

Environmental Management & Pollution

Waste Management

10.1 Waste Generation

Waste generation is closely linked to population, urbanization and affluence. The archaeologist E.W. Haury wrote: ‘Whichever way one views the mounds [of waste], as garbage piles to avoid, or as symbols of a way of life, they...are the features more productive of information than any others.’(1976).

Archaeological excavations have yielded thicker cultural layers from periods of prosperity; correspondingly, modern waste-generation rates can be correlated to various indicators of affluence, including gross domestic product (GDP)/cap, energy consumption/cap, , and private final consumption/cap (Bingemer and Crutzen, 1987; Richards, 1989; Rathje *et al.*, 1992; Mertins *et al.*, 1999; US EPA, 1999; Nakicenovic *et al.*, 2000; Bogner and Matthews, 2003; OECD, 2004).

In developed countries seeking to reduce waste generation, a current goal is to decouple waste generation from economic driving forces such as GDP (OECD, 2003; Giegrich and Vogt, 2005; EEA, 2005). In most developed and developing countries with increasing population, prosperity and urbanization, it remains a major challenge for municipalities to collect, recycle, treat and dispose of increasing quantities of solid waste and wastewater. A cornerstone of sustainable development is the establishment of affordable, effective and truly sustainable waste management practices in developing countries. It must be further emphasized that multiple public health, safety and environmental cobenefits accrue from effective waste management practices which concurrently reduce GHG emissions and improve the quality of life, promote public health, prevent water and soil contamination, conserve natural resources and provide renewable energy benefits.

The major GHG emissions from the waste sector are landfill and, secondarily, wastewater and N₂O. In addition, the incineration of fossil carbon results in minor emissions of CO₂. This lesson focuses on mitigation of GHG emissions from *post-consumer* waste, as well as emissions from municipal wastewater and high biochemical oxygen demand (BOD) industrial wastewaters conveyed to public treatment facilities.

The mitigation of GHG emissions from waste must be addressed in the context of integrated waste management. Most technologies for waste management are mature and have been successfully implemented for decades in many countries. Nevertheless, there is significant potential for accelerating both the direct reduction of GHG emissions from waste as well as extended implications for indirect reductions within other sectors. LCA is an essential tool for consideration of both the direct and indirect impacts of waste management technologies and policies (Thorneloe *et al.*, 2002; 2005; WRAP, 2006).

Because direct emissions represent only a portion of the life cycle impacts of various waste management strategies (Ackerman, 2000), this lesson includes complementary strategies for GHG avoidance, indirect GHG mitigation and use of waste as a source of renewable energy to provide fossil fuel offsets. Using LCA and other decision-support tools, there are many combined mitigation strategies that can be cost-effectively implemented by the public or private sector.

Landfill recovery and optimized wastewater treatment can directly reduce GHG emissions. GHG generation can be largely avoided through controlled aerobic composting and thermal processes such as incineration for waste-to-energy. Moreover, waste prevention, minimization, material recovery, recycling and re-use represent a growing potential for indirect reduction of GHG emissions through decreased waste generation, lower raw material consumption, reduced energy demand and fossil fuel avoidance. Recent studies (e.g., Smith *et al.*, 2001; WRAP, 2006) have begun to comprehensively quantify the significant benefits of recycling for indirect reductions of GHG emissions from the waste sector.

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

10.2 Waste Management

The energy content of waste can be more efficiently exploited using thermal processes than with the production of biogas: during combustion, energy is directly derived both from biomass (paper products, wood, natural textiles, food) and fossil carbon sources (plastics, synthetic textiles). The heating value of mixed municipal waste ranges from <6 to >14 MJ/kg (Khan and Abu-Ghararath, 1991; EIPPC Bureau, 2006). Thermal processes are most effective at the upper end of this range where high values approach low-grade coals (lignite). Using a conservative value

of 900 Mt/yr for total waste generation in 2002, the energy potential of waste is approximately 5–13 EJ/yr. Assuming an average heating value of 9 GJ/t for mixed waste (Dornburg and Faaij, 2006) and converting to energy equivalents, global waste in 2002 contained about 8 EJ of available energy, which could increase to 13 EJ in 2030 using waste projections in Monni *et al.* (2006). Currently, more than 130 million tonnes per year of waste are combusted worldwide (Themelis, 2003), which is equivalent to >1 EJ/yr (assuming 9 GJ/t). The biogas fuels from waste – landfill gas and digester gas – typically have a heating value of 16–22 MJ/Nm³, depending directly on the content.

Both are used extensively worldwide for process heating and on-site electrical generation; more rarely, landfill gas may be upgraded to a substitute natural gas product. Conservatively, the energy value of landfill gas currently being utilized is >0.2 EJ/ yr (using data from Willumsen, 2003).

An overview of carbon flows through waste management systems addresses the issue of carbon storage versus carbon turnover for major waste-management strategies including landfilling, incineration and composting. Because landfills function as relatively inefficient anaerobic digesters, significant long-term carbon storage occurs in landfills, which is addressed in the 2006 IPCC Guidelines for National Greenhouse Gas Inventories (IPCC, 2006). Landfill is the major gaseous C emission from waste; there are also minor emissions of CO₂ from incinerated fossil carbon (plastics). The CO₂ emissions from biomass sources – including the CO₂ in landfill gas, the CO₂ from composting, and CO₂ from incineration of waste biomass – are not taken into account in GHG inventories as these are covered by changes in biomass stocks in the land-use, land-use change and forestry sectors.

A process-oriented perspective on the major GHG emissions from the waste sector is provided in this lesson. In the context of a landfill mass balance emissions are one of several possible pathways for the produced by anaerobic methanogenic microorganisms in landfills; other pathways include recovery, oxidation by aerobic methanotrophic microorganisms in cover soils, and two longer-term pathways: lateral migration and internal storage (Bogner and Spokas, 1993; Spokas *et al.*, 2006). With regard to emissions from wastewater transport and treatment, the microbially produced under strict anaerobic conditions as in landfills, while the N₂O is an intermediate product of microbial nitrogen cycling promoted by conditions of reduced aeration, high moisture and abundant nitrogen. Both GHGs can be produced and emitted at many stages between wastewater sources and final disposal.

It is important to stress that both the CH₄ and N₂O from the waste sector are microbially produced and consumed with rates controlled by temperature, moisture, pH, available substrates, microbial competition and many other factors. As a result, CH₄ and N₂O generation, microbial consumption, and net emission rates routinely exhibit temporal and spatial variability over many orders of magnitude, exacerbating the problem of developing credible national estimates.

The N₂O 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 (Tsujiimoto *et al.*, 1994). Substantial emissions of CH₄ and N₂O can occur during wastewater transport in closed sewers and in conjunction with anaerobic or aerobic treatment.

In many developing countries, in addition to GHG emissions, open sewers and uncontrolled solid waste disposal sites result in serious public health problems resulting from pathogenic microorganisms, toxic odours and disease vectors. Major issues surrounding the costs and potentials for mitigating GHG emissions from waste include definition of system boundaries and selection of models with correct baseline assumptions and regionalized costs, as discussed in the TAR (IPCC, 2001a).

Quantifying mitigation costs and potentials for the waste sector remains a challenge due to national and regional data uncertainties as well as the variety of mature technologies whose diffusion is limited by local costs, policies, regulations, available land area, public perceptions and other social development factors. Discussion of technologies and mitigation strategies in this chapter (Section 10.4) includes a range of approaches from low-technology/low-cost to high technology/high-cost measures. Often there is no single best option; rather, there are multiple measures available to decision makers at the municipal level where several technologies may be collectively implemented to reduce GHG emissions and achieve public health, environmental protection and sustainable development objectives.

10.3 Waste Generation

Regional trends for solid waste generation and landfill carbon storage using a proxy variable. Solid-waste generation rates are a function of both population and prosperity, but data are lacking or questionable for many countries. This results in high uncertainties for GHG emissions estimates, especially from developing countries. One strategy is to use a proxy variable for which national statistics are

available on an annual basis for all countries. For example, using national solid-waste data from 1975–1995 that were reliably referenced to a given base year, Bogner and Matthews (2003) developed simple linear regression models for waste generation per capita for developed and developing countries.

These empirical models were based on energy consumption per capita as an indicator of affluence and a proxy for waste generation per capita; the surrogate relationship was applied to annual national data using either total population (developed countries) or urban population (developing countries). The methodology was validated using post-1995 data which had not been used to develop the original model relationships. The results by region for 1971–2002 (Figure 10.3a) indicate that approximately 900 Mt of waste were generated in 2002. Unlike projections based on population alone, this figure also shows regional waste-generation trends that decrease and increase in tandem with major economic trends. For comparison, recent waste-generation estimates by Monni et al. (2006) using 2006 inventory guidelines, indicated about 1250 Mt of waste generated in 2000.

The annual totals for the mid-1980s and later (>30 MtC/yr) exceed estimates in the literature for the annual quantity of organic carbon partitioned to long-term geologic storage in marine environments as a precursor to future fossil fuels (Bogner, 1992). It should be noted that the anaerobic burial of waste in landfills (with resulting carbon storage) has been widely implemented in developed countries only since the 1960s and 1970s.

10.4 Status of Waste Management

The availability and quality of annual data are major problems for the waste sector. Solid waste and wastewater data are lacking for many countries, data quality is variable, definitions are not uniform, and inter annual variability is often not well quantified. There are three major approaches that have been used to estimate global waste generation:

- 1) data from national waste statistics or surveys, including IPCC methodologies (IPCC, 2006);
- 2) estimates based on population (e.g., SRES waste scenarios), and
- 3) the use of a proxy variable linked to demographic or economic indicators for which national data are annually collected. The SRES waste scenarios, using population as the major driver, projected continuous increases in waste and wastewater CH₄ emissions to 2030 (A1B-AIM), 2050 (B1- AIM), or 2100 (A2-ASF; B2-MESSAGE), resulting in current and future emissions

significantly higher than those derived from IPCC inventory procedures (Nakicenovic *et al.*, 2000).

A major reason is that waste generation rates are related to affluence as well as population – richer societies are characterized by higher rates of waste generation per capita, while less affluent societies generate less waste and practise informal recycling/re-use initiatives that reduce the waste per capita to be collected at the municipal level. The third strategy is to use proxy or surrogate variables based on statistically significant relationships between waste generation per capita and demographic variables, which encompass both population and affluence, including GDP per capita (Richards, 1989; Mertins *et al.*, 1999) and energy consumption per capita (Bogner and Matthews, 2003). The use of proxy variables, validated using reliable datasets, can provide a cross-check on uncertain national data.

Moreover, the use of a surrogate provides a reasonable methodology for a large number of countries where data do not exist, a consistent methodology for both developed and developing countries and a procedure that facilitates annual updates and trend analysis using readily available data (Bogner and Matthews, 2003).

In 1971–2002 trends for regional solid-waste generation using the surrogate of energy consumption per capita. Using UNFCCC-reported values for percentage biodegradable organic carbon in waste for each country, this box also shows trends for landfill carbon storage based upon the reported data.

Solid waste generation rates range from <0.1 t/cap/yr in low income countries to >0.8 t/cap/yr in high-income industrialized countries. Even though labour costs are lower in developing countries, waste management can constitute a larger percentage of municipal income because of higher equipment and fuel costs (Cointreau-Levine, 1994).

By 1990, many developed countries had initiated comprehensive recycling programmes. It is important to recognize that the percentages of waste recycled, composted, incinerated or landfilled differ greatly amongst municipalities due to multiple factors, including local economics, national policies, regulatory restrictions, public perceptions and infrastructure requirements.

10.5 Wastewater Generation

Most countries do not compile annual statistics on the total volume of municipal wastewater generated, transported and treated. In general, about 60% of the global population has sanitation coverage (sewerage) with very high levels (>90%)

characteristic for the population of North America (including Mexico), Europe and Oceania, although in the last two regions rural areas decrease to approximately 75% and 80%, respectively.

In developing countries, rates of sewerage are very low for rural areas of Africa, Latin America and Asia, where septic tanks and latrines predominate. For 'improved sanitation' (including sewerage + wastewater treatment, septic tanks and latrines), almost 90% of the population in developed countries, but only about 30% of the population in developing countries, has access to improved sanitation (Jouravlev, 2004; World Bank, 2005a, b). Many countries in Eastern Europe and Central Asia lack reliable benchmarks for the early 1990s. Regional trends indicate improved sanitation levels of <50% for Eastern and Southern Asia and Sub-Saharan Africa (World Bank and IMF, 2006). In Sub-Saharan Africa, at least 450 million people lack adequate sanitation. In both Southern and Eastern Asia, rapid urbanization is posing a challenge for the development of wastewater infrastructure. The highly urbanized region of Latin America and the Caribbean has also made slow progress in providing wastewater treatment.

In the Middle East and North Africa, the countries of Egypt, Tunisia and Morocco have made significant progress in expanding wastewater-treatment infrastructure (World Bank and IMF, 2006). Nevertheless, globally, it has been estimated that 2.6 billion people lack improved sanitation (WHO-UNICEF, 2005). Estimates for CH₄ and N₂O emissions from wastewater treatment require data on degradable organic matter (BOD; COD) and nitrogen. Nitrogen content can be estimated using Food and Agriculture Organization (FAO) data on protein consumption, and either the application of wastewater treatment, or its absence, determines the emissions.

Aerobic treatment plants produce negligible or very small emissions, whereas in anaerobic lagoons or latrines 50–80% of the CH₄ potential can be produced and emitted. In addition, one must take into account the established infrastructure for wastewater treatment in developed countries and the lack of both infrastructure and financial resources in developing countries where open sewers or informally ponded wastewaters often result in uncontrolled discharges to surface water, soils, and coastal zones, as well as the generation of N₂O and CH₄. The majority of urban wastewater treatment facilities are publicly operated and only about 14% of the total private investment in water and sewerage in the late 1990s was applied to the financing of wastewater collection and treatment, mainly to protect drinking water supplies (Silva, 1998; World Bank 1997).

However, highly organic industrial wastewaters are addressed in this chapter, because they are frequently conveyed to municipal treatment facilities.

10.6 Development Trends for Waste and Wastewater

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

Depending on regulations, policies, economic priorities and practical local limits, developed countries will be characterized by increasingly higher rates of waste recycling and pretreatment to conserve resources and avoid GHG generation. Recent studies have documented recycling levels of >50% for specific waste fractions in some developed countries (i.e., Swedish Environmental Protection Agency, 2005).

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

Trends for sanitary landfilling and alternative waste management technologies differ amongst countries. In the EU, the future landfilling of organic waste is being phased out via the landfill directive (Council Directive 1999/31/EC), while engineered gas recovery is required at existing sites (EU, 1999). This directive requires that, by 2016, the mass of biodegradable organic waste annually landfilled must be reduced 65% relative to landfilled waste in 1995.

Several countries (Germany, Austria, Denmark, Netherlands, Sweden) have accelerated the EU schedule through more stringent bans on landfilling of organic waste. As a result, increasing quantities of post-consumer waste are now being diverted to incineration, as well as to MBT before landfilling to 1) recover recyclables and 2) reduce the organic carbon content by a partial aerobic composting or anaerobic digestion (Stegmann, 2005).

The MBT residuals are often, but not always, landfilled after achieving organic carbon reductions to comply with the EU landfill directive. Depending on the types and quality control of various separation and treatment processes, a variety of useful recycled streams are also produced. Incineration for waste to-energy has been widely implemented in many European countries for decades. In 2002, EU WTE plants generated 41million GJ of electrical energy and 110 million GJ of thermal energy (Themelis, 2003). Rates of incineration are expected to increase in parallel with implementation of the landfill directive, especially in countries such as the UK with historically lower rates of incineration compared to other European countries.

In North America, Australia and New Zealand, controlled landfilling is continuing as a dominant method for large-scale waste disposal with mandated compliance to both landfilling and air-quality regulations. In parallel, larger quantities of landfill CH₄ are annually being recovered, both to comply with air-quality regulations and to provide energy, assisted by national tax credits and local renewable-energy/green power initiatives. The US, Canada, Australia and other countries are currently studying and considering the widespread implementation of ‘bioreactor’ landfills to compress the time period during which high rates of CH₄ generation occur (Reinhart and Townsend, 1998; Reinhart *et al.*, 2002; Berge *et al.*, 2005); bioreactors will also require the early implementation of engineered gas extraction.

10.7 Global Overview

Quantifying global trends requires annual national data on waste production and management practices. Estimates for many countries are uncertain because data are lacking, inconsistent or incomplete; therefore, the standardization of terminology

for national waste statistics would greatly improve data quality for this sector. Most developing countries use default data on waste generation per capita with inter-annual changes assumed to be proportional to total or urban population.

Developed countries use more detailed methodologies, activity data and emission factors, as well as national statistics and surveys, and are sharing their methods through bilateral and multilateral initiatives. For landfill CH₄, the largest GHG emission from the waste sector, emissions continue several decades after waste disposal; thus, the estimation of emission trends requires models that include temporal trends. Methane is also emitted during wastewater transport, sewage treatment processes and leakages from anaerobic digestion of waste or wastewater sludges.

The major sources of N₂O are human sewage and wastewater treatment. The CO₂ from the non-biomass portion of incinerated waste is a small source of GHG emissions. The IPCC 2006 Guidelines also provide methodologies for CO₂, CH₄ and N₂O emissions from open burning of waste and for CH₄ and N₂O emissions from composting and anaerobic digestion of biowaste.

Open burning of waste in developing countries is a significant local source of air pollution, constituting a health risk for nearby communities. Composting and other biological treatments emit very small quantities of GHGs but were included in 2006 IPCC Guidelines for completeness. Overall, the waste sector contributes <5% of global GHG emissions. Table 10.3 compares estimated emissions and trends from two studies: US EPA (2006) and Monni *et al.* (2006). The US EPA (2006) study collected data from national inventories and projections reported to the United Nations Framework Convention on Climate Change (UNFCCC) and supplemented data gaps with estimates and extrapolations based on IPCC default data and simple mass balance calculations using the 1996 IPCC Tier 1 methodology for landfill CH₄. Monni *et al.* (2006) calculated a time series for landfill CH₄ using the first-order decay (FOD) methodology and default data in the 2006 IPCC Guidelines, taking into account the time lag in landfill emissions compared to year of disposal.

The estimates by Monni *et al.* (2006) are lower than US EPA (2006) for the period 1990–2005 because the former reflect slower growth in emissions relative to the growth in waste. However, the future projected growth in emissions by Monni *et al.* (2006) is higher, because recent European decreases in landfilling are reflected more slowly in the future projections. For comparison, the reported 1995 CH₄ emissions from landfills and wastewater from national inventories were

approximately 1000 MtCO₂eq (UNFCCC, 2005). In general, data from Non-Annex I countries are limited and usually available only for 1994 (or 1990). In the TAR, annual global CH₄ and N₂O emissions from all sources were approximately 600 Tg CH₄/yr and 17.7 Tg N/yr as N₂O (IPCC, 2001b). The direct comparison of reported emissions in Table 10.3 with the SRES A1 and B2 scenarios (Nakicenovic *et al.*, 2000) for GHG emissions from waste is problematical: the SRES do not include landfill-gas recovery (commercial since 1975) and project continuous increases in CH₄ emissions based only on population increases to 2030 (AIB-AIM) or 2100 (B2-MESSAGE), resulting in very high emission estimates of >4000 MtCO₂-eq/yr for 2050.

10.8 Adaptation, Mitigation & Sustainable Development

In addition to providing mitigation of GHG emissions, improved public health, and environmental benefits, solid waste and wastewater technologies confer significant co-benefits for adaptation, mitigation and sustainable development. In developing countries, improved waste and wastewater management using low- or medium technology strategies are recommended to provide significant GHG mitigation and public health benefits at lower cost. Some of these strategies include small-scale wastewater management such as septic tanks and recycling of grey water, construction of medium-technology landfills with controlled waste placement and use of daily cover (perhaps including a final biocover to optimize CH₄ oxidation), and controlled composting of organic waste.

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