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EXECUTIVE SUMMARY

Effective waste management is effective GHG mitigation: a range of mature low- to high-technology waste management strategies can concurrently mitigate GHG emissions, promote improved public health, and contribute to sustainable development. In the context of integrated waste management, the choice of a particular technology is a function of many competing variables, including cost and financial incentives, available land area, waste quantity and characteristics, regulatory constraints, collection and transport issues, policy considerations and local circumstances. Collectively, a wide range of environmentally-effective waste management technologies are reducing emissions globally through landfill CH_4 recovery and utilization, improved landfill management practices, engineered wastewater management, and waste-to-energy. In addition, waste minimization, recycling, and re-use represent a growing but largely undefined potential for indirect reduction of GHG emissions through improved energy efficiency and fossil fuel avoidance. Flexible policies and regulations can expand waste management options to achieve GHG mitigation goals. Because waste management decisions are often made locally without concurrent quantification of GHG mitigation co-benefits, the importance of the waste sector for reducing global GHG emissions has been underestimated.

Landfill CH_4 recovery for energy use has been fully commercial since 1975, currently exceeds 105 Mt CO_2e/yr, and is currently stabilizing landfill CH_4 emissions globally via decreased landfill CH_4 emissions from developed countries. In developing countries, however, landfill CH_4 emissions are increasing as more controlled (anaerobic) landfilling practices are implemented. Concurrently, Kyoto mechanisms such as CDM in developing countries and the JI in the EIT have the potential to significantly reduce landfill CH_4 emissions by accelerating the introduction of CH_4 recovery and utilization.

Regarding mitigation costs, with CDM for increased CH_4 recovery in developing countries, a reduction up to 500 Mt CO_2e/yr by 2030 could be achieved at very low cost (< 10 US$/t CO_2e). Additionally, thermal processes for waste-to-energy also offer significant potential to reduce emissions but at a higher cost; this option may become more viable as energy prices increase. Because landfills continue to produce CH_4 for many decades, thermal processes can provide a complementary short term mitigation measure.

Increased infrastructure for wastewater management in developing countries could provide multiple benefits for GHG mitigation, improved public health, conservation of water resources, and the reduction of untreated discharges to surface water, groundwater, soils, and coastal zones. There are numerous existing technologies that can be implemented for improved wastewater collection, transport, recycling, treatment, and use of sludges. A key aspect of sustainable development is the selection of appropriate and sustainable technology for a particular country.

Consistent and coordinated data collection and analysis at the national level could greatly improve the quantification of both direct and indirect GHG mitigation for the waste sector. Currently, the new 2006 IPCC Guidelines for National Greenhouse Gas Inventories provide more advanced default methods, recognize the need to improve field measurement strategies, and allow greater flexibility for quantifying national emissions depending on data quality and quantity. Within this framework, the quantification of global GHG emissions from waste would greatly benefit from increased international coordination of data collection and analysis.

10.1 Introduction

Waste generation is closely linked to population, affluence, and industrial structure. 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.." (Haury, 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 GDP/cap, energy consumption/cap, and private final consumption/cap (Bingemer and Crutzen, 1986; Richards, 1989; Rathje *et al.*, 1992; Mertins *et al.*, 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; 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.

This chapter focuses on GHG mitigation in the context of integrated waste management. Landfill CH_4 and wastewater CH_4 and N_2O are the major GHG emissions from the waste sector. Thus, in contrast to most other sectors but similar to agriculture, the waste sector is dominated by non-CO_2 GHGs. In this chapter, regional and source-related emissions from the TAR and the SRES will be updated, focusing on mitigation of greenhouse gas emissions from *post-consumer* waste management practices, as well as emissions from municipal and industrial wastewaters conveyed to public treatment facilities. Other chapters in this volume address *pre-consumer* GHG emissions from waste in the industry, energy, forestry, agriculture, transportation, and construction sectors which are managed within their respective sectors. Using available data, this chapter will also address emissions of non-methane volatile organic compounds (NMVOCs) from waste, as well as post-consumer end-of-life issues associated with fluorinated gases.

Appropriate waste and wastewater management, including landfill gas recovery, directly reduces emissions from the waste sector. There is significant potential for accelerating the direct reduction of GHG emissions from waste as well as extended implications for indirect reduction within the industrial, agriculture, forestry, and energy sectors. Waste prevention, reuse, and material recovery indirectly reduce GHG emissions by reducing waste generation, energy demand, and raw material consumption. The TAR (IPCC, 2001) included mitigation options related to the following practices:

- mitigation of landfill CH_4 emissions via landfill gas recovery,
- mitigation of wastewater and human sewage emissions of CH_4 and N_2O through improved management practices,
- reductions in fossil fuel use through waste-to-energy (incineration),
- recycling with decreased demand for virgin materials and decreased energy demand during production.

Although new concepts and methodologies are discussed in this chapter, it must be stressed that the major technologies for GHG mitigation from waste are mature and have been successfully implemented for decades. Using a life-cycle approach, there are many combined mitigation strategies which can be cost-effectively implemented by the public or private sector.

It must be further emphasized that multiple benefits accrue from cost-effective waste management practices which concurrently reduce GHG emissions and improve the quality of life, promote public health, prevent water and soil contamination, and conserve natural resources. Thus the mitigation of GHG emissions from waste and wastewater bestows a wide range of public health, safety, and environmental co-benefits. In addition, waste minimization, recycling, and re-use represent a growing but largely undefined potential for indirect reduction of GHG emissions through improved energy efficiency and fossil fuel avoidance.

An overview of carbon flows through waste management systems indicates carbon storage vs. carbon turnover for the major waste management strategies (Figure 10.1). Landfills function as relatively inefficient anaerobic digesters, and, for national inventories, the long-term carbon sequestration that occurs in landfills has now been addressed by the 2006 IPCC Guidelines. The major gaseous C emission from waste is landfill CH_4 with minor CO_2 from incinerated fossil C (plastics). The CO_2 from composting or incineration of waste biomass is not considered in national GHG inventories under the UNFCCC.

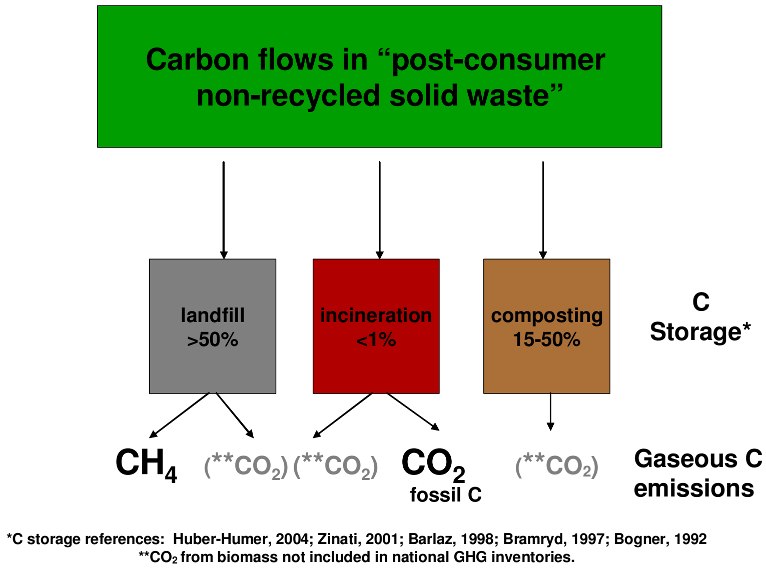
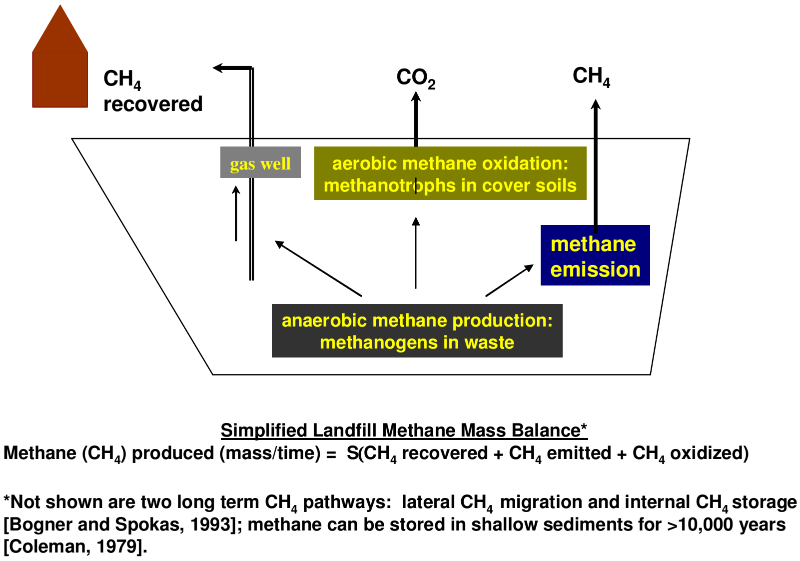


Figure 10.1. *Carbon flows through major waste management systems including C storage and gaseous C emissions. Note: national GHG inventories include CH_4 from landfills and CO_2 from incineration of fossil C.*

A process-oriented perspective on the major GHG emissions from landfills and wastewater provides insight into GHG emissions (Figure 10.2). In the context of a landfill CH_4 mass balance, emissions are one of several possible pathways for the CH_4 produced by anaerobic methanogenic microorganisms in landfills; others include recovery, oxidation, and two longer-term pathways: lateral migration, and internal storage (Figure 10.2a) (Bogner and Spokas, 1993; Spokas et al., 2006). Regarding emissions from wastewater transport and treatment, CH_4 is microbially produced under strict anaerobic conditions as in landfills, while the N_2O is an intermediate product of microbial N cycling promoted by conditions of reduced aeration, high moisture, and abundant N (Figure 10.2b).



a. Simplified landfill methane mass balance: pathways for methane generated in landfilled waste, including methane emitted and oxidized.

b. Overview of wastewater systems. The major GHG emissions from wastewater-- CH_4 and N_2O—can be emitted during all stages from sources to disposal; however, in practice, most emissions occur upstream of treatment.

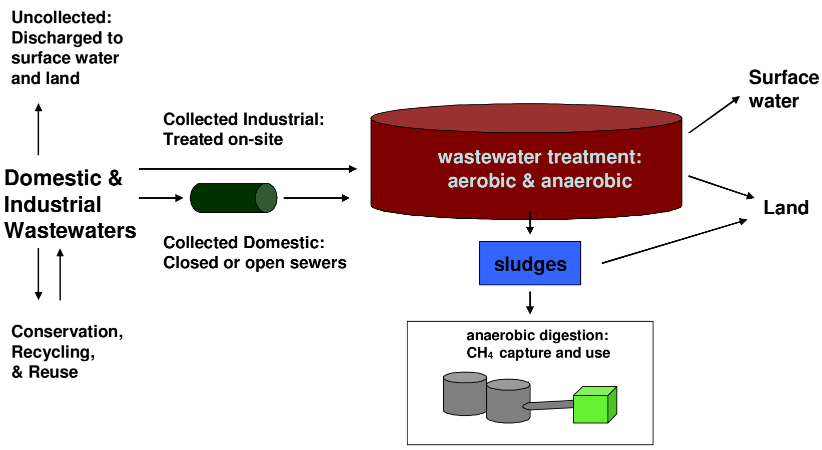


Figure 10.2. *Pathways for GHG emissions from landfills and wastewater systems.*

Therefore both the CH_4 and N_20 from the waste sector are microbially produced and consumed with rates controlled by temperature, pH, available substrates, microbial competition, and other factors. As a result, both CH_4 and N_20 generation and consumption rates can 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 lead to serious public health problems resulting from pathogenic microorganisms, toxic odors, and disease vectors.

Some major mitigation measures for the waste sector were previously addressed in the TAR (IPCC, 2001; Ackerman, 2000). These are updated and expanded in this chapter to encompass landfill CH_4 recovery for flaring or energy use; optimizing methanotrophic CH_4 oxidation in landfill cover soils; reduction at source through waste minimization, recycling, and re-use; alternative strategies to landfilling (incineration and other thermal processes; mechanical and biological pretreatment/MBP); offsetting fossil fuel use via waste-to-energy, and wastewater management to minimize emissions via closed sewers, efficient wastewater treatment, at-source reduction in wastewater quantities, and wastewater recycling/reuse. In particular, it is important to emphasize that landfill CH_4 recovery as an alternative source of renewable energy has been fully commercial since 1975 and is now being implemented at >1150 plants worldwide with emission reductions of >105 Mt CO_2e/yr (Willumsen, 2003; Bogner and Matthews, 2003). This number should be considered a minimum because there are also many sites which recover and flare landfill gas without energy recovery. The energy value (Lower Heating Value, LHV) of landfill gas ranges from 16-22 MJ/Nm^3, depending directly on the % CH_4.

The energy value of mixed municipal waste ranges from <6 to >14 MJ/kg (Khan and Abu-Ghararath, 1991) with high values approaching low-grade coals (lignite)—this energy can be most efficiently exploited using thermal processes. Using the total waste generation shown below (Box 10.1) and converting to energy equivalents (assuming 12 MJ/kg), global waste in 2002 contained a substantial 1.1×10^{10} TJ of available energy.

Concerning costs and potentials for mitigating GHG emissions from waste, the TAR (IPCC, 2001) outlined major issues including definition of system boundaries and choice of models with correct baseline assumptions and regionalized costs. One must also consider local economic and social development factors. Because the waste sector is characterized by mature technologies whose diffusion limited by local costs, policies, available land area, and public perceptions, the discussion of mitigation costs and policies later in this chapter (section 10.4.1) will be organized according to a "technology gradient" approach: from low-technology/low-cost measures to high-technology/high-cost options. There is no single best option; rather there are multiple commercially-available technologies. Because waste management technology decisions are often made locally, the goal of this analysis is to suggest strategies that can be collectively implemented to reduce GHG emissions and achieve sustainable development and public health goals.

10.2 Status of the waste management sector

10.2.1 Waste Generation

The availability and quality of annual data are a major problem for the waste sector. Solid waste and wastewater data are lacking for many countries, the reliability of existing data for many countries is questionable, definitions are not uniform, and interannual variability is often not well quantified (Bogner and Matthews, 2003). There are three major approaches which have been used to estimate global waste generation: country-specific data using approved methods for the IPCC inventory process, population-based estimates used for the SRES waste scenarios, and the use of a proxy variable linked to demographic or economic indicators for which national data are annually collected. 2006 IPCC Guidelines provide regional and country-specific data for waste generation based on statistics, surveys and other sources, and recommend the use of urban population (or population covered by waste collection), with economic indicators to estimate historical or future waste generation. For the national inventories, most countries use IPCC default data, population-based estimates based on regional or national statistics, data from one or more urban areas, or data from an adjoining country with similar demographics. Using population as the major driver, the SRES scenarios (Nakicenovic et al., 2000) project continuous increases in waste and wastewater CH4 emissions to 2030 (A1B-AIM), 2050 (B1-AIM), or 2100 (A2-ASF; B2-MESSAGE). However, waste generation rates are also related to affluence—richer societies are characterized by higher rates of waste generation/cap, while less affluent societies generate less waste as well as practice informal recycling/reuse initiatives that decrease the waste/cap to be collected at the municipal level. It is thus possible to develop statistically significant relationships between waste generation/cap and certain proxy or surrogate variables which encompass both population and affluence, including GDP/cap (Richards, 1989; Mertins et al., 1999) and energy consumption/cap (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 which 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 energy consumption/cap. Using UNFCCC-reported values for % biodegradable organic C in waste for each country, this BOX also shows trends for landfill C storage based upon the reported data.

Box 10.1. 1971-2002 Regional Trends for Solid Waste Generation

***THE PROBLEM OF WASTE GENERATION DATA**:* Solid waste generation rates are a function of both population and prosperity, but data are lacking or questionable for many countries. 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/cap for developed and developing countries. These empirical models were based on energy consumption/cap as an indicator of affluence and a proxy for waste generation/cap; 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. Examining the results by region for 1971-2002, note that almost 900 Tg of waste was generated in 2002 (Figure 10.3a). A conversion to energy equivalents (assuming 12,000 MJ/kg) indicates that waste in 2002 contained a substantial 1.1 X 10^{10} TJ of available energy. Unlike projections based on population alone, this figure shows waste generation from individual regions decreasing as well as increasing in tandem with major economic trends.

Figure 10.3b showing annual C storage in landfills was developed using the same base data, the % landfilled waste for each country (reported to UNFCCC), and a conservative assumption of 50% C storage (Bogner, 1992; Barlaz, 1998)--this storage is long-term. In landfills, lignin is recalcitrant to anaerobic decomposition while some fraction of the cellulose is also non-degraded. The annual totals for the mid-1980's and later (>30 Tg carbon/year) exceed estimates in the literature for the annual quantity of organic C partitioned to long-term geologic storage as a precursor to future fossil fuels (Bogner, 1992). In developed countries, anaerobic burial of waste in landfills has been widely implemented only since the 1960's and 1970's. Landfill C storage has a longer time horizon than is typical for forest biomass.

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

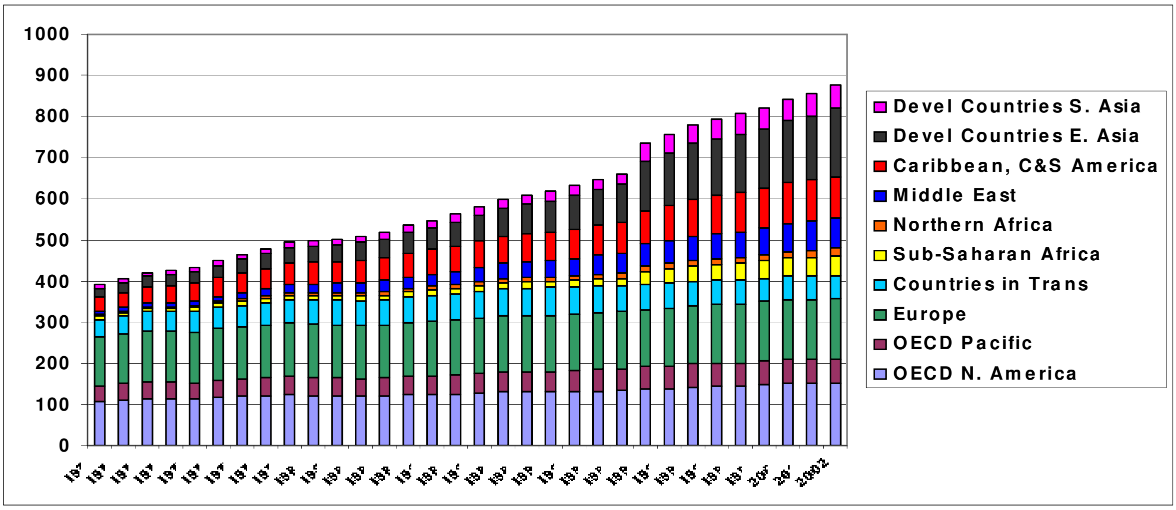
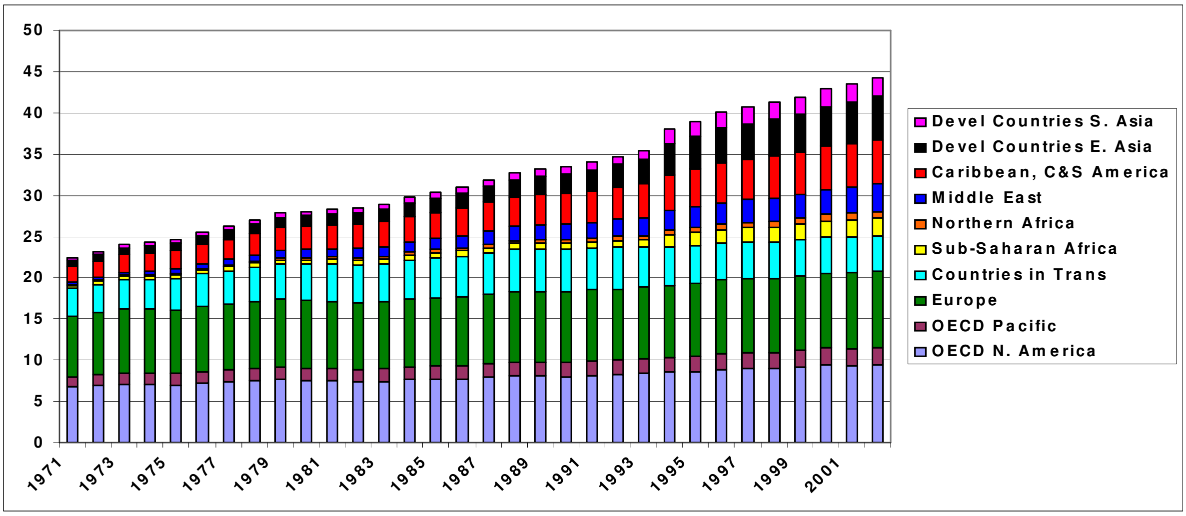


Figure 10.3b *Minimum annual rates of carbon storage in landfills from 1971-2002 (Tg C).*



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 labor costs are lower in developing countries, waste management often constitutes a higher share of municipal income because of higher equipment and fuel costs (Cointreau-Levine, 1994). By 1990, many developed countries had initiated comprehensive recycling programs. It is important to recognize that the % recycled, composted, incinerated, or landfilled differs greatly among municipalities as a result of multiple factors, including local economics, national policies, regulatory restrictions, public perceptions, and availability of open-space for landfill siting.

Table 10.1. *Municipal solid waste generation rates and relative income levels. 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 et al., 2003; Qifei et al., 2006; US EPA, 2003.*

Country	**Low Income**	**Middle Income**	**High Income**
Annual Income (US$/cap-yr)	825 to 3255	3256 to 10065	> 10066
Municipal Solid Waste Generation Rate (t/cap-yr)	0.1 to 0.6	0.2 to 0.5	0.3 to >0.8

10.2.2 Wastewater Generation

In general, 58% of the global population has sanitation coverage (sewerage) with very high levels characteristic for the population of North America (100 %), Europe (92%), and Oceania (93%), although in the last two regions the percentage for rural areas reduces to 74% and 81%, respectively (Jouravlev, 2004; WHO/UNICEF/WSSCC, 2000, DESA, 2005; WHO-UNICEF, 2005; World Bank, 2005; PNUD, 2005). In developing countries, rates of sewerage are very low for rural areas of Africa, Latin America, and Asia, where septic tanks and latrines predominate. Moreover, for wastewater treatment, 88% of the population in developed countries but only 29% of the population in developing countries is served by wastewater treatment. North America has high levels of coverage (90%), followed by Europe (66%). There are no available data for Oceania. Other regions have, in general, low levels of waste treatment, with Asia at 35%, Latin America and the Caribbean at 14%, and much of Africa lacking wastewater treatment (Jouravlev, 2004; World Bank, 2005). Most countries do not collect annual statistics on the volume of wastewater generated, transported, and treated.

Estimates for CH_4 and N_2O emissions from wastewater treatment require data on organic matter (BOD;COD[1]) and nitrogen. Nitrogen content is estimated using FAO data on protein consumption, and the application of wastewater treatment, or lack of treatment, determines the emissions. Aerobic wastewater treatment plants produce negligible or very small emissions, whereas in anaerobic lagoons or latrines 50-80% of the of the CH_4 production potential can be realised. In addition, one must take into account the existence of an established infrastructure for wastewater treatment in developed countries and the lack of infrastructure in developing countries where typically <25% of wastewater is treated. In developing countries, open sewers or informally-ponded wastewaters often result in generation of N_2O and CH_4 as well as uncontrolled discharges to rivers, lakes, and small streams. The majority of urban wastewater treatment facilities are publicly-operated, and only about 14% of the present total private investment in water and sewerage finances wastewater treatment, mainly directed toward protection of drinking water supplies (Silva,1998; World Bank 1997).

Most industrial wastewaters are discussed in other chapters. However, highly organic wastewaters (with the exception of food industry discharges discussed in Section 7.4.7.1) are addressed in this chapter because they are frequently conveyed to municipal treatment facilities. Table 10.2 summarizes their regional and total 1990 and 2001 generation in terms of kg BOD/day or kg BOD/worker/day. These estimates are based on measurements of plant-level water quality (World

[1] BOD measures the amount of carbon that is aerobically biodegradable. COD measures the total material available for chemical oxidation (both biodegradable and non-biodegradable). BOD is used predominantly for domestic, COD for industrial wastewater.

Bank, 2005). The table indicates that total global generation decreased >7% between 1990 and 2001; however, increases were observed for the Middle East (+17%) and the developing countries of South Asia (+24%) with overall 2001 generation 35% higher from developing countries than for developed countries.

Table 10.2. *Regional and global 1990 and 2001 generation of highly organic industrial wastewaters often treated by municipal wastewater systems* (World Bank, 2005).* **T** *= Total;* **A***=Average. (* Note: Chapter 7 discusses other industrial wastewaters.)*

Generation of high organic C industrial wastewaters (often treated in municipal facilities)					**Percentage(%) of total for major industrial sectors (All other sectors were <10% for all regions.)**				
Regions	**Kg BOD/day (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**
OECD North America	**T**3061 **A**1020	**T** 2578 **A** 859	0.20	0.17	9	15	11	44	7
OECD Pacific	2163 541	1747 437	0.15	0.18	8	20	6	46	7
Europe	5154 240	4770 235	0.18	0.17	9	22	9	40	7
Countries in transition	3404 128	2425 162	0.15	0.21	13	8	6	50	14
Sub-Saharan Africa	593 29	512 22	0.23	0.25	3	12	6	60	13
Northern Africa	410 120	387 97	0.20	0.18	10	4	6	50	25
Middle East	255 27	299 30	0.19	0.19	9	12	10	52	11
Caribbean, Central and South America	1482 87	1322 82	0.23	0.24	5	11	8	61	11
Developing countries East Asia	8299 831	7679 852	0.14	0.16	11	14	10	36	15
Developing countries South Asia	1656 352	2046 409	0.18	0.16	5	7	6	42	35
Developed countries	**10378 600**	**9094 509**							
Developing countries	**12694 241**	**12245 240**							

10.2.3 Development Trends for Waste: Public Health, Regulatory, Policy, and Economic Trends for Waste Generation and Treatment

Developed countries are characterized by higher rates of waste recyling and waste pre-treatment. Economics largely dictate that the bulk of the residual solid waste is either landfilled or incinerated, although more costly practices such as anaerobic digestion have been locally implemented. In addition, many countries practice solid waste composting; however, because of compost quality issues, this is best applied to specific biodegradable waste streams that are source-separated (Diaz et al., 2002; Perla, 1997). In North America, Australia, and New Zealand, landfilling is expected to continue as the dominant method for large-scale waste disposal as larger quantities of landfill CH4 are also being recovered for energy use. North America and Australia are also beginning to implement "bioreactor" landfills to compress the time period during which high rates of CH4 generation occur. 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 (Johannessen and Boyer, 1999; Hoornweg, 1999). Incineration has not been widely implemented in North America due to low landfill tipping fees, negative public perceptions, and high capital costs. In parallel, larger quantities of landfill CH4 are being recovered for energy use. In the EU, the landfill directive (Council Directive 1999/31/EC) mandates that by 2010, there must be a 75% reduction relative to 1990 in the mass of biodegradable organic waste that is annually landfilled. As a result, increasing quantities of post-consumer waste are now being diverted to incineration, as well as to mechanical and biological treatment(MBT) before landfilling to 1) recover recyclables; and 2) reduce the organic C content by a partial aerobic composting. Nevertheless, CH4 production will continue at existing landfills. In Japan, where there is little open space for landfill construction, high rates of incineration are practiced with utilization of recyclables and landfilling of residuals. Historically, there have also been "semi-aerobic" Japanese landfills with potential for generation of N2O (Tsujimoto et al., 1994). Aerobic (with air) landfill practices have also been studied or implemented in Europe and the U.S. as an alternative, or in combination with, anaerobic (without air) practices (Ritzkowski and Stegman, 2005).

In developing countries, more controlled landfilling with anerobic decomposition of organic waste and increased CH4 emissions 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. There are also persuasive public health reasons for implementing controlled landfilling - urban dwellers produce more solid waste per capita than rural inhabitants, and large amounts of refuse accumulating in areas of high population density are linked to vermin and disease (Christensen et al., 1999). 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 CO2 (by burning and aerobic decomposition) to anaerobic production of CH4. To a large extent, this is the same transition that occurred in many developed countries in the 1950-1970 timeframe. The effect of increased CH4 from engineered landfills can be mitigated by landfill gas extraction and utilization.

One must not neglect the role of informal waste recycling in developing countries. 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 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 jobs/t waste and recycling of >50% of collected waste can be attained (Iskandar, 2005).

10.3 Emission trends

10.3.1 Global Overview

Historically, for UNFCCC national inventories, a simplified C or N mass balance has been applied to waste and wastewater with some portion of the C or N annually partitioned to gaseous emissions as CH_4 or N_2O. 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; thus the standardization of terminology and 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, and thus estimation of emission trends requires models which consider temporal trends. CH_4 is also emitted from wastewater, 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 also a small source of GHG emissions from this sector. 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 can also be a significant local source of air pollutants which are a health risk for nearby communities. Composting and other biological treatments emit very small quantities of GHGs and are only included in the 2006 IPCC Guidelines for completeness.

Global estimates and trends from the waste sector (Table 10.3) indicate that total emissions have increased and will continue to increase (Monni et al.,2006; Scheehle and Kruger, 2006). However, the percentage of total global GHG emissions from the waste sector has declined 14-19% for Annex I and EIT countries between 1990 and 2003 (UNFCCC, 2005c). The waste sector contributed 2-3% of the global GHG total for Annex I and EIT countries for 2003 but a much higher percentage (4.3%) for non-Annex I countries [various reporting years from 1990-2000] (UNFCCC, 2005c). 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 economic conditions, waste management decisions, and policy initiatives. In developing countries, rapid increases in population and urbanization are resulting in increases in GHG emissions from waste, especially CH_4 from landfills and both CH_4 and N_2O from wastewater. Scheehle and Kruger (2006) project an increase in annual CH_4 and N_2O emissions of 33-36% from 1990-2020, mainly from the non-Annex 1 countries. Monni et al. (2006) project more rapid increases in emissions than Scheehle and Kruger (2006). It is important to emphasize, however, that these are 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 .

There are continuing issues with data quantity and quality in the waste sector, especially for developing countries. Inventory data from non-Annex 1 countries are limited and usually available only for 1994 (or 1990). Information on N_2O emissions from wastewater is minimal, and therefore global estimates are based on human sewage treatment only. The Scheehle and Kruger (2006) studay supplemented data gaps based on the 1996 IPCC Guidelines. Monni et al. (2006) calculated a time series for landfill CH_4 using the methodology and default data in the 2006 IPCC Guidelines, taking into account the time lag in landfill emissions compared to year of disposal. Thus the estimates by Monni et al. (2006) are lower than Scheehle and Kruger (2006) for the period 1990 - 2005 because the former reflect the slower growth in emissions relative to the growth in waste. However, the future projected growth in emissions by Monni et al. (2006) is higher than estimated by Scheele and Kruger (2005) because recent European decreases in landfilled waste are reflected more slowly in the future projections. For comparison, the total global CH_4 and N_2O emissions reported in the TAR (IPCC, 2001b) are approximately 600 Tg CH_4/yr and 17.7 Tg N as N_2O. The direct comparison of reported emissions with the A1 and B2 SRES scenarios (N. Nakicenovic *et al.*, 2000) is problematical because the SRES do not include landfill gas recovery (commercial since 1975) and project continuous increases in CH_4 emissions from the waste sector to 2030 (AIB-AIM) or 2100 (B2-MESSAGE) [see Table 10.3a.], resulting in very high projections for 2050 emissions of >4000 Mt CO_2e per year.

Table 10.3. *Trends for GHG emissions from waste from UNFCCC national inventories and projections.* ***(a)*** *CH_4 and N_2O emission trends for landfills and wastewater from Scheele and Kruger (2006). N_2O trends from human sewage only.* ***(b)*** *Total CH_4 emissions from waste (UNFCCC, 2005a, b). Includes emissions from non-Annex I countries for 1990 and latest available year (reported under 1995 for various years 1990-2000).* ***(c)*** *SRES scenarios AIB and B2 (Nakicenovic et al., 2000). See discussion in text.* ***(d)*** *Additional UNFCCC inventory data for waste (Konte, 2005) (e) Projected emission trends from Monni et al. (2006) using 2006 inventory guidelines.*

Year	1990	1995	2000	2005	2010	2015	2020	2050	Ref
	Mt CO_2eq								
Landfill CH_4	756	777	777	819	882	945	1008		**a**
Landfill CH_4	341	398	448	521	640	798	1003	2908	**e**
Wastewater CH_4	357	399	420	441	462	483	504		**a**
Total CH_4	1113	1176	1197	1260	1344	1428	1512		**a**
Total CH_4	659	1005							**b**
Total CH_4 (SRES AIB/B2)	1281/1302							4011/4662	**c**
Wastewater N_2O	73	78	82	86	90	93	97		**a**
CO_2 from Incineration	33	37							**d**
CO_2 from Incineration	35	41	47	51	55	59	63	81	**e**

10.3.2 Regional Trends: Landfill CH_4

Landfill CH_4 has historically been the largest source in the waste sector. Despite growing rates of waste generation, increased rates of landfill CH_4 recovery and other measures have resulted in curbing the growth of emissions during the last 20 years. Figure 10.4 compares regional estimates for the years 1990-2020, from Scheehle and Kruger (2006) to historical estimates for 1971-2002 (Bogner and Matthews, 2003). Note that the Scheehle and Kruger (2006) estimates for OECD North America and the developing countries of S and E. Asia are typically higher than those referenced to energy consumption; however, the European and OECD Pacific trends converge at the present time.

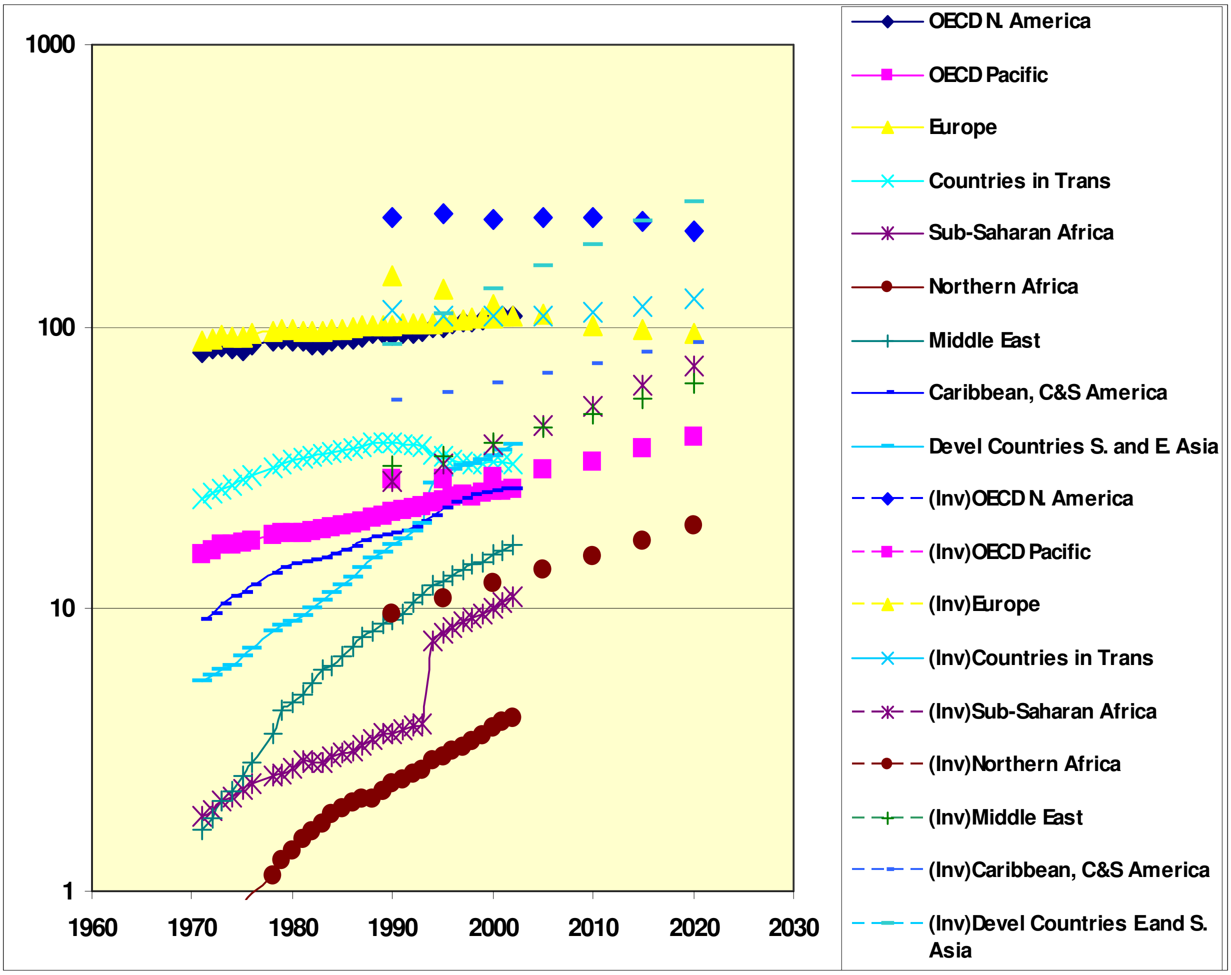


Figure 10.4. *Regional landfill CH_4 emission trends. [Mt CO_2e]*

(1) National inventory estimates and projections for 5-year intervals from 1990-2020 (Scheele and Kruger, 2005, in review). Labeled "Inv".
(2) Annual emission trends from 1971-2002 using methodology from Bogner and Matthews, 2003.

Landfill CH_4 recovery has been fully commercial since the first U.S project in 1975 and has already achieved significant emissions reductions in many countries. Currently, >105 Mt CO_2e/yr are recovered globally with the largest number of projects in the U.S. (Willumsen, 2003). A comparison of the present rate of landfill CH_4 recovery to estimated global emissions from Scheehle and Kruger (2006) in Table 10.3 indicates that annual recovery and utilization currently exceed the projected 5 year emissions increase from 2005 to 2010. Thus, it is reasonable to state that landfill CH_4 recovery is beginning to stabilize emissions from this source. Moreover, because there are many projects which recover and flare landfill gas without energy use, it is likely that the present rate of landfill CH_4 recovery may be much higher than 105 Mt CO_2e per year. A linear regression using historical data from the early 1980s to 2003 indicates a growth rate for landfill CH_4 utilization of approximately 5% per year (Bogner and Matthews, 2003). It is anticipated that, as developing countries implement more controlled landfilling practices, incentives such as the CDM will increasingly promote landfill CH_4 recovery and use. In addition, since substantial CH_4 can be emitted both prior to and after the period of active gas recovery, it is important to implement early installation of gas extraction (using horizontal collection systems), as well as later solutions to mitigate residual emissions (such as landfill biocovers to microbially oxidize CH_4).

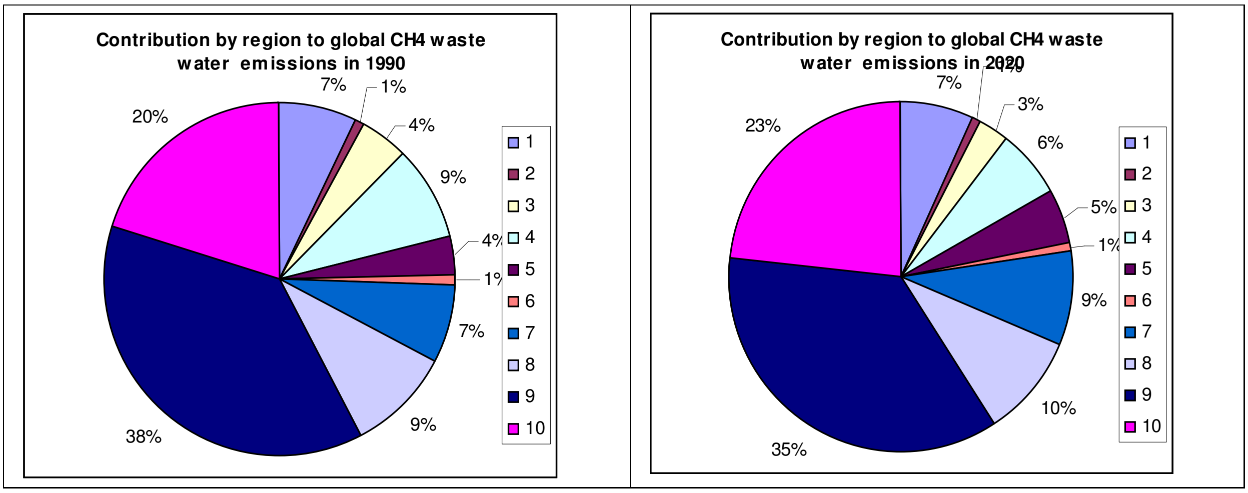
For the EU15, trends indicate that landfill CH_4 emissions are declining. Between 1990 and 2002, landfill CH_4 emissions decreased by almost 30% due to the early implementation of the landfill directive (199/31/EC) and similar national legislation intended to reduce biodegradable waste going to landfills and increase landfill CH_4 recovery at existing sites. Emissions from the waste sector are projected to be more than 50% below 1990 levels in 2010 due to the landfill directive and additional policy measures including increased recovery of landfill CH_4 (EEA, 2004).

10.3.3 Regional Trends: Wastewater and Human Sewage CH_4 and N_2O

Wastewater emissions are significantly correlated to population trends (US EPA, 2001). CH_4 and N_2O are produced and emitted during municipal and industrial wastewater collection and treatment, depending on transport, treatment, and operating conditions. The resulting sludge may also generate CH_4 and N_2O if biodegraded without gas capture. In developed countries there is an extensive infrastructure for wastewater treatment, typically relying on centralized aerobic treatment; thus CH_4 emissions are small and incidental. Wastewater can also be treated anaerobically, with CH_4 being produced and emitted if control measures are lacking; often, however, the resulting biogas is used for heat or onsite electrical generation.

In general, due to rapid population growth, urbanization, and industrialization, wastewater CH_4 and N_2O emissions from developing countries are higher than from developed countries. This can be seen (Figure 10.5) by examining the 1990 estimated CH_4 and N_2O emissions and projected trends to 2020 from wastewater and human sewage (UNFCCC/IPCC, 2004). However, data reliability for developing countries is a major issue. Decentralized "natural" treatment processes and septic tanks in developing countries may produce 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, 2002).

a. Regional distribution of CH_4 emissions from wastewater and human sewage in 1990 and 2020.



b. Regional distribution of N_2O emissions from human sewage in 1990 and 2020.

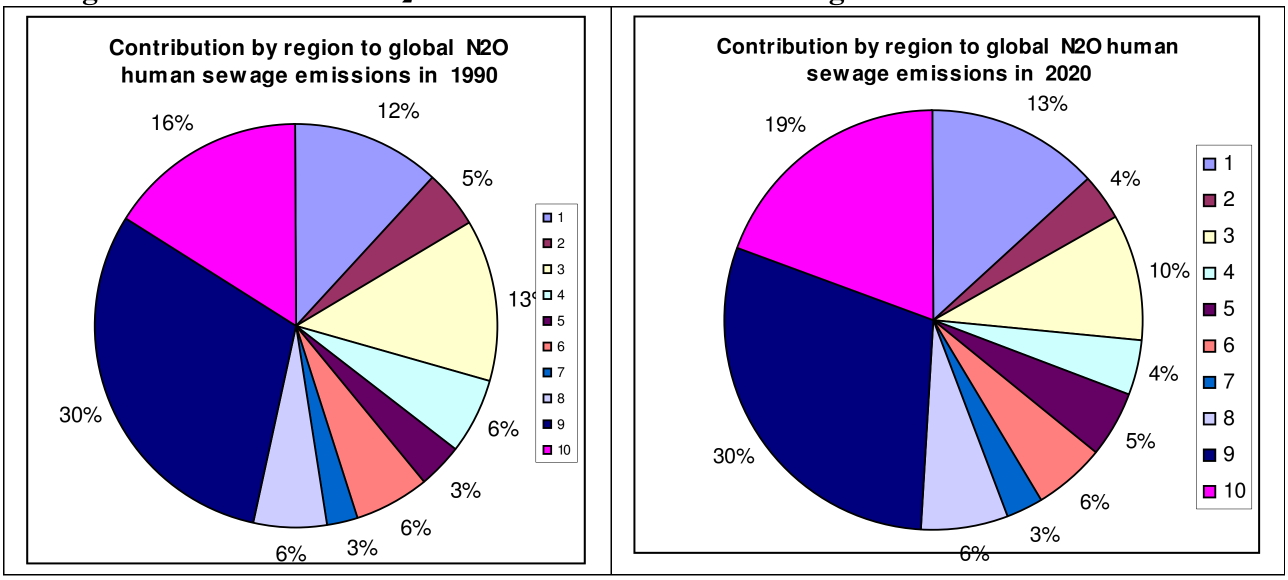


__Figure 10.5.__ Regional distribution of CH_4 and N_2O emissions from wastewater and human sewage in 1990 and 2020 (UNFCCC/IPCC, 2004).

The numbered regions are: 1) OECD N America; 2) OECD Pacific; 3) Europe; 4) Countries in transition; 5) Sub-Sahara Africa; 6) N Africa; 7) Middle East; 8) Caribbean and S America; 9) E Asia; 10) S Asia. The U.S. estimates include industrial wastewater and septic tanks which are not reported by all developed countries. See Table 10.3 for totals.

The highest regional CH_4 emissions from wastewater are from China, India, and the United States (Figure 10.5a). Other countries with high emissions in their respective regions include Korea, Turkey, Bulgaria, Iran, Brazil, Nigeria, and Egypt. Global emissions of CH_4 from wastewater handling are expected to rise more than 40% from 1990 to 2020. The only regions with decreased emissions in 2020 relative to 1990 are Europe and Countries in Transition. Comparing CH_4 emissions in 1990 and 2020 indicates that OECD Annex 1 countries emitted 59 Mt CO_2e in 1990 and are expected to rise about 12% by 2020; the Non-OECD Annex 1 countries emitted 12 Mt CO_2e and are expected to decrease 25% by 2020 (Scheehle and Kruger, 2006). The Non-Annex 1 countries emitted 302 Mt CO_2e and are expected to increase 47% by 2020 with the highest emissions from the developing countries of East and South Asia and the Caribbean, Central and South America.

The contribution of human sewage to atmospheric N_2O is very low and is expected to fluctuate from 70-90 Mt CO_2e/yr during the period 1990-2020 compared to current total global anthropogenic N_2O emissions of about 3500 Mt CO2e (EPA, 2005). 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. (Figure 10.5b) (UNFCCC/IPCC, 2004). It is expected that global emissions will rise 32% by 2020 in comparison with 1990. The regions with the highest emissions are the developing countries of East Asia, the developing countries of South Asia, Europe, and the OECD North America. Regions whose emissions are expected to increase the most by 2020 are: Sub – Saharan Africa 88%, N Africa 75%, the Middle East 60%, the developing countries of S Asia 58%, and the OECD North America 43%. The only regions that are expected to decrease their emissions in 2020 relative to 1990 are Europe and the Countries in Transition.

10.3.4 Carbon Dioxide: Fossil C Incineration

The major GHG emission from waste incineration and other thermal processes is CO_2 from fossil C sources such as plastics. Detailed data on waste incineration are difficult to obtain for most countries. Japan incinerates > 70% of the municipal solid waste generated, typically with power generation or energy recovery (Japan Ministry of the Environment, 2006). while in the EU25 about 17% of municipal solid waste was incinerated with energy recovery in 2003 (Eurostat 2003; Statistics Finland 2005). In the U.S., approximately 14% of waste is incinerated (U.S. EPA, 2005). Incineration is especially important in Denmark and Luxembourg, at 52% and 59% of waste, respectively, as well as in France, Sweden, the Netherlands, and Switzerland. Incineration is increasing in most EU countries as a result of the EU Landfill Directive.

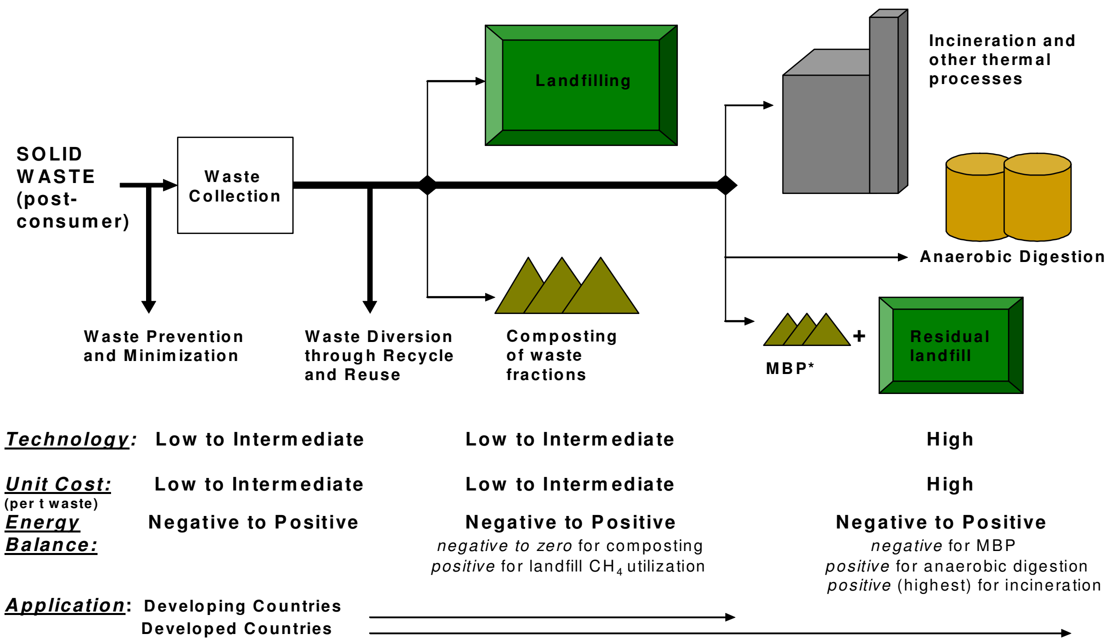
In developing countries, incineration of waste is less common than in developed countries because of high capital and operating costs. Incineration is also not the technology of choice for wet waste, and the waste in many developing countries contains a high percentage of readily degradable food waste with high moisture contents. Uncontrolled burning of waste for volume reduction is, however, commonly practiced in many developing countries, where it also contributes to urban air pollution (World Bank, 1999).

The estimated current emissions from waste incineration are small, around 40 Tg CO_2e/yr, or less than one tenth of CH_4 landfill emissions. Future trends will depend on the prices of energy, as well as incentives and costs of GHG mitigation. Monni et al. (2006) estimated growth in the emissions to 80 - 230 Tg CO_2e/yr in 2050 [not including fossil fuel offsets due to energy recovery] .

10.4 Mitigation of post-consumer emissions from waste

10.4.1 Waste management and GHG mitigation technologies

Mitigation of GHG emissions from waste relies on a range of mature 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 10.6). These technologies include landfilling with landfill gas recovery, post-consumer recycling, composting of selected waste fractions, MBT with landfilling of residuals, anaerobic digestion, and incineration and other thermal processes [production of RDF(refuse derived fuel) and industrial incineration in cement kilns] (Onuma et al., 2004). At the "high technology" end, there are also advanced thermal processes for waste such as pyrolysis and gasification, which have not yet been applied to municipal waste at large scale (thousands of t/d) and are largely inappropriate for mixed waste. Costs and potentials are addressed in section 10.4.7.



***MBP: Mechanical Biological Pretreatment.**

Figure 10.6. *Technology gradient for waste management: Low- to high-technology options applicable to major urban areas*

10.4.2 CH_4 management at landfills

Global CH_4 emissions from landfills are estimated to range from approximately 400 to 800 Mt CO2e/yr (Scheehle and Kruger, 2006; Monni et al. 2006; Bogner and Matthews 2003). However, landfill CH_4 emissions from small scale surface measurements (area <1m^2) can vary over 7 orders of magnitude (0.0001 - >1000 g CH_4 m^{-2} day^{-1}) 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 U.S., and South Africa range from about 0.1 to 1.0 t CH_4 ha^{-1} day^{-1} (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. This technology has been fully commercial since 1975 and has been implemented at more than 1150 facilities worldwide (Willumsen, 2003), primarily in the U.S., Europe, and Australia. 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). Of course, there are fugitive emissions from landfilled waste prior to and after the implementation of active gas extraction; therefore "lifetime" recovery efficiencies may be as low as 20% (Oonk and Boom, 1995). In addition, some sites have less efficient or partial gas extraction systems. 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 gas 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 carbon dioxide 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.

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, and moisture content 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^{-1} (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^{-1} in thick, compost-amended "biocovers" engineered to optimize oxidation (Huber-Humer, 2004; Bogner *et al.*, 2005). The prototype biocover design includes an underlying coarse-grained gas distribution layer to provide more uniform fluxes to the biocover above (Huber-Humer, 2004). Therefore, the combination of engineered gas extraction and natural CH_4 oxidation can be extremely effective to reduce emissions. 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 biofilters which utilize methanotrophic microorganisms to reduce emissions (Gebert and Gröngröft, 2005; Streese and Stegman, 2005). Stable C isotopic techniques have proven extremely useful to quantify the fraction of CH_4 that is oxidized in landfill cover soils in field settings (Chanton and Liptay, 2000; de Visscher and Chanton, 2004) 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.*, 2003).

Other measures to reduce landfill methane emissions include installation of geomembrane composite covers (required in U.S. 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. Aerobic and semi-aerobic landfills have also been implemented to reduce CH_4 production and emissions; however, such systems may have increased N_2O emissions (Tsujimoto, 1994).

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 converted to biogas carbon but remains in the landfill (see references cited on Figure 10.1). Carbon storage makes landfills 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 C storage in landfills can vary over a wide range as a function of the original waste composition and landfill conditions; for example, Hashimoto and Moriguchi (2004) address the Japanese perspective.

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

Incineration reduces the mass of waste and substitutes for fossil fuels; in addition, GHG emissions are avoided except for the contribution from fossil C which is dependent on the percentage of plastics (Consomi et al., 2005). Incineration has been widely applied, especially in countries with limited space for landfilling such as Japan and the Netherlands. Waste-to-energy plants produce heat or electricity for productive use, which improves process economics. In northern Europe, urban incinerators have historically supplied fuel for district heating of residental and commercial buildings. In developing countries, rural areas, and also historically in developed countries, waste has often been inefficiently burned to reduce volume and recover noncombustible recyclables, especially metals.

Waste incinerators have been extensively used for more than 20 years, primarily in Europe and Japan, with increasingly stringent emission standards. Mass burning is relatively expensive (range of 50-150 €/tonne) (Faaij *et al.*, 1998). Typical electrical efficiencies are 15% to >20% with more efficient designs (>30%) now available. Starting in the 1980s, large waste incinerators with stringent emission standards were widely deployed in Germany and the Netherlands. Typically such plants have a capacity of about 1 Mt waste/yr, moving grate boilers (which allow mass burning of very diverse waste properties), low steam pressures and temperatures (to avoid corrosion) and extensive flue gas cleaning. In recent years advanced combustion concepts have penetrated the market, including fluidized bed technology.

10.4.4 Biological treatment including composting, anaerobic digestion, and MBP (Mechanical Biological Pretreatment)

Many developed and developing countries practice composting and anaerobic digestion of mixed waste or biodegradable waste fractions (kitchen or restaurant wastes, garden waste, manures, sewage sludge). Both processes are best applied to source-separated waste fractions: anaerobic digestion is particularly appropriate for wet wastes while composting is more appropriate for drier feedstocks. Composting decomposes waste aerobically into CO_2, water and a humic fraction. Anaerobic digestion produces CH_4, CO_2 and biosolids; the CH_4 can be used for process heating or onsite electrical generation. In particular, Denmark, Germany, Belgium, and France have implemented anaerobic digestion systems for waste processing. The CO_2 emissions from both composting and anaerobic digestion are biogenic and therefore not included in UNFCCC inventories. 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. Minor quantities of CH_4 can also be vented from digesters during start-ups, shut-downs, and malfunctions. However, the GHG emissions from controlled biological treatment are small in comparison to uncontrolled CH_4 emissions from landfills (e.g. Petersen *et al.* 1998; Hellebrand 1998; Vesterinen 1996; Beck-Friis 2001; Detzel *et al.* 2003). The advantages of biological treatment are reduced volume, waste stabilisation, and pathogen destruction. Depending on quality, the residual solids can be recycled as fertiliser or soil amendments, used as a CH_4-oxidizing biocovers on landfills (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 and other EU countries. Mixed waste is subjected to a series of mechanical and biological operations which reduce volume and achieve partial stabilisation of the organic C. Typically, mechanical operations such as shredding and crushing produce waste fractions for further treatment (composting, anaerobic digestion, combustion, recycling); then the subsequent biological processing includes either composting or anaerobic digestion. Composting may occur either in open windrows or in closed buildings with gas collection and treatment. Reductions of as much as 40 - 60% of the organic C are possible with MBT (Kaartinen 2004), and CH_4 generation can theoretically be reduced by 90% compared to landfilling (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, reuse and recycling of secondary materials

Material efficiency can be defined as a reduction in primary materials for a particular purpose, such as packaging or construction, without negatively impacting existing human activities. Efficient use of materials also reduces waste. At several stages in the life cycle of a product, material efficiency can be increased by 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 are deployed in many countries at large scale for reuse of metals (steel, aluminum) and recycling of paper, plastics, and wood. All these measures lead to indirect energy savings and reductions in GHG emissions. Recycling directly reduces GHG emissions through lower energy demand for production (avoided fossil fuel) and by substitution of recycled feedstocks for virgin materials. This is especially true for products resulting from energy-intensive production processes such as metals, glass, plastic, and paper (Tuhkanen *et al.*, 2001). However, the GHG benefits of recycling are highly dependent on the specific materials involved, the recovery rates for those materials, and the local options for managing those materials.

10.4.6 Wastewater and sludge treatment

There are many available technologies for wastewater management, collection, treatment, reuse and disposal, ranging from energy-intensive advanced technologies to natural purification processes. Systematic decision-making tools are now available which include both environmental tradeoffs and costs (Ho, 2000). However, systematic global studies of GHG reduction potentials and costs for the wastewater sector are still needed. When efficiently applied, wastewater transport and treatment technologies reduce or eliminate CH_4 and N_2O generation and emissions, as well as promote water conservation by preventing pollutants from entering the water or requiring a smaller volume of water to be treated. Since the size of treatment systems is primarily governed by the volume of water to be treated rather than the mass loading of pollutants, smaller volume also implies smaller treatment plants and lower capital costs that can be more extensively deployed for treatment and GHG mitigation. 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 capital costs reduced by 30-50% compared to 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. Also, 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 on 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 reuse, drying and incineration. The use of composted sludge as a soil conditioner in agriculture and horticulture returns C, N, P and other elements essential for plant growth back to the soil. Heavy metals and some toxic chemicals are difficult to remove from sludge; either 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. Some sludges are landfilled, but this practice may result in volatile siloxanes or H_2S in the landfill gas. Treated wastewater can either be reused or discharged, but reuse 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

All climate change policies and measures necessitate some costs. In the waste sector, it is often not possible to clearly separate costs for GHG mitigation from costs for waste management. Thus one must be particularly careful about baseline assumptions, assumed costs, local availability of technologies, and economic and social development issues when costing alternative waste management strategies. Tables 10. 4 and 10.5 summarise cost data for waste management and GHG mitigation. However, it is important to emphasize that waste management costs can exhibit high variability depending on local conditions.

Table 10.4. *Cost analysis for GHG gases from waste management strategies compared to landfilling (Bates and Haworth, 2001). AD= anaerobic digestion; MBP=mechanical-biological pretreatment. The 2001 rate of landfill gas recovery for the EU as a whole was estimated to be 20% while 70% was assumed to be the maximum % CH_4 recovery over the lifetime of an individual site. Units in column 2*

Option		Composting	Composting	AD	AD	MBP	Incineration	Incineration	Paper recycling
Applicability (1=UK; 2=Netherlands)		1	2	1	2	1+2	1	2	1+2
cost per t waste treated									
capital cost	€1990/t waste/yr	154	182	172	208	154	228	517	455
operating cost	€1990/t waste	32	37	26	54	32	22	25	154
diposal of residues	€1990/t waste	8	8	3	0	20	0	0	0
income from energy	€1990/t waste	0	0	-5	-3	0	-15	-15	0
other income	€1990/t waste	-10	-10	-17	0	0	0	0	-207
avoided cost of landfilling	€1990/t waste	30	30	30	30	30	30	30	30
annualised cost per t waste treated									
at 2% discount rate	€1990/t waste	13	27	-10	37	35	-9	12	-59
at 4% discount rate	€1990/t waste	15	29	-8	39	37	-6	18	-53
at 6% discount rate	€1990/t waste	17	32	-6	42	39	-3	25	-46
total reduction in GHG emissions									
Assuming 20% recovery of LFG	t CO2 eq/t waste	1.2	1.2	1.3	1.3	1.2	1.1	1.1	1.2
Assuming 70% recovery of LFG	t CO2 eq/t waste	0.5	0.5	0.5	0.5	0.5	0.4	0.4	0.5
Cost-effectiveness(CH4 and CO2)									
Assuming 20% recovery of LFG									
at 2% discount rate	€1990/t CO2 eq	10	16	-8	29	28	-9	11	-47

at 4% discount rate	**€1990/t CO2 eq**	**12**	**17**	**-6**	**31**	**30**	**-6**	**17**	**-43**
at 6% discount rate	**€1990/t CO2 eq**	**13**	**19**	**-4**	**33**	**31**	**-3**	**24**	**-37**
Assuming 70% recovery of LFG									
at 2% discount rate	**€1990/t CO2 eq**	**28**	**41**	**-19**	**73**	**75**	**-23**	**31**	**-126**
at 4% discount rate	**€1990/t CO2 eq**	**32**	**46**	**-15**	**78**	**79**	**-16**	**47**	**-114**
at 6% discount rate	**€1990/t CO2 eq**	**36**	**51**	**-11**	**83**	**83**	**-8**	**65**	**-100**

Table 10.5. *Costs for mitigating CH_4 emissions from waste*

a Cost-effectiveness of mitigating CH_4 emissions from waste in the Netherlands, including low- to high-technology strategies and assuming a 20 year project life (de Jager and Blok, 1996).

measure	**capital cost**	**operating cost**	**profit**	**CH_4 emission reduction**	**net cost**	**net cost**
	\$/ t/yr (CH_4)	\$/ t/yr (CH_4)	\$/ t/yr (CH_4)	kt/yr (CH_4)	\$/t CH_4	\$/t CO_2e
landfill CH_4 recovery with onsite electrical generation	500	28	120	72	-48	-2.3
recovery and utilisation: upgrading of waste gas to natural gas quality	700	105	200	31	-35	-1.7
recovery: flaring	85	0.3	0	51	8	0.4
aerobic composting		950	650	5	300	14.3
anaerobic digestion		1,400	750	1	650	31.0
incineration		10,000	2150	6	7850	373.8

b. Range of investment costs for onsite electrical generation from landfill gas (Willumsen, 2003).

System component	**Cost (2003 US\$/kW installed power)**
landfill gas collection (vertical wells or horizontal collectors; header)	200-400
landfill gas recovery and conditioning (blower/compressor, dehydration, flare)	200-300
landfill gas utilization (engine)	850-1200
planning and design	250-350
Total	**1500-2250**

Estimates for costs and potentials for GHG reduction from waste management are usually based on landfill CH_4 as the baseline (Bates and Haworth, 2001; Delhotal et al. 2005; Nakicenovic et al., 2000; Pipatti and Wihersaari 1998). It is important to stress that, because landfilled waste will generate CH_4 for several decades, landfill gas recovery will also reduce CH_4 emissions from waste landfilled in previous years. In contrast, waste minimisation, recycling and various alternatives to landfilling (such as biological and thermal processes[2]) will only impact emissions in the future. There are few existing studies on the costs and potentials of GHG mitigation in the waste sector which consider these temporal issues.

Monni et al. (2006) prepared baseline and mitigation scenarios for solid waste management using the methodologies in the 2006 IPCC Guidelines, taking into account the timing of emissions. The mitigation scenarios included the potential to reduce emissions in 2030 and 2050 by increased landfill gas recovery, increased recycling and increased incineration. The baseline scenario assumes that waste generation will increase with growing population and GDP (using the same population data as SRES scenario A1b); waste management strategies will not change significantly; and landfill gas recovery and utilization will continue to increase at the historical rate of 5% per year in developed

[2] The term incineration is used here to encompass also waste-to-energy concepts like

countries (Bogner and Matthews,2003; Willumsen, 2003). In a second scenario, increased landfill gas recovery, the recovery was estimated to increase 15% per year, with most of the increase for developing countries as a result of CDM or similar incentives (baseline was estimated based on current CDM projects). A third scenario of increased incineration was also considered where 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.

In the Monni et al. (2006) baseline scenario (Figure 10.7a), emissions increase threefold during the period from 1990 to 2030, and more than fivefold till 2050. Most the increase comes from non-OECD countries whose current emissions are smaller due to lower waste generation rates and a larger share of waste degrading under aerobic conditions. The estimated growth rates in waste generation and emissions do not include current or planned legislation on waste minimisation or bans on landfilling of organic waste—thus future emissions may be overestimated. The mitigation scenarios (Figure 10.7b) show that reductions by individual measures in 2030 range from 5 to 20% of total emissions, and increase proportionally with time. In 2050 the corresponding range is approximately 10 to 30%. As the measures in the scenarios are largely additive, a total mitigation potential of approximately 30% in 2030 and 50% in 2050 are projected, compared to the baseline scenario. Nevertheless, the estimated abatement potential is not capable of mitigating growth in emissions.

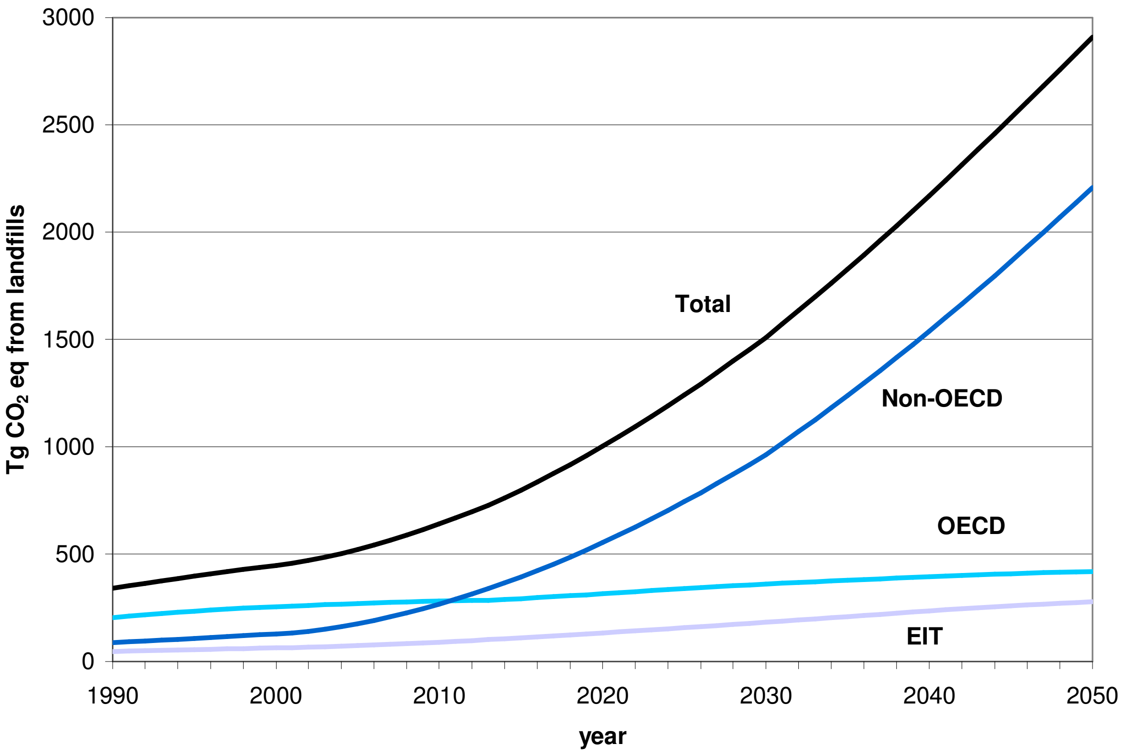


Figure 10.7a. *CH_4 emissions (Tg CO_2 eq) from landfills in different regions in the Baseline scenario by Monni et al. (2006).*

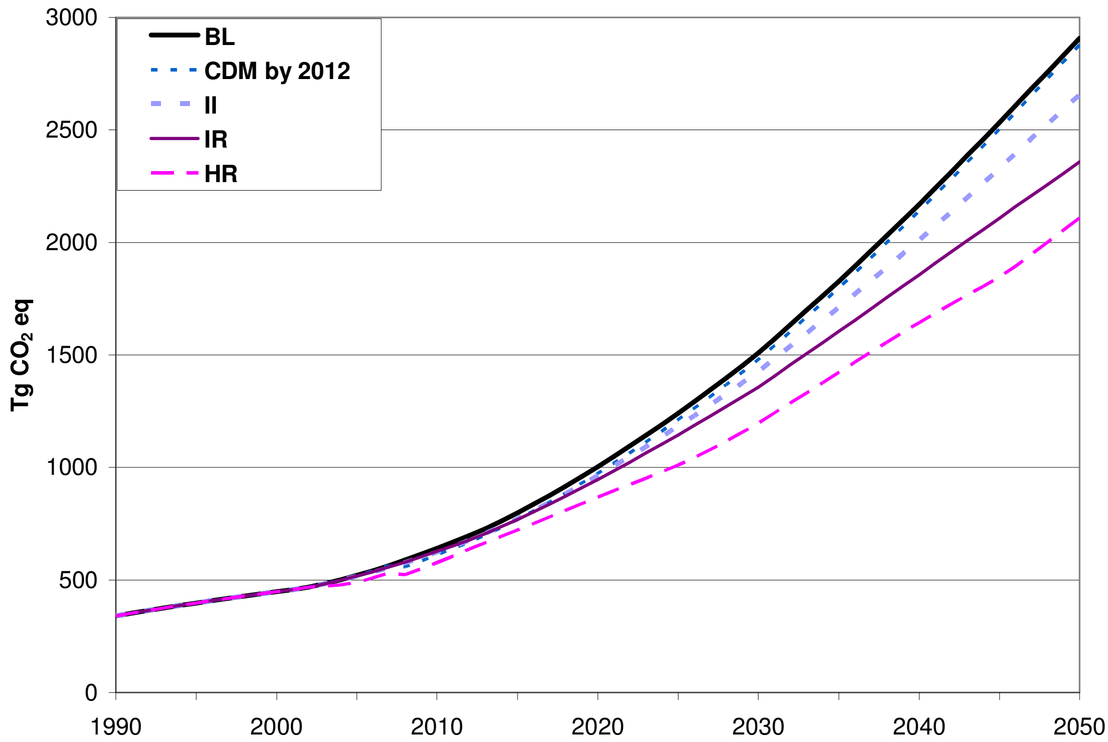


Figure 10.7b. *Global CH_4 emissions from landfills in baseline (BL) scenario compared to the following mitigation scenarios: increased incineration (II), CDM ending in 2012 (end of the first Kyoto commitment period), increased recycling (IR), and high landfill methane recovery rates (HR) including continuation of CDM (Monni et al., 2006). The emission reductions estimated in the mitigation scenarios are largely additional during the consideration period.*

Scenario development was complemented with estimates on mitigation potentials at given mitigation cost levels. Some modifications were required in the assumptions used for scenario development, e.g. recycling was excluded due to its economic complexity whereas biological treatment was considered and the efficiency of landfill gas recovery was assumed to be the same in all countries. Cost data were taken from the EMF-21 study (USEPA 2003) and the model runs were made with the Global Times model. Substantial emission reductions can be achieved at low or negative costs (see Table 10.6). For example, at costs below 20 US$/CO2e/yr an emission reduction of almost 1000 Tg CO_2e/yr would be achievable in 2030, and at higher costs, more significant reductions would be possible. At higher cost levels, most of the additional mitigation potential would come from thermal processes for waste-to-energy. With early implementation of mitigation measures, the time frame could be shortened. In the near term, the largest reductions with least cost are achieved with landfill gas recovery. However, for sustainable reductions in the long term, other measures are needed including thermal processes, waste minimisation and recyling, and biological processes.

***Table 10.6**. Economic reduction potential of methane emissions from landfilled waste by level of marginal costs for total GHG emission reduction assessed for the year 2030[3].(Monni et al., 2006)*

		Marginal Costs (USD/t CO_2 eq)				
Mitigation Option	**Region**	**0**	**10**	**20**	**50**	**100**
Anaerobic digestion	OECD	0	0	1	5	5
	EIT	0	0	0	20	24
	Non-OECD	0	0	30	68	95
	Global	0	0	31	94	124
Composting	OECD	0	0	0	0	3
	EIT	0	0	0	6	19
	Non-OECD	0	0	0	58	81
	Global	0	0	0	64	102
Mechanical biological treatment	OECD	0	0	0	0	0
	EIT	0	0	0	0	0
	Non-OECD	19	19	19	19	19
	Global	19	19	19	19	19
LFG recovery - energy	OECD	27	43	41	23	22
	EIT	56	29	15	0	0
	Non-OECD	328	368	306	138	43
	Global	411	440	362	162	65
LFG recovery - flaring	OECD	0	6	1	0	0
	EIT	0	17	0	0	0
	Non-OECD	0	12	0	0	0
	Global	0	34	1	0	0
Waste incineration with energy recovery[a,b]	OECD	124	222	237	266	266
	EIT	0	101	156	156	140
	Non-OECD	0	0	166	515	653
	Global	124	323	558	936	1059
Total	OECD	151	270	280	295	296
	EIT	56	147	171	182	182
	Non-OECD	347	399	521	798	890
	Global	554	817	972	1275	1369

[a] This category includes all waste-to-energy options, e.g. gasification
b Combustion of waste causes also fossil CO2 emissions, which have been taken into account in the calculations, but this table presents only emissions savings from landfills. However, emissions from waste-to-energy concepts are typically overcompensated by the corresponding savings when waste based energy replaces fossil fuels in the energy system.

[3] The emission reduction potentials are assessed using a steady state approach which can overestimate instantaneous annual reductions but gives correct values when integrated over time.

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

The CFCs and HCFCs regulated as 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 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 only 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, 2005a), 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; CFC-11 and CFC-12 were the main blowing agents until the mid-1990s. After the mid-1990's, 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).

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 buried in landfills, either directly or following shredding and 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 U.S. and some 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, 2005a). Then, when landfilled, compactors reduce the size of residual foam materials and enhance gaseous releases.

In the anaerobic landfill environment, however, some fluorinated gases may be biodegraded because CFCs and, to some extent, HCFCs can undergo dechlorination (Scheutz *et al.*, 2005b). 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 studies are needed to verify that CFCs and HCFCs are being attenuated in field settings. Such data are needed to guide future policy decisions.

10.4.9 Air quality issues associated with waste management activities: NMVOCs and combustion emissions

Landfill gas contains trace concentrations of aromatics, chlorinated and fluorinated hydrocarbons, reduced S gases, and other species. Uncontrolled emissions of collected landfill gas are not permitted in most developed countries, but high hydrocarbon destruction efficiencies are typically achieved in enclosed flares (>99%), which are recommended over lower efficiency open flares. In some landfill gas utilization projects (engines, turbines, or gas upgrading), landfill gas must be pretreated to remove NMVOCs and H_2S to comply with manufacturer's specifications. Hydrogen sulfide is mainly a problem at sites which co-disposed large quantities of construction and demolition debris containing gypsum board. The type and level of landfill gas treatment depend on site-specific factors (gas flow rate, trace gas concentrations, proposed use, hardware vendor specifications). Treatment techniques can include solid adsorption, chemical oxidation, liquid absorption, and membrane processes. Emissions of NO_x can sometimes be a problem for permitting biogas engines as new sources 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 on the order of 10^{-8} to 10^{-5} $g{\cdot}m^{-2}{\cdot}d^{-1}$ for individual species (Scheutz *et al.*, 2003; Bogner *et al.*, 2003). In general the emitted compounds consist of species recalcitrant to aerobic degradation (especially higher chlorinated compounds), while 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. Uptake (negative emission) occurs when air in urban areas and above landfill sites contains elevated NMVOCs (especially aromatics from mobile sources), and soil gas profiles indicate that the direction of diffusive flux is from the atmosphere into the soil. In contrast, emissions from temporary cover areas are mainly positive and higher, on the order of 10^{-5} to 10^{-4} $g{\cdot}m^{-2}{\cdot}d^{-1}$ for individual species.

Uncontrolled emissions resulting from waste incineration are not permitted in developed countries; typically, incinerators must be equipped with advanced emission controls. For reducing incinerator emissions of volatile heavy metals and dioxins/dibenzofurans, the removal of batteries, plastics, and other waste materials containing heavy metals (Pb.Cd) and chlorinated compounds is recommended prior to combustion. Modern incinerators must meet stringent emission control standards in Japan, Germany and the rest of the EU, the U.S., and other developed countries.

10.5 Policies and measures: waste management and climate

GHG emissions from waste are directly affected by numerous policy and regulatory strategies which encourage energy recovery from waste, restrict choices for ultimate waste disposal, promote waste recycling and reuse, 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 10.7 provides an overview of policies and measures which are discussed below.

Table 10.7. 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
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	Performance standards for incinerators	CO_2 CH_4	Regulation
Tax exemption for electricity generated by waste incinerator and for waste disposal with energy recovery	Energy recovery from incineration of waste	CO_2 CH_4	Economic incentive
Promoting waste minimization, reuse, and recovery			
Extended Producer Responsibility (EPR)	Manufacturing 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	Economic incentive
Separate collection and recovery of specific waste fractions	Recovery of used products Disposal of waste	CO_2 CH_4 fluorinated gases	Regulation
Subsidies for activities such as reuse, recycling, and composting	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 waste water treatment system	Management of waste water 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		CO_2 CH_4	Kyoto mechanism

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. The U.S. has implemented regulations under the Clean Air Act (CAA) which require large landfills to capture and combust landfill gas (U.S. Department of State, 2002). The EU requires member states to insure that landfill gas will be captured and flared at all landfills receiving biodegradable waste (Commission of the European Community, 2001). More broadly, 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 (Commission of the European Community, 2001). An increase in the availability of landfill alternatives is required (Price, 2001) to achieve these regulatory goals; alternatives include increased recycling, composting, incineration, and combined strategies such as mechanical biological treatment (MBT) prior to landfilling.

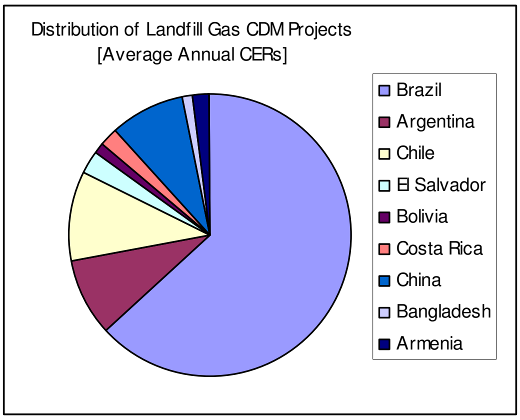
Landfill CH_4 recovery has also been encouraged by several country-specific economic and regulatory incentives. In the U.K., for example, the Non Fossil Fuel Obligation (NFFO), requiring a portion of electrical generation capacity from non-fossil sources, provided a major incentive for landfill-gas-to-electricity projects during the 1980's and 1990's. In other European countries, the decentralization of electrical generation capacity via renewable sources provides greater incentives for the development of on-site electrical generation from landfill CH_4. In the U.S., as mentioned above, the implementation of Clean Air Act (CAA) regulations in the early 1990's provided a regulatory driver for gas recovery at large landfills; in parallel, the U.S. EPA Landfill Methane Outreach Program (LMOP) has provided technical support and tools to facilitate landfill gas projects. More recently, the U.S. Methane to Markets initiative, in cooperation with LMOP, has started to provide assistance for developing CH_4 recovery projects in many countries. Also, periodic tax credits in the U.S. have provided an economic incentive for landfill gas utilization—for example, almost 50 of the 400+ commercial projects in the U.S. came on line in 1998, just before the expiration of federal Section 29 tax credits. A small U.S. 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. Other drivers include state requirements that a portion of electrical energy be derived from renewables as well as green power projrams that allow consumers to select renewable energy power providers.

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 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 and the recent availability of the Clean Development Mechanism (CDM) are providing strong economic incentives for both improved landfilling practices (to permit gas extraction) and landfill CH_4 recovery. The box (below) summarizes the important role of landfill CH_4 recovery within CDM and gives an example of a successful project in Brazil.

Box 10.2: Significant Role of Landfill Gas Recovery for CDM Projects: Overview and Example

As of May, 2006, 194 CDM projects have achieved registration with the Kyoto EB. These include 22 landfill gas projects which collectively total 15% of the annual average registered CERs (>7 million of approximately 48.5 million CERs/yr). (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 the LAC region (88% of CERs), dominated by Brazil (8 projects; 63% 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 to be encouraged, an initial flaring project under CDM makes good economic sense because it: a) simplifies the CDM process (fewer participants); b) lowers capital costs for project implementation; and c) permits definition of composite gas flow rates and gas quality prior to capital investment in gas utilization hardware.

An example of a successful Brazilian project is the ONYX SASA Landfill Gas Recovery Project at the VES landfill, Trémembé, Sao Paulo State. The recovered landfill gas is being flared; additionally, landfill gas is being used to evaporate leachate. As of December, 2005, approximately 93600 CERs had been delivered (Veolia Environmental Services, 2005).



Reserve for PHOTO of Trémembé Project

10.5.2 Promoting incineration and other thermal processes for waste-to-energy

Thermal processes can most efficiently exploit the energy value of post-consumer waste. 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 also been adopted. As discussed above, landfill taxes have been implemented in a number of EU countries to elevate the cost of landfilling to encourage incineration and other thermal processes for energy recovery from waste.

10.5.3. Promoting waste minimization, reuse, and recycling

Widely implemented policies include Extended Producer Responsibility (EPR), unit pricing (or PAYT/Pay As You Throw), and landfill taxes. The EPR regulations extend producers' responsibility to the post-consumer period, thus providing a strong incentive to redesign products more amenable to recycling (OECD, 2001). In general, EPR programs are expensive (Hanisch, 2000), and their economic and environmental benefits are still under debate. On the other hand, unit pricing has been widely adopted to decrease landfilled waste and increase recycling (Miranda *et al.*, 1996). Waste decreases can also be partly explained by concurrent recycling programs, waste minimization, and other measures (Miranda *et al.*, 1994; Fullerton and Kinnaman, 1996). Some municipalities have reported a secondary increase in waste generation after a rapid waste decrease following implementation of unit pricing, but the 10-year sustainability of these programs has been demonstrated (Yamakawa and Ueta, 2002). Another potential economic instrument to reduce waste is the landfill tax, an environmental tax added to tipping fees for waste disposal by landfill. The purpose of this tax is to reduce landfilled waste by artificially increasing costs to levels commensurate with competing technologies such as incineration, thereby encouraging the alternatives. In the U.K., the landfill tax has been used as a funding mechanism for environmental and community projects as discussed by Moriis *et al.* (2000) and Grigg and Read (2001).

Separate and efficient collection of recyclables is needed with both PAYT and landfill tax systems. For curbside programs, the percentage recycled is related to the efficiency of curbside collection and the duration of the program (Jenkins *et al.*, 2003). Other policies and measures include local subsidies and educational programs for collection of recyclables, domestic composting of biodegradable waste, and procurement of recycled products (green procurement). In the U.S., 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 nor 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 solid waste management in EIT and developing countries, the JI and CDM have already proven to be useful mechanisms for external investment from industrialized countries. As described in Section 10.3, open dumping is the common disposal method for solid waste in many developing countries where pollutant and GHG emissions occur concurrently with odor, public safety, and health problems. Thus the benefits from JI and CDM are twofold: improving waste management practices and reducing GHG emissions. This is especially true for landfill gas recovery projects because an engineered landfill with cover materials is required to minimize air intrusion during gas extraction to prevent internal landfill fires. Thus landfilling practices in many developing countries will require upgrading so that sites are suitable for active gas extraction. 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, the GHG credits are determined directly from quantification of the CH_4 captured and combusted. In many countries in Europe, Asia, and N America, the anaerobic digestion of wastewater and sludges also produces a useful biogas containing 50-60% CH_4 for heat or onsite electrical generation (Government of Japan, 1997; Government of Republic of Poland, 2001); such projects are also suitable for JI and CDM.

10.5.6 Non-climate policies affecting GHG emissions from waste

The EIT and many developing countries have implemented market-oriented structural reforms which 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. To date, solid waste generation does not support an environmental Kuznets curve (Dinda, 2004) because environmental problems related to waste can be externalized. Decoupling waste generation from economic and demographic drives, or dematerialization, is often discussed in the context of sustainable development, but the literature shows no absolute decline in material consumption in developed countries (Bringezu *et al.*, 2004). In Asia, China and Japan are 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 (Yuan et al., 2006). This approach is expected to achieve an efficient economy while discharging fewer pollutants.

In 2002, the Johannesburg Summit agreed on the Millenium goal 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 odors, 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 AMSD

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, e.g. 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 Clean Development Mechanism (CDM), which is being increasingly 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, reuse, and energy recovery. Huhtala (1997) studied optimal recycling rates for municipal solid waste using a model which included recycling costs (including social 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, paper/cardboard, and glass (OECD, 2002).

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 landfill cover designs to increase CH_4 oxidation ("biocovers") can largely mitigate site-specific CH_4 emissions (Huber-Humer, 2004). These technologies are simple (“low tech “) 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 mitigation potential for the waste sector. When the fossil fuel offset is also taken into account, the GHG impact can even be negative (e.g., Lohiniva *et al.* 2002; Pipatti and Savolainen 1996). High cost, however, is a major barrier to the increased implementation of waste-to-energy, but advanced technologies are expected to become more competitive as both energy prices and emissions trading increase.

In some developing countries, small-scale anaerobic digestion with CH_4 recovery and use is locally deployed as a simpler waste-to-energy strategy. These 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.

The mitigation potential of recycling technologies is still largely unexplored with existing studies yielding variable results, in part because of the differing assumptions and methodologies applied. A recent study (Myllymaa *et al.*, 2005) examined the environmental benefits of alternative waste management strategies.

10.6.2 Wastewater Management

GHG emissions from wastewater are lower than emissions from solid waste management. In addition, the quantity of wastewater collected and treated is increasing in many parts of the world to maintain and improve potable water quality. This will decrease GHG emissions because well-managed wastewater treatment plants result in lower emissions than septic tanks, latrines, or uncontrolled discharges into waterways. Wastewater can also become a secondary resource in countries with water shortages. Future trends in wastewater technology will include buildings where black water and gray water are separated, recycling the former for fertilizer and the latter for toilets. This will permit smaller treatment plants with reduced nutrient loads and concurrently lower emissions of CH_4 and N_2O.

10.6.3 Adaptation, Mitigation and Sustainable Development in the waste sector

In addition to providing GHG mitigation, improved public health, and environmental benefits, solid waste and wastewater technologies that confer significant co-benefits for adaptation, mitigation, and sustainable development (Table 10.8). 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, and implementation of landfill biocovers to optimize microbial CH_4 oxidation. The major impediment in developing countries is the lack of capital. Secondly, developing countries may 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 sustainable waste and wastewater strategies is very important for both the mitigation of climate change and achieving truly sustainable development. Unlike developed countries, the acute lack of capital in the developing world jeopardizes improvements in solid waste and wastewater management for improved public health, soil and water quality, and preservation of local ecosystems—thus endangering the fulfillment of Johannesburg Summit goals.

Table 10.8. *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	Largely unquantified indirect benefits for reducing GHG emissions from waste. Reduces use of energy and raw materials.
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 Odor reduction. (non-CH_4 gases)	Positive Job creation. Energy recovery potential.	Positive	Primary control on landfill CH_4 emissions with >1200 commercial projects. Important local source of renewable energy: replaces fossil fuels for process heat or electrical generation. Landfill gas projects comprise 15% of annual registered CERs under CDM (April, 2006: http://cdm.unfccc.int/ Projects/registered.html) 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 Odor reduction. (non-CH_4 gases)	Positive Job creation.	Positive	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 Odor reduction. (non-CH_4 gases)	Positive Job creation.	Positive	Important secondary control on landfill CH_4 emissions and emissions of NMVOCs. Utilizes other secondary materials (composted sludges). Low-cost low-technology strategy for developing countries.
Uncontrolled disposal (open dumping & burning)	Highly vulnerable. Detrimental effects: warmer temperatures promote pathogen growth and disease vectors.	Exacerbates adaptation problems. Recommend implementation of more controlled disposal and recycling practices	Negative	Negative	Negative	To be avoided. Consider lower-cost medium technology solutions (e.g. landfill with controlled waste placement, compaction, and daily cover materials)

Thermal processes including incineration and more advanced processes for waste-to-energy (e.g., fluidized bed technology with advanced flue gas cleaning)	Low vulnerability.	Minimal implications. Requires emission controls to prevent emissions of heavy metals, acid gases, dioxins, and other air toxics.	Positive Odor reduction. (non-CH_4 gases)	Positive Job creation. Energy recovery potential.	Positive	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 for process heat or electrical generation.
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 Odor reduction. (non-CH_4 gases)	Positive Job creation. Use of compost products.	Positive	Reduces GHG emissions. Can produce useful secondary materials (compost) if quality control on inputs and process operations
Anaerobic biological treatment (anaerobic digestion)	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 Odor reduction. (non-CH_4 gases)	Positive Job creation. Energy recovery potential.	Positive	Reduces GHG emissions. Replaces fossil fuels for process heat or electrical generation. Can emit minor quantities of CH_4 during start-ups, shut-downs, 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 adapation implications. High potential for reducing uncontrolled GHG emissions. Residuals (biosolids) from aerobic treatment may be anaerobically digested.	Positive Odor reduction. (non-CH_4 gases)	Positive Job creation. Energy recovery potential from anaerobic processes.	Positive	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.

REFERENCES

Ackerman, F., 2000: Waste Management and Climate Change, Local Environment 5(2), 223-229.

Austrian Federal Government, 2001:Third National Climate Report of the Austrian Federal Government, Vienna, Austria.

Barlaz, M., 1998: Carbon storage during biodegradation of municipal solid waste components in laboratory-scale landfills, Global Biogeochemical Cycles, **12**(2), 373-380.

Bates, J., and A. Haworth, 2001: Economic Evaluation of Emission Reductions of Methane in the Waste Sector in the EU: Bottom-up Analysis, Final Report to DG Environment, European Commission by Ecofys Energy and Environment, by AEA Technology Environment and National Technical University of Athens as part of Economic Evaluation of Sectoral Emission Reduction Objective for Climate Change, 73 pp.

Beck-Friis, B.G. 2001: Emissions of ammonia, N_2O, and CH_4 during composting of organic household waste. PhD Thesis, Swedish University of Agricultural Sciences, Uppsala, 331 pp.

Bernache-Perez, G., et al., 2001): Solid Waste Characterization Study in Guadalajara Metropolitan Zone, Mexico, Waste Management & Research, 19, 413-424.

Bingemer, H.G., and P.J. Crutzen, 1987: The production of CH_4 from solid wastes, J. Geophysical Research., **92**(D2), 2182-2187.

Binner, E. 2002: The impact of mechanical-biological pretreatment on the landfill behaviour of solid wastes. Workshop on Biowaste. Brussels, April 8-10, 2002. 16 pp.

Bogner, J., 1992: Anaerobic burial of refuse in landfills: increased atmospheric methane and implications for increased carbon storage, Ecological Bulletin, **42**, 98-108.

Bogner, J., M. Meadows, and P. Czepiel, 1997a.: Fluxes of methane between landfills and the atmosphere: natural and engineered controls, Soil Use and Management, **13**, 268-277.

Bogner, J. and E. Matthews, 2003: Global Methane Emissions from Landfills: New Methodology and Annual Estimates 1980-1996, Global Biogeochemical Cycles **17**, 34-1 to 34-18.

Bogner, J., C. Scheutz, J. Chanton, D. Blake, M. Morcet, C. Aran, and P. Kjeldsen, 2003: Field measurement of non-methane organic compound emissions from landfill cover soils, Proceedings Sardinia '03 International Solid and Hazardous Waste Symposium, published by CISA, Univ. of Cagliari, Sardinia.

Bogner, J., and K. Spokas, 1993: Landfill CH_4: rates, fates, and role in global carbon cycle, Chemosphere, **26**(1-4), 366-386.

Bogner, J., K. Spokas, and E. Burton, 1997b: Kinetics of methane oxidation in landfill cover materials: major controls, a whole-landfill oxidation experiment, and modeling of net methane emissions. Environmental Science and Technology, **31**, 2504-2614.

Bogner, J., K. Spokas and E. Burton E., 1999: Temporal variations in greenhouse gas emissions at a midlatitude landfill. Journal of Environmental Quality, **28**, 278-288.

Bogner, J., K. Spokas, E. Burton, R. Sweeney, and V Corona, 1995: Landfills as atmospheric methane sources and sinks, Chemosphere, **31**(9), 4119-4130.

Bogner, J., K. Spokas, J. Chanton, D. Powelson, and T. Abichou, 2005: Modeling landfill methane emissions from biocovers: a combined theoretical-empirical approach, Proc Sardinia '05 International Solid and Hazardous Waste Symposium, October, 2005, published by CISA, Univ. of Cagliari, Sardinia.

Borjesson, G., 1996: Methane oxidation in landfill cover soils, Doctoral Thesis, Dept. of Microbiology, Swedish University of Agricultural Sciences, Uppsala, Sweden,

Borjesson G. and B. Svensson 1997a: Nitrous oxide release from covering soil layers of landfills in Sweden, Tellus B, **49**, 357-363, 1997.

Borjesson, G., and B. Svensson, 1997b: Seasonal and diurnal methane emissions from a landfill and their regulation by methane oxidation, Waste Management and Research, **15**(1), 33-54.

Bramryd, T., 1997: Landfilling in the perspective of the global CO_2 balance, Proc Sardinia '97 International Landfill Symposium, October, 1997, published by CISA, Univ. of Cagliari, Sardinia.

Burnley, S., 2001: The impact of the European landfill directive on waste management in the United Kingdom, Resources, Conservation and Recycling, **32**, 349-358.

Bringezu, S., H. Schutz, S.Steger, and J. Baudisch, 2004: International comparison of resource use and its relation to economic growth: the development of total material requirement, direct material inputs and hidden flows and the structure of TMR, Ecological Economics, **51**, 97-124.

CALEB, 2000: Development of a global emission function for blowing agents used in closed cell foam. Final report prepared for AFEAS. Caleb Management Services, Bristol, United Kingdom.

CalRecovery, Inc., 2004: Waste Analysis and Characterization Study, Asian Development Bank, Report TA - 3848-PHI.

CalRecovery, Inc., 2005: Solid Waste Management, UNEP, Japan.

Chanton J. , and K. Liptay, 2000: Seasonal variation in methane oxidation in a landfill cover soil as determined by an in situ stable isotope technique, Global Biogeochemical Cycles, **14**, 51-60.

Christiansen, T., 1989: Environmental aspects of sanitary landfilling, in Sanitary Landfilling, Christensen, T., et al. (ed.), Academic Press, San Diego, pp.19-29.

Cointreau-Levine, S., 1994: Private Sector Participation in Municipal Solid Waste Services in Developing Countries, Vol. 1 The Formal Sector. Urban Management and the Environment, 13, UNDP/ UNCHS(United Nations Centre for Human Settlements), World Bank, Washington, DC, 52 pp.

Coleman, D.D., 1979: The origin of drift-gas deposits as determined by radiocarbon dating of methane. In: R. Berger and H.E. Seuss (Editors), Radiocarbon Dating, University of California Press, Berkeley, pp. 365-387.

Commission of the European Community, 2001: Third Communication from the European Community under the UN Framework Convention on Climate Change, Brussels.

Consomi, S., M. Giugliano, and M. Grosso, 2005: Alternative strategies for energy recovery from municipal solid waste. Part B: emission and cost estimates. Waste Management, **25**, 137-148.

Czepiel, P., B. Mosher, R. Harriss, J.H. Shorter, J.B. McManus, C.E. Kolb, E. Allwine, and B. Lamb, 1996; Landfill methane emissions measured by enclosure and atmospheric tracer methods, J. Geophysical Research, **D101,** 16711-16719.

Daskalopoulos E., O. Badr, and S.D. Probert, 1998: Municipal solid waste: a prediction methodology for the generation rate and composition in the European Union countries and the United States of America, Resources, Conservation and Recycling, **24**, 155-166.

de Jager, D. and K. Blok, 1996: Cost-effectiveness of emission-reduction measures for CH_4 in the Netherlands, Energy Conserv. Management, **37**, 1181-1186.

Delhotal, C., 2005: Methane and Nitrous Oxide from Non-Agricultural Sources, Chapter 3, International Non-CO_2 Greenhouse Gas Marginal Abatement Report, U.S. EPA Office of Air and Radiation (Draft).

DESA (Dept. of Economic and Social Affairs)/UN, 2005: Country, Regional and Global Estimates on Water and Sanitation, Statistics Division, MDG Report - WHO/UNICEF WES estimate, http://www.unicef.org/wes/mdgreport/who_unicef_WESestimate. pdf (updated 10Nov04).

Detzel, A., R. Vogt, H. Fehrenbach, F. Knappe and U. Gromke, 2003. Anpassung der deutschen Methodik zur rechnerischen Emissionsermittlung und internationale Richtlinien: Teilberich Abfall/Abwasser. IFEU Institut - Öko-Institut e.V. 77 p.

de Visscher, A., D. Thomas, P. Boeckx, and O. Van Cleemput, 1999: Methane oxidation in simulated landfill cover soil environments, Environmental Science and Technology, **33**(11), 1854-1859.

de Visscher A., I. De Pourcq, and J. Chanton , 2004: Isotope fractionation effects by diffusion and methane oxidation in landfill cover soils, Journal of Geophysical Research, **109** (D18), paper D18111.

Diaz, L.F. and L.L. Eggerth, 2002: Waste Characterization Study, Ulaanbaatar, Mongolia, WHO/WPRO, Manila, Philippines.

Diaz, L.F., G. Savage, and C. Goluke, 2002, Solid waste composting, Chapter 12 in Tchobanoglous, G., and Kreith, F., Eds., Handbook of Solid Waste Management, McGraw-Hill.

Dinda, S., 2004: Environmental Kuznets curve hypothesis: a survey, Ecological Economics, 49, 431-455.

EEA(European Environment Agency), 2004: Greenhouse gas emission trends and projections in Europe 2004. EEA Report no5/2004, Progress EU and its member states towards achieving their Kyoto targets, Luxembourg, pp., ISSN 1725 -9177, 40 pp.

EEA(European Environment Agency), 2005: European Environment Outlook, EU Report 4/2005, ISSN 1725-9177, Luxembourg, published by EEA, Copenhagen, 92 pp.

Eurostat, 2003**:** Waste generated and treated in Europe. Data 1990 - 2001. Office for Official Publications of the European Communities, Luxemburg, 140 pp.
Faaij, A., M. Hekkert., E. Worrell, and A. van Wijk, 1998, Optimization of the final waste treatment system in the Netherlands. Resources, Conservation, and Recycling, 22, 47-82.
Flugsrud, K., B. Hoem, E. Kvingedal and K. Rypdal. 2001: Estimating net emissions of CO2 from harvested wood products. SFT report 1831/200. Norwegian Pollution Control Authority, Oslo, 47 pp. http://www.sft.no/publikasjoner/luft/1831/ta1831.pdf
Fullerton, D. and T.C. Kinnaman, 1996: Household responses to pricing garbage by the bag, American Economic Review, **86**(4), 971-984.
Galle, B., J. Samuelsson, B. Svensson, and G. Borjesson, 2001: Measurements of methane emissions from landfills using a time correlation tracer method based on FTIR absorption spectroscopy, Environmental Science and Technology, **35**(1), 21-25.
Gamlen, P.H., B.C. Lane, and P.M. Midgley, 1986: The production and release to the atmosphere of CCl_3F and CCl_2F_2 (Chlorofluorocarbons CFC-11 and CFC-12), Atmospheric Environment, **20**(6), 1077-1085.
Gebert, J., and A. Gröngröft, 2005: Microbial Oxidation of Landfill Methane in a Biofilter System - Passive Ventilation and Oxygen Supply, Proceedings Sardinia '05 International Solid and Hazardous Waste Symposium, October, 2005, CISA, Univ. of Cagliari, Sardinia.
Government of Japan, 1997: Japan's Second National Communication to the UNFCCC, Tokyo.
Government of Japan, 2002: Japan's Third National Communication to the UNFCCC, Tokyo.
Government of Norway, 2002: Norway's Third National Communication to the UNFCCC, Oslo.
Government of the Netherlands, 2001: Third Netherlands National Communication on Climate Change Policies, The Hague.
Government of Republic of Poland, 2001: Third National Communication to the COP of the UNFCCC, Warsaw.
Griffiths, A.J. and K.P. Williams, 2005: Thermal Treatment Options, Waste Management World, July-August 2005.
Grigg, S.V.L. and A.D. Read, 2001: A discussion on the various methods of application for landfill tax credit funding for environmental and community projects, Resources, Conservation and Recycling, 32, 389-409.
Hanisch, C., 2000: Is extended producer responsibility effective? Environmental Science & Technology, 34(7), 170A-175A.
Hashimoto, S. and Y. Moriguchi, 2004: Data Book: Material and Carbon Flow of Harvested Wood in Japan, CGER REPORT D034, National Institute for Environmental Studies, Japan. Tsukuba. 40 p. www.cger.nies.go.jp/publication/D034/D034.pdf.
Haury, E.W., 1976: The Hohokam: Desert Farmers and Craftsmen, University of Arizona Press, Tucson, Arizona.
Hellebrand, H.J. 1998: Emissions of N2O and other trace gases during composting of grass and green waste. J. Agric. Engineering Research, **69**, 365-375.
Hiramatsu, A., K. Hanaki, and T. Aramaki, 2003: Baseline options and greenhouse gas emission reduction of clean development mechanism project in urban solid waste management, Mitigation and Adaptation Strategies for Global Change, **8**, 293-310.
Ho, G., 2000: Proceedings of the Workshop on Sustainable Wastewater and Stormwater Management, Regional Workshop for the Latin America and the Caribbean, 27 - 31 March 2000, International Environmental Technology Centre, Report Series - Issue 10, United Nations, Osaka, Shiga, pp. 115-156.
Hoornweg, D., 1999: What a Waste: Solid Waste Management in Asia, Report of Urban Development Sector Unit, East Asia and Pacific Region, World Bank, Washington, D.C.

Houghton, J.T., Filho. L., Griggs, D., and K. Maskell, 1997: An Introduction to Simple Climate Models used in the IPCC Second Assessment Report, IPCC Technical Paper, UNEP/WMO.

Hovde, D.C., A.C. Stanton, T.P. Meyers, and D.R. Matt, 1995: Methane emissions from a landfill measured by eddy correlation using a fast-response diode laser sensor, Journal of Atmospheric Chemistry, **20**, 141-162.

Huber-Humer M. , 2004: Abatement of Landfill Methane Emissions by Microbial Oxidation in Biocovers made of Compost, PhD Thesis, University of Natural Resources and Applied Life Sciences (BOKU), Vienna, 279 pp.

Huhtala, A. 1997: A post-consumer waste management model for determining optimal levels of recycling and landfilling. Environmental and Resource Economics, **10**, 301-314.

Idris, A., et al., 2003: Overview of municipal solid waste landfill sites in Malaysia, Proceedings of the 2nd Workshop on Material Cycles and Waste Management in Asia, Tsukuba, Japan.

IPCC, 2006: 2006 IPCC Guidelines for National Greenhouse Gas Inventories. IPCC/IGES. Hayama, Japan. http://www.ipcc-nggip.iges.or.jp/public/2006gl/ppd.htm (Prepublication Draft).

IPCC, 2001a: Climate Change 2001: Mitigation (Contribution of Working Group III to the third assessment report of the Intergovernmental Panel on Climate Change). Cambridge: Cambridge University Press.

IPCC, 2001b: Climate Change 2001: The Scientific Basis (Contribution of Working Group I to the third assessment report of the Intergovernmental Panel on Climate Change). Cambridge: Cambridge University Press.

IPCC, Intergovernmental Panel on Climate Change: 2005: Special Report on Safeguarding the Ozone Layer and the Global Climate System: issues related to Hydrofluorocarbons and Perfluorocarbons, Cambridge University Press, Cambridge, UK

Iskandar, L., 2001, The Informal Solid Waste Sector in Egypt: Prospects for Formalization, published by Community and Institutional Development, Cairo, Egypt, 65 pp.

Japanese Ministry of the Environment, 2006: State of Discharge and Treatment of Municipal Solid Waste in FY 2004.

Jenkins, R.R., S.A. Martinez, K. Palmer, and M.J. Podolsky, 2003: The determinants of household recycling: a material-specific analysis of recycling program features and unit pricing, Journal of Environmental Economics and Management, **45**(2), 294-318.

Johannessen, L.M., and Boyer, 1999: Observations of Solid Waste Landfills in Developing Countries: Africa, Asia, and Latin America, Report by Urban Development Division, Waste Management Anchor Team, World Bank, Washington, D.C.

Jouravlev, A., 2004: Los servicios de agua potable y saneamiento en el umbral del siglo XXI, Santiago de Chile, julio 2004, CEPAL – Serie Recursos Naturales e Infraestructura No 74.

Kaartinen, T. 2004: Sustainable disposal of residual fractions of MSW to future landfills. M.S.Thesis, Technical University of Helsinki, Espoo, Finland. In Finnish.

Kaseva, M.E., et al., 2002: Recycling Inorganic Domestic Solid Wastes: Results from a Pilot Study in Dar es Salaam City, Tanzania, Resources Conservation and Recycling, **35**, 243-257.

Kightley, D., D. Nedwell, and M. Cooper, 1995: Capacity for methane oxidation in landfill cover soils measured in laboratory-scale microcosms, Applied and Environ. Micro.**, 61**, 592-601.

Khan, M.Z.A., and Abu-Ghararath, A.H., 1991: New approach for estimating energy content of municipal solid waste, J. Environ. Eng., 117, 376-380.

Kjeldsen, P. and M.H. Jensen, 2001: Release of CFC-11 from disposal of polyurethane from waste.Environmental Science and Technology, **35**, 3055-3063.

Kjeldsen, P. and C. Scheutz, C., 2003: Short and long term releases of fluorocarbons from disposal of polyurethane foam waste, Environmental Science and Technology, **37**, 5071-5079.

Konte, 2005: UNFCCC Metadata, UNEP/DEWA/GRID, Geneva, Switzerland. http://ghg.unfccc.int.

Kuehle-Weidemeier and Doedens, 2003: Landfilling and properties of mechanical-biological treated municipal waste, Proc Sardinia '03 International Solid and Hazardous Waste Symposium, October, 2005, published by CISA, Univ. of Cagliari, Sardinia.

Lohiniva, E., K. Sipilä, T. Mäkinen and L. Hietanen, 2002: Waste-to-energy and greenhouse gas emissions. Espoo, VTT - Tiedotteita - Research Notes 2139, 119p. In Finnish (to be published in English in 2006)

Mertins, L., C. Vinolas, A. Bargallo, G. Sommer, and J. Renau, 1999: Development and Application of Waste Factors - An Overview, Technical Report No. 37, European Environment Agency, Copenhagen.

Micales, J.A. and K.E. Skog, 1997: The decomposition of forest products in landfills, International Biodeterioration and Biodegradation, **39**(2-3), 145-158

Miranda, M.L., J.W. Everett, D. Blume, and B.A. Roy, 1994: Market-based incentives and residential municipal solid waste, Journal of Policy Analysis and Management, **13**(4), 681-698.

Miranda, M.L., S.D. Bauer, and J.E. Aldy, 1996: Unit pricing programs for residential municipal solid waste: an assessment of the literatures, Report prepared for U.S. Environmental Protection Agency, Washington D.C.

Monni, S., R. Pipatti, A. Lehtilä, S. Syri and I. Savolainen, 2006. Global climate change mitigation scenarios for solid waste management. Espoo, Technical Research Centre of Finland. VTT Publications 603.

Morris, J., 2001: Effects of waste composition on landfill processes under semi-arid conditions, PhD Thesis, Faculty.of Engin.,Univ. of the Witwatersrand, Johannesburg, S. Africa. 1052 pp.

Moriis, J.R., P.S. Phillips, and A.D. Read, 2000: The UK landfill tax: financial implications for local authorities, Public Money and Management, **20**(3), 51-54.

Mosher, B., P. Czepiel, R. Harriss, J. Shorter, C. Kolb, J.B. McManus, E. Allwine, and B. Lamb, 1999: Methane emissions at nine landfill sites in the northeastern United States, Environmental Science and Technology, **33**(12), 2088-2094.

Myllymaa, T., H. Dahlbo, M. Ollikainen, S. Peltola and M. Melanen, 2005: A method for implementing life cycle surveys of waste management alternatives' environmental and cost effects. Helsinki, Suomen Ympäristö - Finnish Environment 750, 108 pp.

Nakicenovic, N., J. Alcamo, G. Davis, B. de Vries, J. Fenhann, S. Gaffin, K Gregory, A. Grübler, T-Y. Jung, T. Kram, E.L. La Rovere, L. Michaelis, S. Mori, T. Morita, W. Pepper, H. Pitcher, L. Price, K. Riahi, A. Roehrl, H.-H. Rogner, A. Sankovski, M. Schlesinger, P. Shukla, S. Smith, R. Swart, S. van Rooijen, N. Victor, and Z. Dadi, 2000: Special Report on Emissions Scenarios, Intergovernmental Panel on Climate Change (IPCC), http://www.grida.no/climate/ipcc/emission/ index.html.

Nozhevnikova, A.N., A.B. Lifshitz, V.S. Lebedev, and G.A. Zavarin, 1993: Emissions of methane into the atmosphere from landfills in the former USSR, Chemosphere, **26**(1-4), 401-417.

Oonk, H. and T. Boom, 1995; landfill gas formation, recovery and emissions. TNO-report 95-130, TNO, Apeldoorn, the Netherlands.

OECD, 2001: Extended Producer Responsibility: A Guidance Manual for Governments, OECD publishers, Paris.

OECD, 2002: Environmental Data. Waste. Compendium 2002. Environmental Performance and Information Division, OECD Environment Directorate. Working Group on Environmental Information and Outlooks. 27 pp.

OECD, 2003: OECD Environmental Data Compendium 2002, Paris, www.oecd.orgn

OECD, 2004: Towards Waste Prevention Performance Indicators, OECD Environment Directorate. Working Group on Waste Prevention and Recycling and Working Group on Environmental Information and Outlooks. 197 p.

Ojeda-Benitez, S., et al., 2003: Characterization and Quantification of Household solid wastes in a Mexican city, Resources, Conservation and Recycling, **39**(3), 211-222.

Onuma, E. et al., 2004: Consideration of CO_2 from Alternative Fuels in the Cement Industry, http://arch.rivm.nl/env/int/ipcc/docs/ITDT/ITDT%20Energy%20Intensive%20Industry%20Session.pdf.

Penman, J., D. Kruger. I. Galbally T. Hiraishi, B. Nyenzi, S. Enmanuel, L. Buendia, R. Hoppaus, T. Martinsen , J. Meijer, K. Miwa, and K Tanabe (eds), 2000: Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories. IPCC/OECD/IEA/IGES, Hayama, Japan.

Penman, J., M. Gytarsky, T. Krug, D. Kruger. T. Hiraishi, R. Pipatti, L. Buendia, K. Miwa, T. Ngara, K. Tanabe and F. Wagner (Eds), 2003: Good Practice Guidance for Land Use, Land-Use Change and Forestry, Institute for Global Environmental Strategies (IGES), Hayama, Japan.

Perla, M., 1997: Community composting in developing countries, Biocycle, June, 48-51.

Petersen, S.O., A.M. Lind and S. G. Sommer, 1998: Nitrogen and organic matter losses during storage of cattle and pig manure. J. Agric. Sci., **130**, 69-79.

Pingoud, K., A-L. Perälä, S. Soimakallio and A. Pussinen, 1996: Greenhouse impact of the Finnish forest sector including forest products and waste management. Ambio, **25**, 318-326.

Pipatti, R., and M. Wihersaari, 1998: Cost-effectiveness of alternative strategies in mitigating the greenhouse impact of waste management in three communities of different size. Mitigation and Adaption Strategies for Global Change **2**, 337 -358.

Pipatti, R., and I. Savolainen, 1996, Role of energy production in the control of greenhouse gas emissions from waste management, Energy Conservation Management, **37**(6-8), 1105-1110.

PNUD(Programa de las Naciones Unidas)/UNDP, 2005: Informe sobre Desarrollo Humano 2005: la cooperación internacional ante una encrucijada, Cuadro 7 – Agua, Saneamiento y Nutrición, publicado para el Programa de las Naciones Unidas para el Desarrollo, Ediciones Mundi – Prensa 2005, Barcelona, Spain. http://hdr.undp.org/statistics

Price, J.L., 2001: The landfill directive and the challenge ahead: demands and pressures on the UK householder, Resources, Conservation and Recycling, **32**, 333-348.

Qifei, H, et al., 2006: The current situation of solid waste management in China, J. Mater Cycles Waste Manag **8**. 63-69.

Rathje, W.L., W.W. Hughes, D.C. Wilson, M.K. Tani, G.H. Archer, R.G. Hunt, and T.W. Jones, 1992: The archaeology of contemporary landfills, American Antiquity, **57**(3): 437-447.

Richards, K., 1989: Landfill gas: working with Gaia, Biodeterioration Abstracts, 3(4), 317-331.

Rinne, J., M. Pihlatie, A. Lohila, T. Thum, M. Aurela, J-P Tuovinen, T. Laurila, and R.Vesala, 2005: N_2O emissions from a municipal landfill, Environmental Science and Technology, **39**, 7790-7793.

Ritzkowski, M., and Stegman, R., 2005: Reduction of GHG Emissions by Landfill In Situ Aeration, Proceedings Sardinia '05 International Solid and Hazardous Waste Symposium, October, 2005, published by CISA, Univ. of Cagliari, Sardinia.

Savage, G., L. Diaz, C. Golueke, C. Martone, and R.Ham, 1998: Guidance for Landfilling Waste in Economically Developing Countries, ISWA Working Group on Sanitary Landfilling, published under U.S. EPA Contract 68-C4-0022. ISBN No. 87-90402-07-3, 300 pp.

Scharf, H., Oonk, H., Hensen, A., and van Rijn, D.M.M., 2002: Emission Measurements as a Tool to improve methane emission estimates, Proceedings Intercontinental Landfill Research Symposium, Asheville, NC.

Scheehle, E. and M. Doorn, 2002, Improvements to the U.S. Wastewater CH_4 and N_2O emissions estimates, U.S. EPA report June 2002.

Scheehle, E. and D. Kruger, D, 2006: Global anthropogenic methane and nitrous oxide emissions, Energy Journal, (in press).

Scheutz., C., J. Bogner, J. Chanton, D. Blake, M. Morcet, and P. Kjeldsen, 2003: Comparative oxidation and net emissions of CH_4 and selected non-methane organic compounds in landfill cover soils, Environmental Science and Technology **37**, 5143-5149.

Scheutz, C., Y., Dote, A.M. Fredenslund, H. Mosbæk, and P. Kjeldsen, 2005a: Attenuation of insulation foam-released fluorocarbons in landfills. Environmental Science and Technology, accepted.

Scheutz, C., A.M. Fredenslund, M. Tant, P. and Kjeldsen, 2005b: Release of fluorocarbons from insulation foam in home appliances during shredding. Environmental Science and Technology, accepted.

Silva, G., 1998: Private Participation in the Water and Sewerage Sector – Recent Trends, in Public Policy for the Private Sector(Viewpoint): Water, World Bank, Washington D.C. pp.12-20.

Spokas, K., J. Bogner, J. Chanton, M. Morcet, C. Aran, C. Graff, Y. Moreau-le-Golvan, N. Bureau, and I. Hebe, 2006: Methane mass balance at three landfill sites: what is the efficiency of capture by gas collection systems? Waste Management, **26**, 516-525.

Statistics Finland, 2005: Environment Statistics. Environment and Natural Resources 2005:2, Helsinki, 208 pp.

Streese, J., and Stegman, R., 2005: Potentials and Limitations of Biofilters for Methane Oxidation, Proceedings Sardinia '05 International Solid and Hazardous Waste Symposium, October, 2005, CISA, Univ. of Cagliari, Sardinia.

TFFEoL (Task force on Foam End-of-Life Issues), 2005: Report of the UNEP task force on foam end-of-life issues. Task force on Foam End-of-Life Issues, May 2005, Montreal Protocol on Substances that Deplete the Ozone Layer. UNEP Technology and Economic Assessment Panel, 113 pp.

Tregoures, A., A. Beneito, P. Berne, M.A. Gonze, J.C. Sabroux, D. Savanne, Z. Pokryszka, C. Tauziede, P. Cellier, P.Laville, R. Milward, A. Arnaud, and R. Burkhalter, 1999: Comparison of seven methods for measuring methane flux at a municipal solid waste landfill site, Waste Management and Research, **17**, 453-458.

Tsujimoto Y., J. Masuda, J. Fukuyama, and H. Ito, 1994: N_2O emissions at solid waste disposal sites in Osaka City, Air Waste, 44, 1313-14.

Tuhkanen, S., A. Lehtilae, and I. Savolainen, 1999: The role of CH_4 and N_2O emission reductions in the cost-effective control of the greenhouse gas emissions from Finland, Mitigation and Adaptation Strategies for Global Change, **4** (2), 91-111

Tuhkanen, S., R. Pipatti, K. Sipilä, and T. Mäkinen, 2001: The effect of new solid waste treatment systems on greenhouse gas emissions. In: Williams, D.J., Durie, R.A., Mcmullan, P., Paulson, C.A.J. and Smith, A.Y. (Eds). Greenhouse Gas Control Technologies. Proceeding of the Fifth International Conference on Greenhouse Gas Control Technologies (GHGT-5). Collingwood: CSIRO Publishing, pp. 1236-1241.

UNEP/GPA-UNESCO/IHE, 2004: Improving Municipal Wastewater Management in Coastal Cities, Training Manual, version 1, February 2004, UNEP/GPA Coordination Office, The Hague, Netherlands, pp 49-81 and 103-117.

UNFCCC, 2005a: National Greenhouse Gas Inventory Data for the Period 1990-2003 and Status of Reporting, Report FCCC/SBI/2005/17.

UNFCCC, 2005b: Inventories of Anthropogenic emissions by Sources and Removals by Sinks of Greenhouse Gases, Report Fccc/SBI/2005/18/Add.2

UNFCCC, 2005c: Key GHG Data. //unfccc.int/resource/docs/publications/key_ghg.pdf.

UNFCCC/IPCC, 2004: Historical Data and Projections of Greenhouse Gas Emissions – CH_4 and N_2O.

US EPA, 2001: Non-CO_2 Greenhouse Gas Emissions from Developed Countries: 1990-2010, EPA-430-R-01-007, Office of Air and Radiation, Washington, DC.

US EPA, 2003: International Analysis of Methane and Nitrous Oxide Abatement Opportunities: Report to Energy Modeling Forum, Working Group 21. U.S. Environmental Protection Agency June, 2003. http://www.epa.gov/methane/intlanalyses.html

US EPA, 2005: Municipal Solid Waste Generation, Recycling and Disposal in the United States: Facts and Figures for 2003, Washington, D.C., USA.www.epa.gov./epaoswer/non-hw/muncpl/pubs/msw05rpt.pdf

US EPA, 2006: Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020, Office of Atmospheric Programs, Climate Change Division. http://www.epa.gov/ nonco2/econ- inv/pdfs/global_emissions.pdf

U.S. Department of State, 2002: U.S. Climate Action Report 2002, Washington, D.C.

Veolia Environmental Services, 2005: Monitoring Report, Onyx SASA Landfill Gas Recovery Project, Tremembe, Brazil. Period 1st January 2003 to 31st December 2005.

Vesterinen, R. 1996: Greenhouse gas emissions from composting. SIHTI-Research Programme, Seminar 13-14-3-1996. Hanasaari, Espoo, Finland. 3 pp. In Finnish.

WHO/UNICEF, 2005: Joint Monitoring Programme: Worldwide Sanitation, http://www.who.int/mdg/publications/MDG_Report_08_2005.pdf/mdg_report/en/index

WHO/UNICEF/WSSCC, 2000: Global Water Supply and Sanitation Assessment: 2000 Report, WHO/UNICEF Join Monitoring Programme for Water Supply and Sanitation, ISBN924156202 1, 2000. http://www.who.int

Willumsen, H.C., 2003, Landfill gas plants: number and type worldwide, Proc. Sardinia '05 International Solid and Hazardous Waste Symposium, October, 2005, published by CISA, Univ. of Cagliari, Sardinia.

World Bank, 1997: Toolkits for private sector participation in water and sanitation, World Bank, Washington D.C.

World Bank, 1999: What a Waste: Solid Waste Mangement in Asia. World Bank, Washington, DC. 43 pp.

World Bank, 2005: World Development Indicators 2005:Environment, Table 2.15 Disease Prevention: Coverage and Quality, Table 3.11: Urban Environment; Table 3.6 Water pollution, http://www.worldbank.org/data/wdi2005/wditext

Yamakawa, H. and K. Ueta, 2002: Waste reduction through variable charging programs: its sustainability and contributing factors, Journal of Material Cycles and Waste Management, 4, 77-86.

Yuan, Z., J. Bi, and Y. Moriguchi, 2006: The circular economy-a new development strategy in China, Journal of Industrial Ecology **10**, 4-8