citations were handed to the outside consultant who conducted the putative literature review.[3]

But, if the critical errors in definition discussed below are corrected, then a substantially more accurate basis for estimation can be made for landfill gas capture rates.

DEFINITIONAL ERRORS

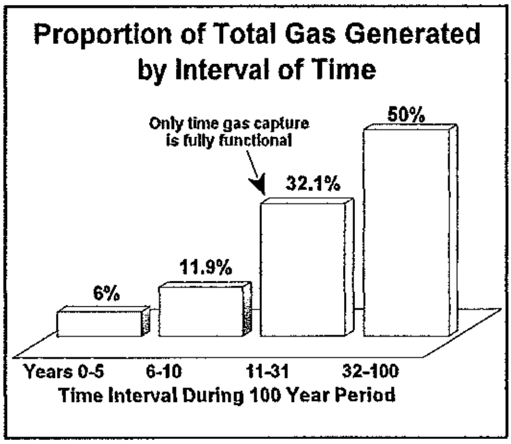
In addition to its arbitrary basis, there are also two fatal definitional errors underlying EPA's assumptions. The first error involves the time period contemplated, and the second, the use of the best case rather than the typical situation.

Lifetime, Not Point-in-Time, Efficiency Rate

EPA uses a definition about collection efficiency that is patently wrong. The 75% capture rate, is actually conceptualized as an *instantaneous* rate.[4] That is one which is only applicable for the year in which the calculation is made, and as applied, is for landfills in which the collection systems largely are installed and mostly functioning, rather than to the entire *lifetime* that landfills generate gas.

That distinction is of overriding importance because the regulations in EPA's landfill air rule do not require gas collection for the first five years of a landfill's life.[5] Moreover, recent fundamental changes in operational practices at landfills have served to both significantly increase near term gas generation while also severely worsening gas collection efficiency, as described in the note.[6]

Furthermore, those rules allow removal of the collection systems from service approximately 20 years after the site's closure. Following the post-closure period when the landfill is no longer actively managed, the barriers "will ultimately fail," as the EPA has repeatedly acknowledged. Once the barriers fail, precipitation will re-enter the landfill, and, in time, accumulating moisture will cause a second wave of decomposition and gas generation without any controls.[7]



Therefore, substantial volumes of gas will be generated in both periods before and after the time when there is no or little gas collection – all of which is ignored by an instantaneous rate. Because so much gas escapes without any or very limited controls, operators would have to capture 225% of the gas during the time gas collection is fully functional in order to achieve a lifetime rate of 75%. This is a mathematical impossibility, and it shows there is no way EPA's unsupported assumption can be considered within the realm of reasonableness once the correct definitions are used. *See* CHART above.

EPA's continued use of an instantaneous rate, in the face of repeated efforts to bring this to the attention of the agency's staff, is also incompatible with the protocols set forth by the IPCC. The international agency overseeing the rules of the road for GHG accounting specifically states that the analysis "should be based on the effects of the greenhouse gases over a 100-year time horizon."[8]

Moreover, EPA's use of an instantaneous rate for the capture rate – which makes collection efficiency seem substantially larger than it really is – is also contradicted by the agency's decision to use a 100-year time period in other GHG calculations – where the effect is to reduce landfills' responsibility for GHGs.[9]

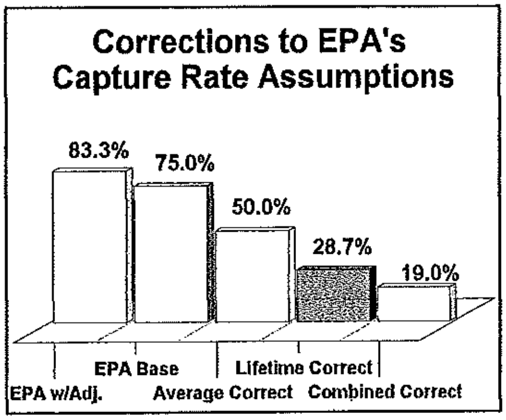
Correcting for the incorrect time frame definition – while leaving the EPA 75% value as an instantaneous rate – results in a corrected 100-year lifetime capture rate of only 28.5%. For there is no collection system for 56% of the gases landfills produce, and only a partially functional one for another 12% of the time.

Average Instead of Best Operation

EPA also used the wrong definition of the appropriate landfill population upon which to base collection efficiency. It uses a *best-case* construct to illustrate what in the real world is represented by the *average* landfill.

The Agency acknowledges that it defines its assumed collection efficiency rate to be for "well-managed sites," and what sites "should or could achieve," rather than what the weighted average of all landfills actually attains. This even though it previously acknowledged the self-evident fact that: "[t]o be useful for estimating methane emissions, the landfills in the data set must be representative of landfills generally in the U.S."

Because there is presently no way to measure landfill gas emissions, nor any emission rate or air quality standard to enforce even if there were,[10] in the real world the private sector would have little to no incentive to minimize gas emissions. The only constraint would be the palpable need to prevent subsurface migration into adjoining structures that cause explosions and to reduce offensive odors to nearby neighbors that cannot be achieved with misting or buyouts.



Nor, as discussed later, does EPA impose any specific design requirements for control systems other than it be an undefined "well-designed and well-operated gas collection system." Similarly neither have regulators prevented the new practice in the landfill industry that further reduces the effectiveness of the design and operation of typical collection systems over time.

Thus, there is little basis to contend that actual performance in the field resembles the best of what can theoretically be achieved.

No one knows what the average capture rate is for systems that are up and running. But, the weight of independent guesstimates in the technical literature are in the range of 40% to 50%.[11] If one conservatively uses an assumption of 50% for the average instantaneous rate to reflect typical conditions, that would reduce the 28.5% efficiency factor (which reflected the correction of the instantaneous 75% rate to a lifetime rate) to 19% (see CHART above).[12]

New Conventional Wisdom

There was a time when this conclusion – which puts landfill gas emissions four times greater than previously assumed – was controversial. That is no longer the case. The most recent draft solid waste report from the IPCC reflects a new consensus about the implications for capture rates once EPA's definitional flaws are recognized:

> "Some sites may have less efficient or only partial gas extraction systems, and there are fugitive emissions from landfilled waste prior to and after the implementation of active gas extraction; therefore estimates of 'lifetime' recovery efficiencies may be as low as 20%."[13]

With the adoption by the IPCC of a value essentially the same as ours when gas collection is properly defined, this once contrarian view has become the new conventional wisdom. A copy of the IPCC's final draft report, from which this quotation is extracted, is attached.

APPROPRIATE REMEDIES

Because, until now, conventional wisdom has considered EPA's assumption of a high collection efficiency rate to be correct, efforts at reducing GHGs in the U.S. have focused on recovering the energy value in that methane. In California, there has also been discussion about encouraging better gas collection practices. However, once the facts about landfill gases' very low capture rates is recognized, then the fatal shortcomings of these approaches can be understood. The more appropriate response by the European Union, which is being followed in the Bay Area, is to divert the source of the problem – the organics – from landfills in the first place.

Energy Recovery

The Congress, EPA and several states in the U.S. have actively encouraged landfill-gas-to-energy (LFGTE) as a means of reducing GHGs. This policy grew out of a belief that electricity generated at the wellhead of the gas collection systems displaces power production, and its associated emissions elsewhere, thereby turning landfills into "green energy parks."

When all of the input values are those used by EPA, 14% of the uncontrolled releases from landfills are assumed to be offset by avoided generation somewhere else. However, the presentment is wrong. There are four reasons why this facially cogent theory does not hold up upon examination.

Wrong Premise. The implicit – but unacknowledged – basis for the claim of offsetting benefits from LFGTE is that there are no alternatives to managing our wastes that do not produce significant volumes of methane. Therefore, this view continues, anything that can be done to lessen or offset the release of the methane from landfills into the atmosphere must be to the good.

However, because this premise is not correct, the wrong baseline is used for comparison. For there is no methane in our discards. Rather, only when a decision is made to dispose of organic matter in a lined landfill are the distinct oxygen starved conditions created that, alone, produce CH_4 as a byproduct of the resulting anaerobic decomposition. Otherwise, decomposition of organic material would usually occur aerobically, which is a process that does not produce significant methane.

Therefore, if landfilling decomposables were phased out, the organic material in lined landfills, which is the source of methane generation from wastes, would be largely eliminated. This is precisely the policy the European Community chose in 1999 in its Landfill Directive that ordered the phase out of organics in landfills, because it recognized they cannot be safely managed in the ground.[14]

In the U.S., a small but growing movement has developed, led by cities in California, to separate food and soiled paper at the source for composting and energy production in order to prevent organics from ever going into the landfill in the first instance. These efforts can be found concentrated in programs in the Bay Area around San Francisco, as well as in the Toronto area, and throughout the province of Nova Scotia, where the first efforts began.

The disproportionate benefit that comes from addressing climate change at its source, instead of with palliative end-of-pipe measures, can be better appreciated when it is recalled that the methane released from anaerobic decomposition in the ground has at least 23 times the warming potential as the CO_2 that is avoided – even if EPA's supporting numbers were true, which they are not. Thus, viewed from this perspective, EPA's numbers show that diverting one metric ton of organics from landfills will avoid the GHG generation of 0.273 metric tons carbon-equivalent (MTCE) of GHGs.

On the other hand, capturing the energy from that ton of waste will only avoid 0.04 MTCE, even if all of EPA's assumptions are used. That is to say, eliminating the problem at the source has at least seven times the impact – and that is only under the mathematically impossible collection efficiency guesstimates used by EPA.

Were the far lower capture rates recognized by the IPCC used, only 0.01 MTCE would be avoided. That is, keeping organics out of landfills is at least 25 times as important a factor in reducing GHGs as is landfill-gas-to-energy. Moreover, there are further corrections necessary in EPA's calculation of avoided emissions discussed below. These wind up reducing the hypothesized advantage to such a low a level that simply avoiding the landfilling of organics in the first place will be 67 times as powerful a tool to address climate change as LFGTE.

Landfill-gas-to-energy is a non-productive approach that fails to overcome the fact that, especially in a world concerned with climate change, land disposal alone, of all the other options to manage discards, creates the enormous volumes of methane that are among the most significant contributors to anthropogenic greenhouse gas emissions.

Low gas capture lowers offsets. Once low landfill gas collection efficiency is recognized, then most of the gases generated in landfills escape uncontrolled. The more GHGs that escape, the less that is actually collected and utilized for energy generation to offset production on the utility system. Ultimately, a point is passed when LFGTE no longer provides sufficient net benefits with which to soften the impact of its direct emissions, even on its own terms that use the wrong basis of comparison.

If we were to use all of the other EPA assumptions, other than correcting collection efficiency from 75% to 19%, the *net* GHG gains from avoiding emissions elsewhere would only be 3% instead of 14%. Three percent – when using all the agency's other assumptions – is a negligible advantage, even if the other estimates were correct, which they are not.

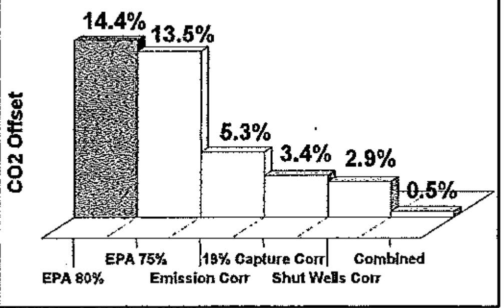
Displaced plants cleaner than LFGTE. As another example, the power plants that are displaced from the utility grid, in general, are no longer dirtier than the small generating units used at landfills. This further undermines the entire basis for the offset thesis, on top of the distinct impact of low collection efficiency.

Prior to deregulation, the more common impact when LFGTE was dispatched onto the utility system was for mostly polluting coal units to be replaced. However, for complex reasons involving changes in how power is now priced and dispatching performed, the more typical situation under deregulation is for the cleanest and advanced combined-cycle natural gas units to be displaced instead. At the same time, in practice it has turned out that almost all of the LFGTE units have been internal combustion engines (ICE), which are highly polluting machines. That is to say, today the offset factor actually results in worse air pollution in more instances.[15]

The effect of correcting for the change in regulation, and the consequent reordering of base load units that LFGTE displaces, is to decrease the amount of carbon dioxide emissions that are actually avoided. On the basis of how much CO_2 is emitted per kilowatt hour generated, the offset is reduced from 14% to 5%.[16]

When the earlier correction for lower capture rates is added to the lower estimates of avoided emissions elsewhere, the remaining offset is reduced from the original 14% to 1%.

Energy recovery landfills operated differently. As yet another example, when a landfill is operated for energy recovery, the objective of maximizing gas capture is sacrificed. This is because the generators that recover the energy from landfill gas require the gas to have a high Btu content, which cannot be met when the methane portion is not close to 50% of the gas produced in landfills. The other half of landfill gas is largely carbon dioxide with only a fifth the energy value of methane.


Effect of Corrections on LFGTE Offset Factor

Continuous extraction of landfill gas can make it impossible to maintain high Btu gas. For when a vacuum is exerted to extract methane out of the waste load, significant volumes of condensed moisture — which are necessary for further methane production — get drawn out of the refuse at the same time. The surrounding field soon becomes tapped out as a source of CH_4 for producing power.

To prevent that from happening, operators throttle back on those wells where low methane ratios are recorded to give the surrounding field time to recharge. But, when gas collection around a well is damped down, more landfill gases escape uncontrolled into the atmosphere. The fact that the escaping gases may only contain 40%, instead of 50%, methane slightly reduces, but does not substantively avoid, major GHG emissions. There is no reporting of how often throttling is utilized, but anecdotal evidence suggests that about 15% of the fields at a LFGTE landfill will be turned down at any point in time. This would reduce lifetime capture rates from 19% to 16%, and equate to a loss in the offset, after combining all these corrections, to just one-half of 1% (*see* CHART above).

Improved Gas Collection

California is considering a proposal to encourage improvements in gas collection as a part of its greenhouse gas strategy. However, the realities of the regulatory environment and industry practice do not provide confidence that this will be a productive endeavor.

As noted earlier, even if there was a will to do so, there is no practical means to enforce any significant and sustained improvement in gas collection practices. For landfills are a non-point source that defy reliable measurement.[17] Neither is there any evidence of the necessary will to regulate, as the following history of landfill gas regulation shows.

Its roots began in 1969, when twenty-five soldiers were almost burned alive in the Winston-Salem National Guard Armory. Methane from an adjoining landfill migrated into the building through underground utility pipes and was ignited by someone lighting a match. Through the 1970s, across the country, hundreds more narrowly escaped death from gas explosions caused by landfills.

The cause of this problem laid in the fact that, in that period, the sites were covered with dirt and then compacted in order to reduce odors and vermin, which were the source of public complaints. But, efforts to engineer around the inherent challenges from burying biologically active and dangerous materials in the ground have persistently created whole new problems. In this case, the covers led to the very anaerobic, or oxygen starved, conditions in landfills that, for the first time, generated major volumes of methane, which can be explosive, as well as a greenhouse gas.

Also in those sites of the time, the less permeable cover on top would often make it easier for that gas to escape by migrating underground into adjoining buildings. This was something that had been widely documented as far back as 1959. Yet, for over a decade after that Armory explosion, EPA limited its reaction over the near loss of human life to studying the causes of the problem. The reports culminated not in any regulations to control gas migration, but in a recommendation, swiftly rejected by real estate interests, that restrictions be placed on siting building structures near landfills.

Not until the end of the 1980s was any serious contemplation given to the installation of the commercially available active gas collection systems. Those systems had been developed in 1974 when the Los Angeles County Sanitary District's (LACSD) Palos Verdes landfill caused an explosion at the next door Covenant Church the prior year, just a few hours before the congregation was to arrive for service. By the next year, the LASCD engineered rigid vertical pipes that were perforated so gases could be drawn out of the surrounding waste mass when the several wells were connected by headers at the surface and subjected to a vacuum.

However, the fact that these collection systems did not expand much beyond a few publicly owned landfill until more than twenty years after the Armory explosion was peculiar. It suggested that the motivation was more for reasons of self-interest, unrelated to preventing people from being killed.

A decade after the threats from gas leaks were recognized, composite liners were beginning to be required in the 1980s to reduce groundwater pollution unrelated to the gas problem. These liners consisted of 2 feet of compacted clay overlaid with a geomembrane, or a $^1/_{16}$" sheet of plastic, and were also installed on top as covers to keep out rain.[18] That sheet at the bottom was less permeable to gas transmission, and, therefore, also serendipitously succeeded, for the moment, in blocking the troubling subsurface gas migration. However, again, the gain was at the price of creating another new problem that worked to encourage the use of gas collection, because the barriers provided no ready way for major volumes of gas to be safely released as a new era of mega-sized landfills began.

With the requirement for costly engineered liners in the offing, the industry had begun to build bigger landfills in order to achieve economies of scale that could overcome the cost of those liners on a per ton basis, as well as to reduce the number of sites needing to be permitted. But, with massive size, the sheer volume of gas became too great for passive venting to relieve the pressure. Expanding gases generated in the confined wastes of megafills had no where to go, and began to bulge open the covers on top of the landfills, especially in those larger megafills with the mass to generate upwards of 200 million cubic feet of gas annually. At these lined, super-sized landfills, the cost to install active gas collection systems became less than continually repairing the caps.

By 1990, the need for gas collection systems had already begun to be internalized at major facilities in order to protect their owners' investment just as new laws required some action. In that year, the Clean Air Act Amendments (CAAA) imposed "new source performance standards" (NSPS) on new sources, including landfills, for criteria and hazardous air pollutants, not then understood to include methane. The following year, EPA issued its proposed landfill air rules, which were largely based upon the work of California's South Coast Air Quality Management District (SCAQMD) from the early 1980s, except that EPA's proposal was to apply to only large landfills.

However, the practices that South Coast had developed, while advanced in their day, had solely been intended and validated for the limited purpose of addressing the only air issue of that time, namely odors. They had nothing to do with any particular level of atmospheric methane, smog or non-methane organic compounds, which only became landfill issues later. Nor did they have anything to do with what constituted a reasonable control strategy in 1991 as global warming was recognized, nonetheless what might be needed 20 years later to dramatically reduce greenhouse gas emissions as the issue became prominent. But, at least the proposal had some enforceable standards requiring a specific design system that had to be installed within two years after wastes were deposited.

By the time the final rules came out in 1996, each of the specific design requirements in the proposed rule had been stripped from the code in response to industry objections. All that remained was an essentially meaningless and unenforceable admonition for there to be "a well-designed and well-operated gas collection system," and that, only after five rather than two years. Also, the thresholds that determined how large a landfill needed to be to be covered by the rule were raised by 40%, restricting the putative requirements to only 5% of all landfills. Essentially, the final product reduced the effect of the rules to what was becoming the industry practice anyway for the purpose of avoiding damage to the caps in the very large landfills where passive venting was inadequate. But that had no necessary relation to societal concerns about global warming.

Even worse was EPA's decision to violate a key CAAA requirements. Section 112 required far stricter standards for hazardous air pollutants (HAP), than for non-hazardous criteria pollutants. Sources that release HAPs had to employ the maximum abatement system (MACT), rather than just the typical system (BDT), because toxic emissions directly affected human health.

EPA did acknowledge that "vinyl chloride [from landfills] can adversely affect the central nervous system and has been shown to increase the risk of liver cancer in humans, while benzene is known to cause leukemia in humans [and the] degree of adverse effects to human health from exposures to these HAP can range from mild to severe." Yet, notwithstanding the CAAA's peremptory requirements, EPA did nothing about the impacts on landfills neighbors, which epidemiological studies suggested might be associated with observed higher rates of leukemia, gastroschisis and exomphotos, and, in babies, low birth weights and abdominal wall defects.[19]

When, nine years later, the agency did issue rules in 2003 that it claimed were intended to comply with the law's higher requirements for HAPs, it imposed nothing on 99% of the 2,500 or so permitted landfills. Only a few dozen new "bioreactor" landfills were ostensibly affected. Landfills operated as bioreactors deliberately flooded the waste with sewage sludge, as well as runoff and recirculated leachate, in order to more aggressively accelerate the rate of decomposition.

That moisture also dramatically increased gas generation in the early years. For these few facilities, the new rule required gas collection to begin after six months, instead of after the five years required of dry tomb landfills, because the onset of gas generation was so much sooner. On the other hand, the far larger number of landfills that do not add outside liquids, but instead follow the increasingly common practice of just recirculating leachate, also advances the onset of gas generation. Yet they were not covered by the six-month rule that only applied to bioreactors.

Had MACT procedures been followed, all landfills would have had to do things deployed at the best sites, such as double the well density, horizontal pipes with each lift and each cell capped when full. These would have achieved substantive reductions in GHGs at the same time. But, nothing like what MACT required was done.

Moreover, neither did the rule substantively require much of anything for the few bioreactor landfills that it did apply to. The same flexible horizontal tubes, which are laid down with each day's lift to inject moisture into the landfill and accelerate decomposition, could also be counted as a gas extraction system if their use was alternated between liquid injection and gas extraction. Effective gas collection under these conditions – involving co-utilization of the piping system, flexible pipes that often collapse, saturated conditions and rapid differential settlement, all without a seal on top to prevent oxygen infiltration – is impossible. Or, to use the words of bioreactor's proponents, the task is "challenging." The learned professions often use such euphemisms to describe untoward results, such as the accounting profession's characterization of offshore tax havens as "aggressive" accounting, rather than "illegal" as determined by the IRS.

In tandem with the frayed fabric of regulation, industry practice under EPA's deregulatory philosophy have continued to degrade gas collection performance. For example, the first vertical gas collection pipes in the early 1990s had been spaced about 150 feet apart. But, over time their density was reduced to approximately every 350 feet, with a concomitant reduction in coverage. This was not done because anyone had data to show that the same proportion of methane could be collected with less than half the piping, but only because, in conjunction with aggressive misting during hot and humid summer day, odor complaints could be kept within politically manageable levels.[20]

A worse example involved prolonged delays in the installation of the final cover. In practice caps were not installed at the same time as the gas collection equipment was installed, even though these covers are essential for the systems to function properly. This is because, without a seal on top, gas collection pipes will also draw oxygen from the surface, along with landfill gas from the wastes surrounding the well. If more than 5% oxygen is in the collected gas, the mixture becomes combustible, and the system must be throttled back to reduce the draw from the surface to prevent landfill fires and explosions. As mentioned earlier, in an effort to improve profitability by recovering air space, the common industry practice today is to delay the installation of the final cap for as long as possible, ten years and more, at a significant cost in dramatically reduced collection efficiency.[21]

Over the course of those twenty years before self interest forced megafill operators to capture gas, even the direct loss of human life was insufficient to motivate regulators or private industry to address this issue, other than in isolated cases, such as at publicly owned LACSD landfills. And, this prolonged period of inaction involved an issue in regard to which the problem was known and the consequences were palpably visible, and indeed fatal. That is in contrast to something like methane in its manifestation as a greenhouse gas. For methane's release from landfills into the atmosphere cannot be measured, and it produces neither smoke, odor nor fatalities that can be readily detected.

There are many inspiring success stories in the annals of regulation. This does not number among them. Reliance improved gas collection to meet California's climate change strategy is exceedingly unlikely to be met unless the entire regulatory edifice is reformed first.

The Compost Alternative

For the past nine years, the European Union, recognizing those inherent limits on controlling landfill gas emissions, has focused on removing decomposable material from the landfill. In 1999, Brussels ordered phasing out the land disposal of decomposable discards. Without the decomposition of organics under anaerobic conditions, little or no methane will be generated in the first instance.

One way to do this is by separating food scraps and soiled paper in our homes, offices and stores for composting or energy, just as we already successfully separate our bottles, cans and newspaper for recycling. A problem can be transmuted into a solution by using the nutrient value to restore fertility to depleted soils. Many cities in California have moved in this direction or are actively planning to do so, including: Alameda, Albany, Arvin, Berkeley, Castro Valley, Dixon, Dublin, Emeryville, Fremont, Gilroy, Hayward, Healdsburg, Livermore, Morgan Hill, Newark, North Hollywood, Oakland, Pleasanton, Portola Valley, San Francisco, San Juan Bautista, San Leandro, San Lorenzo, Sonoma County and Stockton. So, too, are the provinces of Ontario and Nova Scotia.

As Mr. Kenneth Newcombe, founder of the Prototype Carbon Fund, stated for the World Bank in a FOREWORD to our upcoming report on landfill gas, when he was presented with the facts showing that gas collection efficiency is extremely poor:

> "That revelation has enormous implications for policy makers, especially when we recall where all that CH_4 comes from.
>
> "For there is no methane in household or commercial garbage. Ironically, those emissions only occur when we bury our unsorted trash in lined landfills intended to isolate the waste. Although once considered state-of-the-art, not only will the barriers eventually deteriorate, threatening groundwater, but also they foster the oxygen-starved conditions in which methanogenic microbes thrive...
>
> "Simply put, in order that methane never gets generated in the first place, we should stop dumping decomposable material into landfills. Tinkering with ultimately ineffective gas collection regimens, as we are doing, is not a productive enterprise ...
>
> "As Europe recognized six years ago, safe management of organic matter in the ground is currently not feasible. For real progress to be made in alleviating the threat of global warming, those decomposable materials will need to be separated at the source so that only inert matter winds up buried. Once diverted, the grass, leaves, food and soiled paper we discard can be safely used for their value as compost to restore fertility to our land, or for producing methane to generate power.
>
> "That is the constructive path many of us in the World Bank hope to follow in creating markets for greenhouse gas emissions under the Kyoto Protocols."[22]

CONCLUSION

The first years of the 21st century have been a transcendent experience for regulators as the evidence of global warming has become palpable.

No longer are the consequences of those debilitating political compromises that cripple progress localized somewhere else. Unlike regulatory decisions of the past, in matters affecting significant greenhouse gas emissions, business-as-usual means leaving an highly uncertain world as the legacy for all our children, not just for the offspring of the powerless.

To continue ignoring the long term consequences of regulatory failures would be especially unfortunate today, because climate change has redrawn the lines that define political interests.

The imposition of a carbon cap means that each industrial sector will be required to reduce their emissions (or pay for others to do so for them) by some percentage. If one sector, like the landfill industry, is drastically undercounting its base line emissions, then it will need do little. But others, like the utility industry, will have to do that much more to compensate.

Because of AB 32, California is now largely in a zero sum game among the different sectors of its economy, and inappropriate political compromises to benefit one are at others' expense.

The sooner that this new inescapable reality can be understood, the sooner real progress can be made to achieve the law's intent. ☐

ENDNOTES

[1] EPA makes three upward adjustments in its base 75% capture rate, none of which are supportable. First, the actual averaging process generates a rate of 78%. An examination of its data base and conversations with staff shows that it uses 75% as the default assumption, but accepts higher self-reports from operators when provided by those with sites exhibiting higher performance, ignoring the probability that those with worse performance are exceedingly unlikely to volunteer that fact.

Second, EPA assumes that 10% of the methane is oxidized in the overlying soil layer on top of a closed landfill. U.S.E.P.A., *Greenhouse Gas Emissions from Management of Selected Materials in Municipal Solid Waste* (EPA 530-R-98-013)(September 1998), at p. 106. Based upon a study by Czepiel, which found in field and laboratory studies during 1994 that 10% of the methane generated in a landfill was oxidized in the cover soil over the course of a year. P. M. Czepiel, et al., "Quantifying the effect of oxidation on landfill methane emissions," *Journal of Geophysical Research* (July, 20, 1996)., at p. 16,720. See, also, David Kightley, *et al*, "Capacity for Methane Oxidation in Landfill Cover Soils Measured in Laboratory-Scale Soil Microorganisms," 61 *Applied and Environmental Microbiology* 592 (February 1995). Alex de Visscher, et al, "Methane Oxidation in Simulated Landfill Cover Soil Environments," 33 Environmental Science & Technology 1854 (1999). When the gases are diffused throughout the overlying soil blanket, as would have been the case with most properly maintained clay cover landfills constructed before 1991, this study would be applicable. However, modern landfills gases are not diffused at the surface throughout that earthen layer, because, in most cases, since 1991 a composite cap has been required under that soil blanket, including in practice a 60-mil (or $^1/_{16}$") high density polyethylene plastic membrane that effectively impedes the passage of gases from the waste into that cover soil. This is key. It means that instead of the methane diffusing throughout the topsoil for maximum oxidizing effect, the gases that are released above the landfill not using alternative covers are concentrated in high fluxes at a handful of cracks and tears in the plastic sheet. Concentrated high flux emissions quickly overwhelm the capacity of the topsoil to oxidize the escaping methane through these hot spots. Czepiel expressly stated that not only was his study not done at a landfill with a synthetic geomembrane, but also, "[p]eriodic maintenance of the cover materials has minimized significant surface cracks" in the clay layer, as well. That is to say, nothing in his study can be used to describe what happens to the methane that flashes through a small number of hot spots on the top face of the landfill. He further reemphasized again in his conclusion that his findings did not apply when gases are released in high fluxes through narrow cracks:

> "Waste settlement, surface erosion and soil dessication often promote significant surface cracking, providing paths of minimal resistance to gas flow, effectively bypassing microbial influence. Our study generally lacked surface cracks, although his characteristic may not be representative of the entire spectrum of landfill surfaces."

Third, for landfills with energy recovery, EPA makes incorrect assumptions concerning the amount and concentration of emissions avoided elsewhere when power is generated with landfill gas, which is described later in the text at p.5

[2] Stephen Piccot, "Field Assessment of a New Method for Estimating Emission Rates from Volume Sources Using Open-Path FTIR Spectroscopy," 46 *Journal of the Air & Waste Management Association* 159 (February 1996), at p. 159; Gunnar Borjesson, *Methane Fluxes from Swedish Landfills* (Swedish EPA AFR-Report 263, October 1999). Ram Hashmonay, *et al.*, "Field Evaluation of a Method for Estimating Gaseous Fluxes from Area Sources Using Open-Path Fourier Transform Infrared," 35 *Environmental Science & Technology* 2309 (2001). Bo Galle, *et al.*, "Measurements of Methane Emissions from Landfills Using a Time Correlation Tracer Method Based on FTIR Absorption Spectroscopy," 35 *Environmental Science & Technology* 21 (2001). P.M.Czepiel, "Landfill methane emissions measured by enclosure and atmospheric tracer methods," *Journal of Geophysical Research* (July 20, 1996), at p. 16,711.

[3] First, EPA's internal survey refused to consider any work suggesting low collection efficiencies when the systems are operating. Proctor & Gamble's scientists did a comprehensive survey of anecdotal reports in 1999, which found that the reasonable self-reported assumed values fell largely in the 40% - 50% range. Peter White, *Integrated Solid Waste Management: A Lifecycle Inventory* (Aspen Pub. 1999), at p. 275, as did a wide range of other neutral studies referenced in note ? . These citations have been provided to EPA staff not only have the authors and other private parties, but also by its own Region 9 office, which it also ignored. EPA has not advanced its credibility by pretending that low estimates do not exist. Neither has its consultant, ICF Consulting, when it attempted to buttress the Agency's 75% assumption by claiming that it was supported by all four commenters of the Agency's original 1998 global warming report in which the 75% assumption was used for estimating landfills' contribution to global warming. ICF's Randy Reed placed special emphasis on the fact that Ms. Maria Zannes from the Integrated Waste Services Association (IWSA), the trade association for the waste-to-energy industry, also supported it. Exhumation of the peer reviewers' written comments show nothing of the kind. As concerns the ISWA comments, not only did Ms. Zannes make no comment that could be construed as supporting 75%, she said she was "*baffled* by this assumption" EPA used concerning overall capture rates. With regard to the only other non-landfill industry comments of Karen

Harrington for the Minnesota Office of Environmental Assistance (MOEA), neither did she concur in a 75% lifetime capture rate. Ms. Harrington actually supports the view that most of the gas is produced when there are no collection systems functioning after the post-closure period ends, the gas and liquid removal systems are turned off, the barriers deteriorate, water reenters the site and gas production resumes of the undecomposed fraction of the waste load.

[4] Interviews with Henry Ferland, Dina Kruger and Elizabeth Scheele at U.S.E.P.A.

[5] 40 C.F.R. §60.755(b).

[6] In the first 10 years of a landfill's life, the amount of landfill gas that is generated, and the proportion of that which is uncontrolled, is greater today than was ever contemplated under the terms of the agency's landfill rules.

As created, the rules in 1991 provided for the early use of liners and covers to isolate the wastes from moisture in a so-called "dry tomb." 40 C.F.R. §258.28. The intent was to minimize biological activity that generates leachate and gas that are difficult to manage. For the period of time that the barriers retained their integrity, these efforts minimized gas generation by minimizing moisture. Later in 1996, rules were promulgated requiring the installation of active gas capture systems after five years of the first waste emplacement. 40 C.F.R. §60.755(b). This supplemental rule was intended to collect the gas generated from moisture entrained with the incoming waste and from rainfall on the active working face, beginning in that fifth year.

However, in a more recent effort to recover air space and increase profits, over the past several years the common industry practice has reversed the rules' original intention by the deliberate addition of as much moisture as possible before covering the site in an effort to accelerate decomposition. This has been accomplished by deliberately maximizing the liquids funneled into the landfill in a number of ways. These include recirculating leachate, delaying installation of the cover so more rainfall can be captured, re-grading to maximize runoff, and sometimes injecting sewage sludge.

Effective gas collection is impossible in the rapid differential settlement that ensues. For example, often the same piping is used to inject liquids and to remove gas in order to reduce costs, but most importantly, the essential seal on top of the landfill to prevent oxygen infiltration into the gas collection system is delayed by as much as ten years and possibly longer.

Landfill regulators have yet to address the profound implications for global warming of the deliberate decision to shift methane generation from decades' hence to the present, and at a time and under conditions when gas collection is ineffective. At the same as the basis for the current rules rely upon so-called dry tomb principles, EPA has, under the false pretext of allowing for limited research and testing, effectively allowed the industry to unilaterally convert over to an entirely different wet cell basis without consideration of the cumulative impacts.

[7] 53 Federal Register. 168, at pp. 33344-33345 (August 30, 1988). 46 Federal Register 11128-11129 (February 5, 1981). Similar: "A liner is a barrier technology that prevents or greatly restricts migration of liquids into the ground. No liner, however, can keep all liquids out of the ground for all time. Eventually liners will either degrade, tear, or crack and will allow liquids to migrate out of the unit. Some have argued that liners are devices that provide a perpetual seal against any migration from a waste management unit. EPA has concluded that the more reasonable assumption, based on what is known about the pressures placed on liners over time, is that any liner will begin to leak eventually." Federal Register (July 26, 1982), at pp. 32284-32285.

[8] International Panel on Climate Change, *Second Assessment - Climate Change 1995* (1995).

[9] In calculating greenhouse gas emissions, the different types of warming gases are converted into a carbon dioxide-equivalent basis for ease of comparison. To do this, the fact that methane breaks down in the atmosphere over a shorter interval than CO_2 must be accounted for. EPA uses a 100 year time to recognize CO_2's longer residence time than CH_4. If instead, EPA consistently used a single year as the time period for calculation, the multiplier to convert CH_4 to a CO_2-equivalent basis would be more than *twenty times* the 23× conversion factor that EPA currently uses in estimating landfills' GHG responsibility. EPA's use of diametrically opposite time periods for comparison, applied improbably in a way that consistently minimizes landfills' responsibility for GHGs, is not easily explained on a rational basis.

[10] The only actual test for landfill air emissions uses a protocol that statistically is unable to detect significant leaks, and, in any event, has no relation to minimizing methane emissions as opposed to offensive odors to neighbors.

[11] See, *e.g.*, Peter White, *Integrated Solid Waste Management: A Lifecycle Inventory* (Aspen Pub. 1999), at p. 275. See, also, European Commission, *A Study on the Economic Valuation of Environmental Externalities from Landfill Disposal and Incineration of Waste* - Final Appendix Report (October 2000), at p. 144; and Ofira Ayalon, *et al.*,

"Solid Waste Treatment as a High-Priority and Low Cost Alternative for Greenhouse Gas Mitigation," 27 *Environmental Management* 5 (May 2001), at p. 699, TABLE 1.

12 The mathematics for these calculations are as follows. To correct the 75% assumed instantaneous capture rate to a lifetime rate, more than 60% of the gases generated occur either before or after effective gas collection systems are operating, with at least one half of the potential gas emissions after the systems may be removed from service, and, when using the EPA First Order Decay model, 6% before the pipes are required to be installed. From year 5 to about year 10 when final covers may be installed, there will be ineffective collection about 12% of the time, during which capture efficiency, at best, might be half of what normally might be achieved.

Calculation: 0.75 * (1 - 0.60) = 0.28.5

To correct the assumption of what the best operator might achieve instead of what actual operators do achieve inasmuch as there are no measurements taken of violations that could lead to enforcement, 50% is used.

Calculation: 0.285 * [(1- 0.75- 0.50)/0.75] = 0.19.

13 IPCC Final Draft Chapter 10, at p. 22, lines 23-25. A copy of the full chapter is attached.

14 The European Community also reached this conclusion based on the further fact that the entire theory of lined landfills is fatally flawed in that all manmade barriers will, as EPA has recognized as well, "ultimately fail." This means we have only postponed, not prevented, groundwater pollution.

15 Prior to deregulation, when the utility dispatcher purchased base load electricity from an Independent Power Producer, such as a LFGTE generator, he or she would have displaced an equivalent quantity of power from the utility's most operationally expensive base load plant. That would often be old, inefficient, and expensive to operate, coal plants. EPA uses the composite emissions profile for all fossil plants in 1996 to calculate LFGTE's offsetting effects. At the time, that was a reasonable proxy.

Since 1996, however, there have been two major changes that upend the original assumptions. First, a significant part of U.S. base load capacity now comes from cleaner natural gas, instead of more polluting coal, and much of that from very efficient units. Second, the wholesale utility markets have been largely deregulated, moving dispatching to Independent System Operators, who purchase power in a spot market from utility and non-utility independent power producers.

While many of the dirtiest old coal plants have been largely depreciated so that they can be bid on their operating costs alone, the newer ones will not, and therefore will need to be priced based upon both their capital and operating costs. The effect, increasingly, is to displace these more efficient gas units that exhibit very low emissions.

On the other hand, 90.2% of installed LFGTE capacity is polluting internal combustion engines (ICE), burning landfill gas, which is significantly dirtier than pipeline natural gas.

16 The 2,010 pounds of CO$_2$/MWH assumed in EPA's estimates would be reduced to 790 lbs. CO$_2$/MWH. LFGTE's generators, incidently, emit 2,040 lbs. CO$_2$/MWH, but that is generally considered to be part of the carbon cycle, which does not add new CO$_2$ into the atmosphere.

17 There is one putative standard in the air rule that is intended to limit concentrations of methane at the surface to 500 ppm, the so-called "sniff test." 40 C.F.R. §60.753(d) and §60.755(c). But, first, the sniff test was developed by the South Coast Air Quality Management District in the early 1980s because methane was believed to be a precursor of odor complaints by neighbors, and at levels greater than 500 ppm, odor complaints were noted. But, there is no relationship whatever between 500 ppm and what needs to be done to truly minimize GHG emissions from landfills to meet the demands of a coherent global warming strategy. Second, this test is predicated upon a regimen that only works if emissions are diffused across the entire face of the landfill, which is longer the case at Subtitle D landfills. Most of them have low permeable geomembranes that limit most releases to a few localized tears in the liners. Using a Poisson Distribution, the statistical probability of detecting 10 leaks at a landfill is 2.3974227905e-38, and that is even if the test could not be gamed, which it can and is.

18 40 C.F.R. §258.40(a)(2)(b), for the liner, and 40 C.F.R. §258.60(a)(1), for the cover (which strictly speaking does not directly require a composite liner, if a bottom liner is approved with less barrier performance). Also, alternative covers are authorized as part of Research, Development and Demonstration permits, 40 C.F.R. 258.4(b).

[19] State of New York Department of Health, *Investigation of Cancer Incidence and Residence Near 38 Landfills With Soil Gas Migration Conditions, New York State, 1980-1989* (1998); Paul Elliot, "Risk of adverse birth outcomes in populations living near landfill sites," 323 *British Medical Journal* 363 (Aug. 2001); 56 FEDERAL REGISTER 24472 (May 3, 1991).

[20] Note that the common practice by private industry of reducing collection performance was not followed by many in the public sector, many of whose landfills continued to use narrow spacing.

[21] This inappropriate operating practice has been further encouraged because, following promulgation of EPA's first national landfill standards in 1991, experience showed that the final covers contemplated in the code did not work. The very geomembrane, which was found necessary to reduce infiltration, exhibited too slippery a surface to stabilize the overlying soil layer. As a result, there are very few large landfills today that have capped any of their completed cells because there is no known way to properly do so.

[22] Center for a Competitive Waste Industry, *from Beneath the Ground: Gas from Landfills Threaten to Overheat the Earth* (upcoming Fall 2007).