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Global climate change mitigation scenarios for solid waste management

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Abstract

The waste sector is an important contributor to climate change. CH₄ produced at solid waste disposal sites contributes approximately 3–4 percent to the annual global anthropogenic greenhouse gas emissions. Emissions from solid waste disposal are expected to increase with increasing global population and GDP. On the other hand, many cost-efficient emission reduction options are available.

The rate of waste degradation in landfills depends on waste composition, climate and conditions in the landfill. Because the duration of CH₄ generation is several decades, estimation of emissions from landfills requires modelling of waste disposal prior to the year whose emissions are of interest. In this study, country- or region-specific first-order decay (FOD) models based on the 2006 IPCC Guidelines are used to estimate emissions from municipal solid waste disposal in landfills. In addition, IPCC methodology is used to estimate emissions from waste incineration. Five global scenarios are compiled from 1990 to 2050. These scenarios take into account political decision making and changes in the waste management system. In the *Baseline* scenario, waste generation is assumed to follow past and current trends using population and GDP as drivers. In the other scenarios, effects of increased incineration, increased recycling and increased landfill gas recovery on greenhouse gas (GHG) emissions are assessed. Economic maximum emission reduction potentials for these waste management options are estimated at different marginal cost levels for the year 2030 by using the Global TIMES model.

Global emissions from landfills are projected to increase from 340 Tg CO₂ eq in 1990 to 1500 Tg CO₂ eq by 2030 and 2900 Tg CO₂ eq by 2050 in the *Baseline* scenario. The emission reduction scenarios give emissions reductions from 5% (9%) to 21% (27%) compared to the *Baseline* in 2030 (2050). As each scenario

considered one mitigation option, the results are largely additive, and the total mitigation potential can be assumed to be up to 30% in 2030 and 50% in 2050. The most favourable mitigation scenario was *High landfill gas recovery* scenario where increased rates of landfill gas recovery were assumed in developed and developing countries. In developing countries CDM type activities have appeared to be favourable mechanisms to stimulate this development. Due to the time lag in the emissions from landfills, the impact of increased recycling and incineration in mitigating the emissions from the waste sector is seen more slowly than that of landfill gas recovery.

According to the calculations of economic potentials, one third of global CH₄ emissions from landfills could be reduced at zero to negative costs in 2030. Below 10–20 USD/t CO₂ eq, more than half of the emissions could be reduced. The economic maximum potential would be approximately 75% in 2030 when compared with the *Baseline*, but due to the time lag between waste disposal and emissions, this would be reached only if measures with very high marginal cost levels could be implemented in 2010. These assessments of potentials based on specific assumptions are appropriate for generalized global comparisons; however, more accurate assessment of the potentials would need more detailed consideration of regional and local conditions.

Preface

The waste sector is an important contributor to climate change, and emissions are expected to increase with increasing population and GDP. On the other hand, many cost-efficient emissions reduction options are available for this sector.

This report presents global climate change mitigation scenarios for the solid waste management sector. The primary aim of this study was to give input for the IPCC 4th Assessment report to supplement and expand upon previous studies, e.g. IPCC SRES Scenarios in the IPCC Special Report on Emission Scenarios and the IPCC 3rd assessment report.

This study was carried out by Suvi Monni from Benviroc Ltd, Riitta Pipatti from Statistics Finland, and Antti Lehtilä, Ilkka Savolainen and Sanna Syri from VTT Technical Research Centre of Finland. One part of VTT's project "New waste management concepts" of ClimBus programme of Tekes (Finnish Funding Agency for Technology and Innovations) includes participation in the development of IPCC 4th Assessment Report. In the framework of this project, Riitta Pipatti provided input data and assumptions for the scenarios and guided the scenario calculations. Suvi Monni developed the dynamic scenarios. Her work was funded by the IPCC WG3 TSU, which is gratefully acknowledged. VTT provided costs and potentials calculations by its own funding.

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List of abbreviations

A1b	scenario in the IPCC Special Report on Emission Scenarios
BL	Baseline scenario
C	carbon
cap	capita
CDM	clean development mechanism
CER	certified emission reduction
CH ₄	methane
CO ₂	carbon dioxide
CO ₂ eq	CO ₂ equivalent calculated using global warming potentials from the IPCC Second Assessment Report
DOC	fraction of degradable organic carbon in waste
EF	emission factor
EIT	economies in transition
ET	emissions trading
FOD	first order decay
GDP	gross domestic product
GHG	greenhouse gas
HR	High landfill gas recovery scenario
II	Increased incineration scenario
IPCC	Intergovernmental Panel on Climate Change
IR	Increased paper recycling scenario
JI	joint implementation
k-value	value representing rate of degradation of waste in landfills
LFG	landfill gas
MCF	methane correction factor
MSW	municipal solid waste
N ₂ O	nitrous oxide
NCV	net calorific value

Non-OECD	countries included neither in economies in transition nor in OECD countries, i.e. developing countries
OECD	OECD countries not included in economies in transition
SRES	IPCC Special Report on Emission Scenarios
SWDS	solid waste disposal site
yr	year

1. Introduction

1.1 The role of the waste sector in global greenhouse gas emissions and related uncertainties

The waste sector is an important source of greenhouse gas emissions. According to recent national estimates this sector produces on average 2–4 per cent of national greenhouse gas emissions (UNFCCC, 2005). Solid waste disposal and wastewater are significant sources of methane (CH₄). They are estimated to contribute about one fifth of global anthropogenic methane emissions (IEA, 2005).

Increased methane (CH₄) concentration in the atmosphere contributes to climate change. CH₄ concentration has more than doubled since pre-industrial times from around 700 ppb to over 1700 ppb (NOAA, 2005). Its contribution to climate change is about one third to a half of that of carbon dioxide (Hansen & Sato, 2001). CH₄ is emitted by anthropogenic and natural sources. Estimates of global methane emissions (Mikaloff Fletcher et al., 2004a, b; IPCC, 2001a; Wuebbles & Hayhoe, 2002; Wang et al., 2004) vary from 500 Tg CH₄ yr⁻¹ to more than 600 Tg CH₄ yr⁻¹, of which 30–40% comes from natural sources, e.g. wetlands.

Figure 1 illustrates ranges for natural and anthropogenic methane emissions from different regions.

The total atmospheric concentration of methane can be measured rather accurately; however, uncertainties in emissions from different sources are large (IPCC, 2001a). Uncertainties for anthropogenic methane sources in industrial countries are estimated to vary between 20 and 50% (Rypdal & Winiwarer, 2001; Monni et al., 2004a, b). Biogenic generation in the digestion systems of ruminants or in anaerobic degradation of organic waste in landfills is complex, and the estimation of emissions by models contains uncertainties. Additional uncertainty is associated with activity data and calculation parameters. However, in the case of CH₄ recovery from landfills or coal mines, emissions reduction can be accurately metered when methane is collected (Rypdal & Winiwarer, 2001).

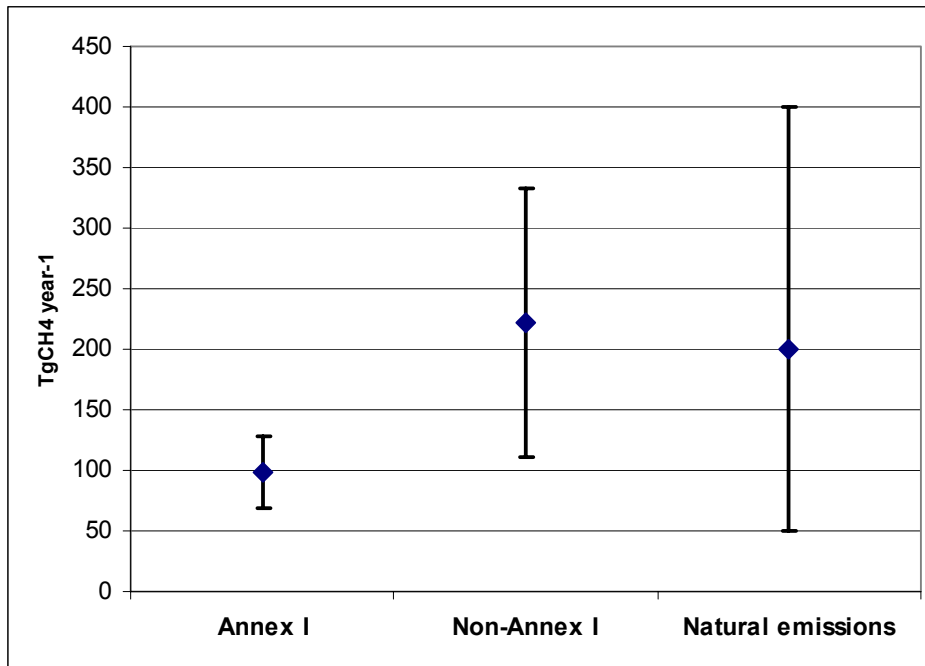


Figure 1. Estimates of total anthropogenic methane emissions from Annex I countries (developed countries) and Non-Annex I countries (developing countries) in 2000 and natural emissions with related indicative approximate levels of uncertainties (UNFCCC, 2005; IEA, 2005)¹.

1.2 Solid waste management options

Waste management encompasses treatment and final disposal or discharge of waste. The major technologies are sanitary landfilling, composting and incineration and other thermal processes. In addition, biological treatment can be used.

Landfills and open dumps are the dominant waste disposal options worldwide. In managed and unmanaged landfills, anaerobic degradation of organic material occurs, causing CH₄ emissions. Management of landfills typically increases

¹ The illustrative uncertainties are drawn as $\pm 30\%$ for Annex I countries, $\pm 50\%$ for non-Annex I countries, and for natural emissions $-75\% \dots +100\%$.

anaerobic conditions. Methane emissions from landfills depend on waste characteristics (composition, density, particle size), conditions in landfills (moisture, nutrients, microbes, temperature, and pH), design and maintenance of cover material, landfill operation and maintenance and special landfill gas controls. Landfill gas (LFG) is about 50–60% methane with the remainder CO₂ and traces of non-methane volatile organics, halogenated organics and other compounds (IPCC, 2006; IPCC, 2001b).

Wood and paper are recalcitrant to anaerobic microbial decomposition in landfills. Therefore, part of the carbon in waste disposed will be stored. Biogenic carbon stored in the landfill will be removed from the carbon cycle, and can therefore be considered as a sink in national GHG inventories. Although this sink can be significant, the default value given for long-term storage by the IPCC (2006) is 50%, it is not considered in the estimates in this publication as it is not part of the current reporting framework under the UNFCCC.

Incineration and open burning of waste containing fossil carbon are the most important sources of CO₂ emissions in the waste sector. These emissions are however a very small fraction of the total global CO₂ emissions. CO₂ is produced also in solid waste disposal sites and burning of non-fossil waste, but this CO₂ is not to be included in the national total emissions as it is of biogenic origin.²

In addition, N₂O is produced as an intermediate gaseous product of microbial nitrogen cycling. N₂O emissions depend on the type of waste treatment as well as conditions during the transport, storage and treatment. These emissions are small compared to total global emissions (IPCC, 2006; UNFCCC, 2005).

The effects of solid waste management options on GHG emissions vary. For example, plastics do not degrade in landfills, but are stored yielding no GHG emissions. In combustion, fossil C in plastics is oxidized and yields fossil CO₂ emissions. On the other hand, food and paper contain no fossil C and generate

² All Parties to United Nations Framework Convention on Climate Change (UNFCCC) report their national greenhouse gas emissions and removals on an annual or period basis using methodologies developed by the IPCC (IPCC 1996; IPCC 2000; IPCC 2003). The reporting conventions (concepts, categories, methodologies, etc.) of the IPCC are used in this report.

no fossil emissions in combustion, but degrade anaerobically in landfills causing CH₄ emissions. According to IPCC (2001b), GHG emissions are roughly comparable from landfilling and composting for yard waste, but for food waste, composting yields significantly lower emissions than landfilling. In case of paper, landfilling causes higher GHG emissions than either recycling or incineration with energy recovery. In addition, when other aspects than only GHGs, e.g. economic and other environmental factors (e.g., emissions of heavy metals), or the whole life cycle emissions are taken into account, priorities of waste management options may change (IPCC, 2001b).

The amounts, composition and management of waste generated vary much depending on regional, national and also local circumstances. In addition, pros and cons of each management option vary for different regions. For example, in developing countries, the low cost and simplicity of composting, together with the high organic content of waste make small-scale composting a promising solution. Furthermore, increased composting of municipal waste could reduce waste management costs and emissions, and create both employment and public health benefits. In industrial countries, increased composting of household food waste would reduce GHG emissions, but would require additional separation of household waste, which may limit the penetration of composting (IPCC, 2001b).

Waste incineration is a favourable option in industrial countries, where there are space limitations and land costs are high. Furthermore, energy content of waste is high when compared to developing countries due to higher portion of paper. In developing countries, on the contrary, lower land and labor costs, the lower heating value of waste due to higher content of putrescibles and the high capital cost of incinerators have discouraged waste combustion (IPCC, 2001b).

The waste sector has been subject to many control measures, which have changed waste sector in the recent years, and will cause changes also in the near future especially in developed countries. The objectives of these measures are usually to limit the health and environmental impacts e.g. to ground water. Space needed for landfilling can also be scarce in many countries. Waste sector measures also often enhance the economic use of resources and they are seen as an important part of the sustainable development.

1.3 Waste sector GHG emissions trends and scenarios

Global waste sector emissions have grown steadily and are expected to increase in the forthcoming decades especially in developing countries because of the increases in population and GDP (e.g., IPCC, 2000). In developed countries, emissions reported to the UNFCCC have shown a stabilising or even declining trend in recent years for many countries (UNFCCC, 2005). The estimation of the past, current and future emissions as well as the mitigation potential in the waste sector has many uncertainties, the most important relating to the poor quality of activity data needed for estimation of emissions. Several studies have tried to collect data on emissions from the waste sector (USEPA, 2005; ADB, 1998). However, these studies only extend out to 2020 and leave many gaps. Waste statistics are lacking in many countries, and due to the differences in waste-related definitions and differences in the coverage of waste collection in different countries, the comparability of national data is uncertain. Thus, CH₄ and other GHG emissions from waste management are uncertain and national estimates may not be comparable. Waste management encompasses different treatment phases and techniques applied in parallel or in a chain, all which may affect the total emissions (IPCC, 2006).

Assessment of trends including future emissions for the waste sector often emphasizes CH₄ emissions from landfills (e.g., IPCC, 2001b; Bogner & Matthews, 2003). These studies indicate that there is a significant potential to reduce CH₄ emission in this sector, and mitigation measures are cost-effective (Delhotal, 2005; USEPA, 2003; Pipatti & Wihersaari, 1998; Tuhkanen, 2000; IEA 1999 and others). For example, the IPCC (2001b) estimated that mitigation potential of waste CH₄ in 2020 is more than 700 Mt CO₂ eq/yr. About 75% of this is CH₄ recovery from landfills at net negative direct cost, and 25% at a cost of about US\$20/tCeq. A majority of emission reductions were assumed to occur in OECD countries (IPCC, 2001b). Similar results were obtained by USEPA (2003) where mitigation potentials ranging from approximately 40–75% were estimated to be achievable with negative or low costs (< 20 US\$/CO₂ eq) by 2030 for a selected set of countries (China, Mexico, South Africa, Ukraine, and the United States).

Degradation of waste in landfills can take several decades depending on climate region and type of waste. Therefore, estimates of actual CH₄ emissions and

mitigation potential from waste disposal require modeling of waste degradation. The global estimates on the mitigation potential in the waste sector in the studies above do not take this time lag in CH₄ emissions at all or fully into account, and may therefore overestimate the reductions in the emissions which can be achieved in the near future.

1.4 Climate change mitigation commitments and the waste sector

The Kyoto Protocol requires Annex I Parties³ to reduce their GHG emissions on average 5% by 2008–2012 compared to the 1990 level (UNFCCC, 1997). Control and reduction of greenhouse gas emissions from the waste sector is often cost-effective, when compared with other sectors of the Kyoto Protocol. The cost-effectiveness of measures reducing methane emissions is particularly high, due to its global warming potential.

In addition to domestic measures, an Annex I country can use emission reductions acquired through flexible mechanisms in another country (where emission reduction is more cost-efficient) to meet Kyoto target. These mechanisms are Emissions Trading (ET), Joint Implementation (JI) and the Clean Development Mechanism (CDM) (UNFCCC, 2002). In ET, emissions can be traded between Annex I Parties, and in JI, an Annex I Party implements an emission reduction project in another Annex I Party, typically in an EIT country. Under CDM, an Annex I Party implements project activities that reduce emissions in a Non-Annex I Party, in return for certified emission reductions (CERs).

In the waste sector, LFG recovery has become an important project type within CDM and JI. According to current information on registered CDM and JI projects (UNEP Risø Centre, 2006; UNFCCC, 2006), landfill gas recovery projects account for 10–15% of emission reductions to be achieved through both CDM and JI in the first commitment period 2008–2012. 95% of the emissions reductions of registered LFG recovery projects occur under CDM. The stronger

³ Developed country parties to United Nations Framework Convention of Climate Change (UNFCCC) listed its Annex I, as amended.

role of CDM compared to JI is to a large extent due to that emission reduction from CDM projects can be obtained from the year 2000 onwards, whereas those from JI are obtainable only during the commitment period. The potential of JI is also limited in the new EU member states in eastern Europe by the EU landfill directive, which restricts landfilling of biogenic waste and thus lowers the baseline emissions of JI projects. This limits the acceptable emission reduction potential of JI projects reducing the number of profitable projects.

1.5 The aim of this study

Estimates of future emissions and their mitigation potentials and costs are needed for the IPCC 4th Assessment Report. This report presents scenarios for solid waste disposal for that purpose. The IPCC SRES Scenarios in the IPCC Special Report on Emission Scenarios and the IPCC 3rd assessment report dealt with waste sector emissions based on projections where population is used as a driver and the time lag in CH₄ emissions is not taken into account. In addition, landfill gas recovery, which has been commercial since 1975 and implemented at increasing rates was not considered in the baseline (IPCC, 2000; IPCC, 2001b).

This study combines two modelling approaches for estimation of waste sector emissions, costs, and mitigation potential: (1) dynamic emission calculations taking into account political decision making and changing waste management systems, as well as the time lag in emissions from landfills and (2) a steady-state calculation for maximum economic potentials at various cost levels using linear optimisation at the global scale.

In the first approach, country-specific and regional emission scenarios are estimated using the newly updated methodology and default activity data and parameters in the 2006 IPCC Guidelines (IPCC, 2006). The methodology to estimate the emission from landfills is based on a first-order decay model which permits estimation of annual emissions taking the time lag in emissions into account. The starting point for the emission estimates from solid waste management is waste generation and management data, which is used in a systematic way to eliminate double-counting of emissions and mitigation potential. By this approach, *Baseline* and four greenhouse gas mitigation

scenarios are compiled for the years 1990 to 2050. The mitigation scenarios take into account different factors that may influence emission reductions. For example, market penetration of waste incineration is assumed to be low in developing countries due to its high capital costs, and waste recycling rates are assumed to be restricted by logistical and economical reasons. Therefore, maximum economic potentials are not reached in most countries – especially developing countries - in the timeframes of the scenarios.

In the second approach, the *Baseline* scenario developed using dynamic models is used as a starting point. The Global TIMES model, which is a partial-equilibrium model, is used to optimise emissions reductions, costs and potentials in 15 world regions in the year 2030. As the cost calculations go up to 100 USD/t CO₂, maximum economic potential of various mitigation measures is reached. At the highest cost levels, the waste management system could be drastically changed. Therefore, this approach gives much higher emission reductions than the first approach.

The scenarios contain many uncertainties, but the systematic approaches chosen are expected to produce realistic estimates of the mitigation potential. Furthermore, the two different approaches chosen give a wide perspective for possible future waste management.

Due to data limitations, only scenarios for disposal of municipal solid waste (excluding wastewater) are developed in this report.

2. Global scenarios for emissions from solid waste management

2.1 Description of the scenarios

In this report, five different scenarios for greenhouse gas emissions from solid waste treatment are considered: the *Baseline* (BL) scenario and four greenhouse gas (GHG) mitigation scenarios. All the scenarios are based on the same assumptions on population and GDP development, consistent with SRES scenario A1b. The *Baseline* scenario assumes that waste generation, landfilling and combustion would follow the past and current trends without any additional efforts to reduce the amount of landfilled waste or the emissions. In the *Baseline* scenario, both emissions from landfills and waste incineration were calculated. For simplicity, emissions from biological treatment were assumed to be insignificant. Table 1 presents amount of waste generated and treated in three regions (OECD, EIT and Non-OECD) in 2000.

Table 1. Average MSW generation, landfilling and incineration in different regions in 2000 based on country-specific calculations. Data from IPCC (2006) and UN (2005) are used as a basis.

Region	Waste generation (managed waste) [Tg]	Waste generation [kg/cap] ^a	% of waste landfilled ^b	% of waste incinerated ^b
OECD	714	650	55%	18%
EIT	91	220	83%	9%
Non-OECD	459	90	78%	2%

^aMass of wet waste managed in region per capita. In EIT and Non-OECD countries, only urban population waste is assumed to be managed.

^bWaste that is neither landfilled nor incinerated is e.g. recycled or treated aerobically.

In *CDM ending in 2012* scenario it was assumed that a certain amount of LFG would be recovered in Non-OECD countries as a result of CDM activities during the first Kyoto period 2008–2012. However, no continuing Kyoto or similar commitments were assumed thereafter. As increase in LFG recovery also after 2012 is considered likely to occur, a second LFG recovery scenario called *High landfill gas recovery* (HR) was developed. In the HR scenario, a more rapid increase in CH₄ recovery from landfills was assumed in all countries to 2050. In

this scenario, maximum economic LFG recovery was assumed to be reached in most countries.

Table 2. Greenhouse gas coverage of the scenarios calculated for solid waste management.

Scenario	Code	Landfill CH₄	Incineration CO₂
Baseline	BL	X	X
Increased incineration	II	X	X
Increased paper recycling	IR	X	
CDM ending in 2012 (CH ₄ recovery)	CDM ending in 2012	X	X
High landfill gas recovery	HR	X	X

In two other scenarios, *Increased paper recycling* (IR) and *Increased incineration* (II) the amount of landfilled waste was assumed to decrease when compared to the BL. In BL, HR and II scenarios, emissions from waste incineration and potential emissions savings if waste incineration replaces other fuels are also calculated. Table 2 presents a summary of the scenarios.

All the scenarios are presented for the years between 1990 and 2050. However, in the calculation of CH₄ from landfills, the first year of calculation was 1950, because degradation of specific waste fractions takes decades, and therefore waste disposed in 1950 still has an effect on current emissions. However, the amount of waste landfilled in the early years is small, and a larger amount of waste was assumed to degrade aerobically (see Table 5) and therefore the effect of waste disposal in 1950–1970 on current and future emissions is small.

Maximum economic mitigation potentials at different cost levels were calculated using the Global TIMES model. The Global TIMES model is a 15-region global energy system model, which is being developed under the IEA ETSAP programme.⁴ In its basic methodology, TIMES is a partial equilibrium model, which assumes competitive markets for all commodities. The results represent a supply-demand equilibrium that maximizes the net total surplus of consumers

⁴ The contents of this report reflect the views of the authors alone, who are responsible for the accuracy of the information presented herein and the data used in the Global TIMES model. In particular, the views expressed here do not reflect those of ETSAP, nor any member organization of the ETSAP programme.

and producers under various constraints related to, for example, energy resources, technological development, and climate policies (Loulou et al., 2005). The regions included in the model are listed in Table 3.

Table 3. World regions in the Global TIMES model.

Code	Region
AFR	Africa
AUS	Australia-New Zealand
CAN	Canada
CHI	China (including Hong Kong, excluding Chinese Taipei)
CSA	Central and South America
EEU	Eastern Europe
FSU	Former Soviet Union (including the Baltic states)
IND	India
JPN	Japan
MEX	Mexico
MEA	Middle-East (including Turkey)
ODA	Other Developing Asia (including Chinese Taipei and Pacific islands)
SKO	South Korea
USA	United States
WEU	Western Europe (EU-15, Gibraltar, Iceland, Malta, Norway, Switzerland)

2.2 Methods and assumptions

2.2.1 Baseline

Landfills

CH₄ emissions from landfills are a product of anaerobic decomposition of organic matter in waste. Waste in landfills decomposes slowly, and the decomposition times can be several decades. The estimation of the emissions requires data on amount and composition of the waste disposed in the landfills.

Emissions from landfills were calculated by using the IPCC First Order Decay (FOD) model (IPCC, 2006). The basic equation for estimating the CH₄ emissions is

$$CH_4 \text{ emission} = (\sum_x CH_4 \text{ generated}_{x,T} - R_T) \cdot (1 - OX_T) \quad (1)$$

where

$CH_4 \text{ emission}$	=	CH_4 emitted in year T, Gg
T	=	year of calculation
x	=	waste category or type/material
R_T	=	recovered CH_4 in year T, Gg
OX_T	=	oxidation factor in year T, fraction.

The CH_4 generation potential is proportional to the amount of remaining degradable organic material (DOC). The mass of DOC which decays over a period of time (dt) is described by equation (2):

$$d(DOCm) = -k \cdot DOCm \cdot dt \quad (2)$$

where

DOCm	=	mass of degradable organic carbon in the disposal site at time t
k	=	decay rate constant in yr^{-1}

The solution to this equation is the basic FOD equation (3):

$$DOCm = DOCm_0 \cdot e^{-kt} \quad (3)$$

where

DOCm	=	mass of degradable organic carbon that will decompose under anaerobic conditions in disposal site at time t
$DOCm_0$	=	mass of DOC in the disposal site at time 0, when the decay reaction starts
k	=	decay rate constant in yr^{-1}
t	=	time in years.

In the model waste disposal over a period of 50 years before is taken into account. The country-specific or regional default values for waste disposal in the year 2000 were used as the starting point and historical values were extrapolated using urban and total population as drivers. Regional default waste compositions were used to estimate the amount of DOC in the waste.

Altogether 95 country-specific or regional FOD models were compiled for the *Baseline* scenario. The population data from 1950 to 2000 was obtained from the UN statistics (UN, 2005). Country-specific or regional data on waste generation/cap was obtained from the IPCC 2006 Guidelines (IPCC, 2006) for the year 2000. This waste generation data covers population whose waste is managed. According to OECD (2002), all population is served by municipal waste services in most OECD countries of this study. Therefore, in OECD countries, total population was used to calculate waste generation in each OECD country. In EIT countries the share of population whose waste is managed varies between 50 and 100% (OECD, 2002; European Communities, 2003). On the other hand, the % of urban population in EIT countries varies between 47 and 74% (Statistics Finland, 2005). Therefore, data on urban population (Statistics Finland, 2005) was used to calculate the amount of managed waste in EIT countries in 2000. This same assumption was also used for Non-OECD countries, where the lowest urbanisation was 15%.

The % urban population before 2000 was used to estimate the total mass of waste prior to 2000 for the countries which comprised one third of emissions in 2000. However, this effect was found to be minor when compared with using the 2000 percentage exclusively, especially when compared with uncertainties related to other assumptions on waste. Furthermore, the effect of development of urbanization between 1950 and 1999 was insignificant in the scenario years of interest (2030 and 2050), and therefore, the share of population whose waste was managed in 2000 was used also for earlier years for the rest of the countries.

Projections for population and GDP were the same in all the scenarios, based on the IPCC SRES scenario A1b. In the SRES scenarios (IPCC, 2000), data was not disaggregated into country level. This disaggregation was later done by the Netherlands Environmental Assessment Agency (MNP) (van Vuuren et al., accepted), and this downscaled data was used in the waste scenarios.

Waste generation and management typically increases with increasing GDP (e.g., Mertins et al., 1999), peaking at around 900 kg/cap annually (Bogner & Mathews, 2003; OECD, 2004; EEA, 2005). Therefore, it was assumed that waste generation/cap (managed waste) reaches a maximum of 900 kg/cap when the GDP reaches that of the USA in 2000, and the years in between were interpolated. Once the maximum waste generation was reached, it was assumed

to remain constant for the rest of the scenario period. However, there were some countries, whose GDP was already close to or higher than that of the USA in 2000, but whose waste generation/cap was lower. In these cases, waste generation/cap was assumed to remain constant even though GDP increased. For the Middle East, neither regional nor country-specific data were available, and therefore an average of South-Central Asia and East Europe was used.

The share of generated waste disposed to landfills varies between different countries and regions. IPCC (2006) gives default shares for landfilling for 2000, which were used for most countries for the entire time series in the BL scenario. However, in countries where waste incineration occurred in 2000, increase in incineration was assumed to be linear between 1950 and 2000. In addition, landfilling of waste has notably decreased in some OECD countries since 1990 (OECD, 2002; European Communities, 2003). In these countries, the % of waste landfilled in 1990 (instead of the % landfilled in 2000) was used as a basis for estimates for the share of waste landfilled prior to 1990. Regional averages for waste landfilling and incineration are presented in Table 1 in Section 2.1.

Country-specific or regional waste composition (% wood, paper and cardboard, food, plastics, textiles, rubber and leather and “other inert”) was also obtained from the IPCC (2006) for nearly 20 different regions. Waste composition was assumed constant for the entire time series, as there is not enough information on the changes in waste composition to make other assumptions.

The amount of degradable organic carbon (DOC) in waste disposed was calculated from the default values for DOC in different MSW components given by IPCC (2006). The default DOC values are presented below in Table 4.

Table 4. DOC content of different waste fractions with data ranges from the IPCC (2006).

MSW component	DOC (% of wet waste)
Paper/cardboard	40% (36–45%)
Textiles	24% (20–40%)
Food waste	15% (8–20%)
Wood	43% (39–46%)

The Methane Correction Factor (MCF) represents the management of the landfill. A low MCF value means that much of the waste is decaying under aerobic conditions and is not generating methane. For managed landfills, MCF value is 1. The MCF values used are presented in Table 5. The table shows that in OECD and EIT countries all the landfills are assumed to be managed since 2000. The uncertainty in MCF factor 0.4 is estimated at $\pm 30\%$ (as 95% confidence interval), and that of MCF value 1 from -10% to 0% (IPCC, 2006). However, the characteristics of landfills in different countries in the groups are variable, especially in case of developing countries. The uncertainties are large for the year 2000 and even larger for the years before and after that.

Table 5. MCF values used for different regions in different years (years in between are interpolated).

Region	Year	MCF = 0.4	MCF = 1
OECD and EIT	1950–1970	100%	0%
OECD and EIT	2000–2050	0%	100%
Non-OECD	1950–1970	100%	0%
Non-OECD	2000	80%	20%
Non-OECD	2030	50%	50%
Non-OECD	2050	25%	75%

The decay rate for the anaerobic decomposition (k-value) is an important parameter in estimating the emission. Here k-values that represent the rate of degradation in the IPCC 2006 Guidelines were used for four climate zones: 1) moist and wet tropical, 2) dry tropical, 3) moist boreal and temperate and 4) wet boreal and temperate (see Table 6). All the countries were assigned to climate zones based on IPCC (2003). There are large uncertainties in the k-values and more accurate estimates could be obtained by using k-values based on national research and conditions. National values were however not available for this study.

Another approach is to use a weighted average k-value for mixed MSW (Jensen and Pipatti, 2002). This approach assumes degradation of different types of waste to be completely dependent on each other. Thus the decay of wood is enhanced due to the present of food waste, and the decay of food waste is slowed down due to the wood. The approach chosen here as basis for the

calculations assumes that degradation of different types of waste is independent of each other. As this study aimed at estimating impact of increased recycling, changing the composition of waste, weighted average k-values for mixed waste could not be used. The IPCC 2006 Guidelines does not give priority to either approach as there is little research on the issue and results are not conclusive (Oonk & Boom, 1995; Scharff et al., 2003).

Table 6. K-values [1/year] used for different waste fractions and climate regions (IPCC, 2006). Uncertainty ranges are in brackets.

Type of waste	Climate region			
	Boreal and temperate dry	Boreal and temperate wet	Tropical dry	Tropical moist and wet
Paper/textiles	0.04 (0.03–0.05)	0.06 (0.05–0.07)	0.045 (0.04–0.06)	0.07 (0.06–0.085)
Wood/straw	0.02 (0.01–0.03)	0.03 (0.02–0.04)	0.025 (0.02–0.04)	0.035 (0.03–0.05)
Food waste	0.06 (0.05–0.08)	0.185 (0.1–0.2)	0.085 (0.07–0.1)	0.4 (0.17–0.7)

The IPCC default values were used also for the *fraction of methane in landfill gas* (50%) and *fraction of degradable organic carbon decomposed* (50%), with uncertainties $\pm 5\%$ and $\pm 20\%$, respectively (IPCC, 2006). The oxidation factor used was 0, assuming no oxidation of CH₄ in the surface of the landfill, as this is the assumption in the IPCC Tier 1 method (IPCC, 2006). This may result in an overestimation of CH₄ emissions.

Data on landfill gas recovery was obtained from Willumsen (2003) for the year 2002. In the *Baseline* scenario it was assumed that CH₄ recovery increases 5% annually in OECD and EIT countries, where CH₄ recovery occurred in 2002, consistent with the global historical trend (Bogner & Mathews, 2003). No LFG recovery was assumed to occur in those countries where it did not occur in 2002 according to Willumsen (2003). In Non-OECD countries landfill gas recovery was assumed constant (year 2002 level based on Willumsen, 2003) in the *Baseline*. The maximum CH₄ recovery potential for different country groups was estimated based on estimated maximum share of landfills with LFG recovery (as % of CH₄ generated), and on the estimate of maximum average CH₄ recovery

efficiency (Table 7). Recovery estimates take into account the fact that the efficiency over the lifetime of the landfill is lower than that of the annual efficiency at sites with well-operating recovery, and also that all sites will not be operating perfectly.

Table 7. Estimated maximum CH₄ recovery from landfills.

Region	Max share of landfills with LFG recovery	Max average recovery efficiency	Max CH₄ recovery potential as % of CH₄ generated in landfills
OECD and EIT	70%	80%	56%
Non-OECD	50%	50%	25%

Waste incineration

Fossil CO₂ emissions from waste incineration were calculated by using the Tier 1 method of the IPCC (2006). Fossil CO₂ emissions were calculated for plastics, textiles, paper/cardboard, rubber and leather and “other inerts” (not glass or metal). It was assumed that incinerated waste has the same composition as landfilled waste. Waste generation/cap and waste composition were the same as in *Baseline* for landfills. Dry matter fraction of waste, fraction of carbon in different waste fractions and share of fossil C were the defaults from the IPCC 2006 Guidelines (see Table 8).

Table 8. Dry matter fraction, total carbon fraction and fossil carbon fraction used in waste incineration calculations with data ranges from the IPCC (2006).

MSW component	Dry matter fraction in % of wet weight	Total carbon fraction in % of dry weight	Fossil carbon fraction in % of total carbon
Paper/cardboard	90%	46% (42–50%)	1% (0–5%)
Textiles	80%	50% (25–50%)	20% (0–50%)
Plastics	100%	75% (67–85%)	100% (95–100%)
Rubber and leather	84%	67%	20%
Other inert	90%	3% (0–5%)	100% (50–100%)

The share of waste incinerated in 2000 obtained from IPCC (2006) was assumed to remain constant in the *Baseline* through 2050. By using this assumption, when waste generation increases, the amount of incinerated waste also increases if the share is assumed constant.

2.2.2 Increased incineration (II) scenario

In this scenario, it is assumed that waste incineration will increase in all the countries, e.g. due to policies aiming at reducing the amount of waste landfilled, or space limitations for landfilling. However, high capital costs restrict the use of this technology in developing countries.

In the II scenario it was assumed that amount of waste incinerated increases by 5% each year in the countries where waste incineration occurred in 2000. This corresponds roughly to the average annual growth rate in European countries (European communities, 2003).

In those OECD and EIT countries where waste incineration did not occur in 2000, it was estimated that 1% of waste will be incinerated in 2012 (increases linearly from zero in 2007). Because waste incineration is relatively costly, it was assumed that Non-OECD countries having no incineration in 2000 incinerate 1% of waste in 2030. The 1% of waste incinerated corresponds roughly to construction of one plant in the first year.

The EU legislation limits waste landfilling (Directive 1999/31/EC on the Landfill of Waste). However, countries like Canada, USA, Australia and New Zealand do not have this type of legislation, and space does not restrict landfilling as in many European countries. Therefore, this scenario is not likely to happen in these countries. However, in the II scenario, the estimated waste incineration rates in Australia and New Zealand remained relatively low, i.e. at 6% at its highest. Maximum incineration rates in Canada and USA were 18% and 69% in the II scenario, respectively. Furthermore, it is an open question what will happen in developing countries.

For some countries, amount of waste incinerated increased more than 5% per year in the *Baseline* scenario. For these countries waste incineration in *Baseline* was used in the II scenario.

It was assumed that the maximum share of waste incineration could be 85% of waste generation due to economic and logistic reasons. It was also assumed that only the share of waste that would have otherwise gone to landfills was incinerated in the II scenario. Therefore, in countries where other waste management options are widely used, the maximum share of waste incineration was lower than 85% e.g. 40–50% in many European countries. Only one country (Japan) with high incineration rate in 2000 reached 85% of waste incinerated in the II scenario.

2.2.3 Increased paper recycling (IR) scenario

This scenario assumes growth in paper recycling in all parts of the world. However, recycling rates are restricted by e.g. logistical and economical reasons.

According to Confederation of European Paper Industries (CEPI, 2003), 81% of paper in the market could theoretically be recycled. The remaining 19% is either non-collectable or non-recyclable. Examples are wall paper, soft papers and cigarette papers, or books which are stored for a long time period.

However, financial and environmental reasons (such as long transport distances) restrict the recycling rate in practice (CEPI, 2003). Another restriction is that paper fibres can only be recycled 4–6 times, and a certain amount of virgin fiber is needed (European Declaration on Paper Recovery, 2006). Therefore, it was assumed in the IR scenario that a realistic technical maximum is that 60% of paper and cardboard landfilled in the *Baseline* would go to recycling in all the countries. In the IR scenario, it was assumed that this maximum would be achieved in 2050, increasing linearly from 2001. It is thus assumed that recycling only reduces landfilling, but does not have an effect on other waste management options, e.g. incineration. Even though this assumption is the same for all the countries, in practice it means that a larger share of the paper consumed will go to recycling in countries where recycling rates were already high in 2000. This is a feasible assumption because there is an international

market for recycled paper, and recycling rates in individual countries can be very high. On the other hand, if waste incineration rates are high, the share of paper landfilled is smaller and thus this assumption yields smaller recycling rates in the IR scenario.

2.2.4 CH₄ recovery scenarios

CDM ending in 2012

This scenario describes the effect of LFG recovery CDM projects during the first commitment period of the Kyoto Protocol on emissions by 2030 and 2050. In this scenario, there are no incentives to reduce emissions after 2012.

In this scenario, it was assumed that 30 Mt CO₂ eq of landfill CH₄ is annually recovered in Non-OECD countries in 2008–2012 based on information on registered CDM projects (UNEP Risø Centre, 2006; UNFCCC, 2006) and estimated increases by 2008. As it was also assumed that there is no continuing Kyoto or similar commitments after 2012, it was assumed that no new CH₄ recovery capacity is installed in Non-OECD countries after 2012. In this scenario, recovery rates of the *Baseline* scenario were used for OECD and EIT countries.

High landfill gas recovery (HR) scenario

This scenario assumes that Kyoto or similar commitments will attend CDM after 2012 with a high growth rate for LFG recovery in all the countries. LFG recovery is a cost-efficient emission mitigation option in developed countries and CDM has appeared to be a favourable mechanism to stimulate this development in developing countries. In the majority of countries, an assumed technical potential for LFG recovery is obtained by 2030 in this scenario.

A 15% annual increase is assumed from 2002 onwards in OECD and EIT countries in this scenario. In Non-OECD countries, the same assumptions regarding CDM as were used as in the *CDM ending in 2012* scenario were used by 2012. From 2013 to 2050 landfill gas recovery was assumed to increase at the same rate in Non-OECD countries as in other parts of the world. The choice of

the rate of increase may seem high, but it is possible taking into account the small number of existing landfill gas recovery in developing countries at present, and also the high interest in CDM landfill gas recovery projects (UNFCCC, 2006; Ahonen 2006). In addition, LFG recovery is seen as an interesting option for JI projects, which may increase the number of these projects in EIT countries. Furthermore, rapid growth in LFG recovery has been seen in many developed countries during the first years of the 21st century (UNFCCC, 2005). In the case of OECD and EIT countries with no CH₄ recovery in 2002, only 0.5% of CH₄ generated in 2003 was assumed to be recovered, and a 15% annual increase was assumed thereafter. The maximum landfill gas recovery potentials were the same as in the *Baseline* scenario.

2.3 Economic potentials at different marginal cost levels

The scenario considerations presented in section 2.2 took into account various barriers which may restrict or slow mitigation measures. However, for the purposes of this study, maximum economic potentials at different marginal cost levels were also of interest, and therefore they were assessed using the Global TIMES model which was extended to include solid waste management systems with connections to energy system parts of the model. The methane emissions of the *Baseline* scenario were used as a starting point for the analysis with TIMES. Total annual waste arisings by region were derived for the model from the emission projections by using static aggregate emission coefficients calibrated to the regional dynamic FOD models.

For analysis with the Global TIMES model, the primary source for the data on the technology options was the EMF-21 study, carried out by USEPA (2003). The EMF-21 data covers the following options for reducing methane emissions from municipal solid waste:

- Anaerobic digestion (with direct gas use or with electricity generation);
- Composting (two cost categories);
- Mechanical-biological treatment;
- Increased oxidation of methane at landfill sites;
- Landfill gas recovery with or without utilization for energy (direct gas use, use for electricity or heat production, or gas flaring).

Data for the options of increasing either recycling or the use of waste for energy were not available from the EMF-21 study. In the analysis with the TIMES model, increased recycling options were excluded, due to the lack of credible cost data and the additional complexities related to the emissions with respect to the variable properties of the waste to be recycled.

However, as incineration is also an important option for reducing waste quantities, the waste incineration option was included in the model. The costs and efficiencies of waste incineration were estimated on the basis of several sources (World Bank, 1999; de Feber & Gielen, 2000; OECD, 2005). Table 9 presents a comparison of the data used in the TIMES with data from other sources. Only the conventional grate-fired incineration technology was taken into account, although more advanced technologies based on gasification or pyrolysis may become commercially available by 2030 (de Feber & Gielen, 2000).

The carbon dioxide emissions from waste incineration were assumed to correspond with the average fossil carbon content of waste. The emission factor was calculated to be between 10 and 40 t(CO₂)/TJ based on the BL scenario.

Table 9. Comparison of some estimates for waste incineration plant data.

	World Bank, 1999	de Feber & Gielen, 2000	OECD, 2005 (CZE-WI)	This study (West Europe)
Cost basis	USD 1999	EUR 1995	USD 2003	USD 2000
Construction year	~2000	2030	2010	2030
Investment costs	4100 \$/Kw	4500 €/kW	3600 \$/kW	4500 \$/kW
Annual operating costs	260 \$/kW	70 €/kW	190 \$/kW	250 \$/kW
Electrical efficiency	35%	30%	~30%	28%

Altogether twelve emission reduction options for each of the 15 regions were considered in the calculations. As in the EMF study, no differences in investment costs were assumed between regions. However, differences in labor costs were taken into account in the O&M costs. The required rate of return was assumed 7% for the investments in the mitigation options in all regions. In order

to simulate the full opportunity costs, the costs of waste disposal should also be taken into account. In our runs, we assumed that in 2030 the gate fees would be 30 USD/t in OECD (non-EIT) countries, 20 \$/t in transition economies, and 10 \$/t in non-OECD countries. These estimates can be considered quite conservative, as in many other studies the actual gate fees have been projected to increase considerably in the future, for example up to 185 €/tonne in Europe by 2030 (de Feber & Gielen, 2000).

The technical potentials for the mitigation options were partly based on the regional potentials estimated in the EMF-21 study and partly on assumptions used in our study. The specific assumptions used in our study were related to the potential for landfill gas recovery (maximum of 75% of the landfill sites in industrialized countries, and 50% of the sites in developing countries), and to the maximum potential for waste incineration (85% of the amount of waste assumed to be landfilled in the *Baseline* scenario).

The technical emission reduction efficiency of landfill gas recovery systems was assumed to be 75% in all regions, in conformity with the EMF-21 study. The reduction efficiencies of anaerobic digestion, composting and mechanical-biological treatment were assumed between 95 and 100%.

The potential for mitigation measures in each cost range for the country groups was estimated on the basis of technical and economic characterization of the measures within each region and overall cost minimization.

The baseline demand projections used in the model correspond mostly to the IPCC B2 storyline. Concerning the development of fossil fuel prices, the prices in the model were adjusted to conform to the projections in the IEA World Energy Outlook 2005 (WEO, 2005).

3. Scenario results

3.1 Projected emissions

According to the calculations with the dynamic model, global CH₄ emissions from landfills in the *Baseline* scenario were estimated at 448 Tg CO₂ eq in 2000, and they were expected to increase to 1510 Tg CO₂ eq by 2030 and to 2910 Tg CO₂ eq by 2050. In 2000 the share of OECD countries was 57%, EIT countries 14% and that of Non-OECD countries 29% of global emissions. By 2030 (2050) the relative share of Non-OECD countries increases to 64% (76%), whereas shares of OECD and EIT countries decrease to 24% (14%) and 12% (10%), respectively (see Figure 2).

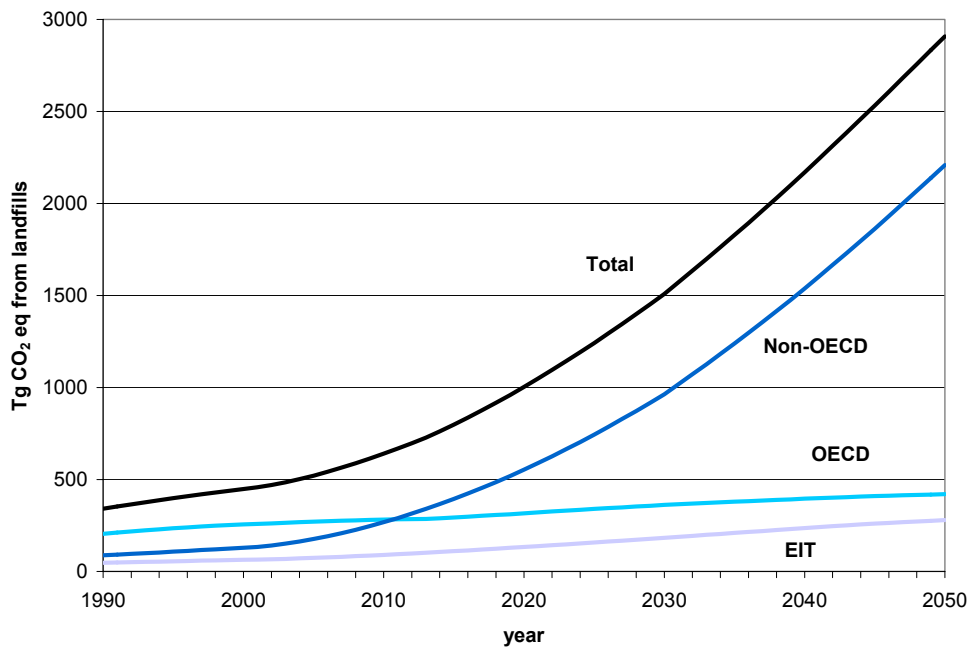


Figure 2. CH₄ emissions (Tg CO₂ eq) from landfills in different regions in the *Baseline* scenario.

Figure 3 compares global CH₄ emissions from landfills among all the scenarios. It can be seen that the lowest emissions in 2050 are reached in the *High landfill*

gas recovery (HR) scenario, where emissions are 21% lower in 2030 than in the Baseline, and 27% lower in 2050.

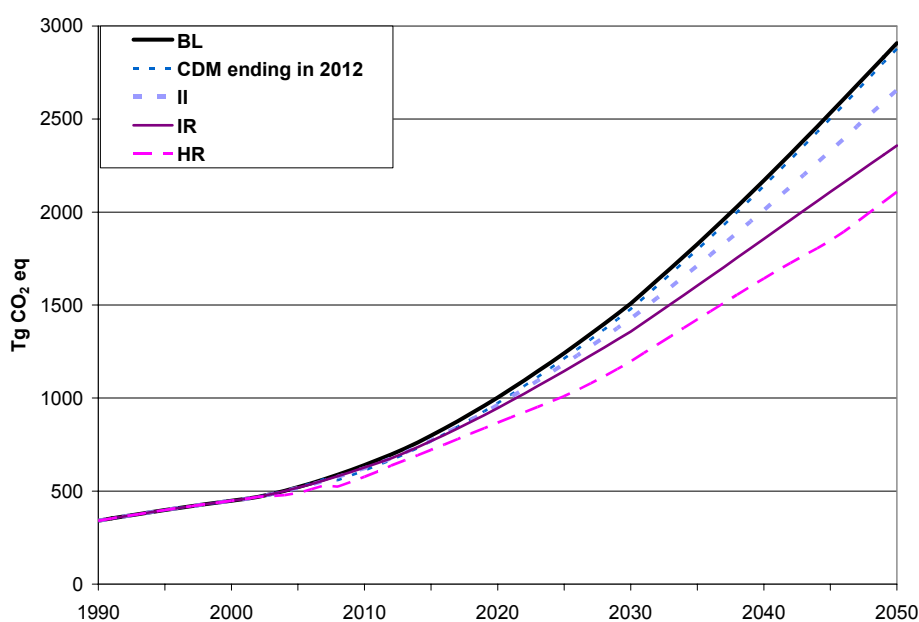


Figure 3. Global CH₄ emissions from landfills in different scenarios. Emissions of waste incineration or energy recovery of waste incineration or LFG are not included.

The scenario which yields the lowest emissions in 2030 and 2050 is different for different regions (Table 10). In OECD, the lowest emissions are obtained in the II scenario. Incineration is a favourable waste management option in OECD countries due to the relatively high energy content of waste, and high costs of land in many OECD countries. In this scenario, emissions from OECD countries in 2050 are close to those in 2000. Nearly all the mitigation scenarios stabilize emissions from OECD countries between 2030 and 2050: In the HR scenario, emissions are nearly the same in 2030 and 2050, and in the IR scenario, emissions are only 2% larger in 2050 than in 2030, despite the increasing mass of waste.

In EIT countries, emissions are lowest in the HR scenario. This is because LFG recovery is assumed to have a high growth rate. Furthermore, the effect of

options which reduce the amount of waste landfilled need more time to affect the emissions. In 2030, emissions from the IR and HR scenarios are similar, but by 2050, the HR scenario yields notably lower emissions.

In Non-OECD countries emissions increase in all the scenarios, but the lowest emissions are achieved in the HR scenario. This is because LFG recovery is assumed to have a high growth rate. On the other hand, waste incineration is too costly for developing countries to be widely applied. However, even in this scenario, emissions are six-fold in 2030 and 13-fold in 2050 when compared with year 2000. This is due to economic growth leading to increased waste amounts and increase in the % of population whose waste is managed.

Table 10. CH₄ emissions from MSW disposal in landfills [Tg CO₂ eq] in different scenarios and from different regions. Emissions of waste incineration or energy recovery of waste incineration or LFG is not included.

Region	OECD			EIT			Non-OECD		
Scenario	2000	2030	2050	2000	2030	2050	2000	2030	2050
BL	256	361	420	63	183	279	129	964	2209
IR		322	327		163	219		872	1810
II		288	257		176	238		962	2161
CDM ending in 2012		361	420		183	279		933	2179
HR		317	317		156	133		724	1658

Table 11 presents amount of energy that could be utilized from recovered landfill gas in different scenarios. If it is assumed that LFG replaces natural gas or coal in electricity generation, emission savings are from 16 (II scenario) to 126 Tg CO₂ eq (HR scenario) in 2030 and 12 to 251 Tg CO₂ eq in 2050, respectively. This is 1–11% of emissions from landfills in 2030 and 0–12% in 2050 depending on scenario. LFG is of biogenic origin, and therefore combustion of LFG does not produce fossil CO₂ emissions.

Table 11. Fuel energy and emissions savings if recovered landfill gas is assumed to replace coal or natural gas in electricity generation in different scenarios⁵. The numbers do not include avoided CH₄ emissions due to LFG recovery from landfills.

Scenario	Energy from LFG [PJ]		Emissions savings - coal [Tg CO ₂ eq]		Emissions savings – natural gas [Tg CO ₂ eq]	
	2030	2050	2030	2050	2030	2050
BL	590	740	56	70	22	27
IR	530	590	50	56	20	22
II	440	330	42	31	16	12
CDM ending in 2012	660	810	63	77	24	30
HR	1330	2640	126	251	49	98

Figure 4 compares emissions from landfills and waste incineration in the BL, II and HR scenarios. Globally, emissions from landfills and incineration in the BL exceed emissions in the II scenario in 2010. However, avoided emissions from offsetting fossil fuels are not included.

Table 12 compares emissions from waste incineration and the fuel energy in incinerated waste in the BL and II scenarios. In addition, emissions savings are presented assuming that waste incineration with energy efficiency of 25% replaces coal combustion in electricity generation with energy efficiency of 35%. It is assumed that NCV of waste is 10 GJ/t_{wet waste} (in reality, NCV varies according to waste type) and the CO₂ emission factor of coal is 95 t CO₂/TJ (IPCC, 1996).

⁵ The assumptions used are energy efficiency of 50% for natural gas combustion in electricity production, 35% for condensing coal power plant and 35% for LFG combustion via internal combustion engine. Emission factors used are 95 tCO₂/TJ for coal and 53 tCO₂/TJ for natural gas. Energy content of LFG is assumed 50 TJ/(Gg CH₄ in LFG).

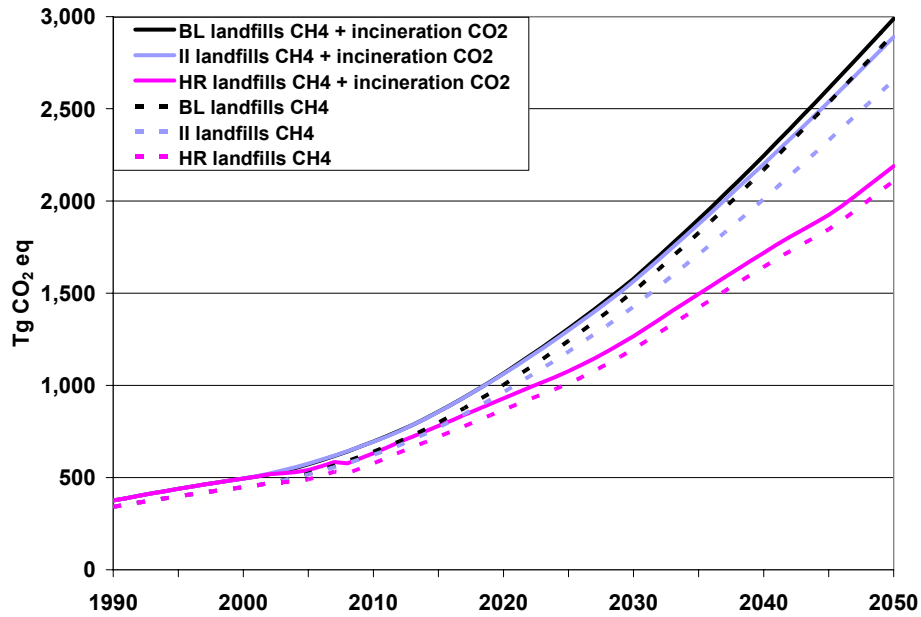


Figure 4. CO₂ equivalent emission from landfills (CH₄) and waste incineration (CO₂) in BL, HR and II scenarios. Emissions savings from energy recovery are not taken into account.

If the emissions savings in Table 12 were taken into account in Figure 4, emissions presented for landfills and incineration (solid blue line in figure) would be 12% lower between 2030 and 2050 for II scenario. If it were assumed that waste incineration replaces natural gas combustion in electricity generation, no emission savings would occur. This is because, even though the emission factor is smaller for waste (10–40 t CO₂/TJ) than for natural gas (50–53 t CO₂/TJ), emissions are nearly the same due to the lower efficiency of waste combustion.

Table 12. CO₂ emissions, fuel energy of combusted waste and emissions savings if it is assumed that waste combustion replaces coal in electricity generation.

Scenario	Energy from waste [PJ]		Emissions from waste incineration [Tg CO ₂]		Emission savings [Tg CO ₂]	
	2030	2050	2030	2050	2030	2050
BL ^a	2290	2690	70	81	85	102
II	4770	8350	138	233	186	334

^aAlso HR and CDM ending in 2012

3.2 Economic potentials at different marginal cost levels

The economic potentials of different mitigation options are presented in Table 13. The table shows landfill methane emissions reduced by different technology options assuming different marginal emission reduction cost levels for total greenhouse gas emissions. The unit costs of the measures used thus fall below the overall marginal emission reduction cost level.

The steady state approach used in assessing economic emission reduction potentials does not take into account the time lag for methane generation in landfills. Therefore, the results for a given year are somewhat overestimated but when integrated over time they are correct. In practice many of the measures should be started much earlier if they should have a noticeable impact on the actual emissions in 2030. For example, if only 15% of waste generated in the *Baseline* would be disposed in landfills due to combustion or other measures from the year 2010, and the maximum estimated LFG recovery is assumed, then the emission reduction in 2030 would be about 75% of *Baseline* emissions.

Table 13. Economic reduction potential of methane emissions from landfill waste by level of marginal costs for total GHG emission reduction assessed for the year 2030⁶.

Tg CO ₂ eq of CH ₄ reduced		USD/t CO ₂ eq				
Category	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	0	0	0	0	19
	Global	0	0	0	0	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	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	328	380	501	779	890
	Global	535	797	953	1255	1369

^a Combustion of waste causes also fossil CO₂ emissions, which have been taken into account in the calculations, but this table only presents emissions savings from landfills. However, these emissions are typically overcompensated by the corresponding savings when waste based energy replaces fossil fuels in the energy system.

In certain categories, energy recovery improves the cost efficiency, particularly at high marginal cost levels. The total additional net emission reduction potential due to the energy recovered and the corresponding amount of fossil fuels

⁶ The emission reduction potentials are assessed using a steady state approach which somewhat overestimates the reductions for a certain year but gives correct values when integrated over time.

replaced can be from about zero to 700 TgCO₂ eq/yr in 2030 if natural gas fired or coal-fired electricity production is assumed to be replaced, respectively.

Among OECD countries, waste incineration appears to have the highest economic potential in all cost classes. In OECD countries, the maximum percentage of waste used for energy (85%) is reached at the cost level 50 USD/t. On the global scale, however, landfill gas recovery has the largest economic potential in cost classes below 20 USD/t. The potential of various biological waste treatment options appears to become significant only at cost levels of 50 USD/t or above, and mostly in non-OECD countries.

One should note that the results show the least-cost allocation of emission reductions between the technology options. If, for example, the proportion of waste that could be used for energy is in practice considerably less than 85%, or waste incineration is for some other reasons not favored, the economic potential of other options could be significantly larger. One can immediately see from the results that landfill gas recovery would have considerably larger economic potential, if the potential for the use of waste for energy was smaller. However, one should also note that only the conventional waste incineration option was considered in the analysis. When more advanced technologies such as waste gasification or pyrolysis become commercially available, the potential for using waste for energy could be even larger.

Nevertheless, the results give a good indication about the maximum combined economic potential of all technology options considered. Table 14 summarizes the total economic potential for CH₄ emission reductions by assumed marginal emission reduction cost level.

Table 14. Economic total reduction potential of methane emissions from landfill waste by marginal cost level assessed for the year 2030^a.

	USD / t CO ₂ equivalent				
	0	10	20	50	100
OECD	48%	86%	89%	94%	95%
EIT	31%	80%	93%	99%	100%
Non-OECD	32%	38%	50%	77%	88%
Global	35%	53%	63%	83%	91%

^a The emission reduction potentials are assessed using a steady state approach which somewhat overestimates the reductions for a certain year but gives correct values when integrated over time.

3.3 Uncertainties and sensitivities

Emissions calculations for SWDS contain uncertainties, both because of lack of good activity data and uncertainties in calculation parameters and their suitability for different conditions in different countries. The uncertainty of each calculation parameter of the FOD model is discussed in Section 2.2. (see Tables 4, 6 and 8).

For most countries, reliable statistics are not available on waste generation, composition and treatment. In the scenario considerations, country-specific or regional data from IPCC 2006 Guidelines (IPCC, 2006) was used for the year 2000, and for the years before and after that extrapolation was used, which introduces additional uncertainty.

The waste generation data (t waste/cap) obtained from the IPCC (2006) was then multiplied by the population whose waste was assumed to be collected. In the case of OECD countries, total population was used and in case of other country groups, urban population. This assumption introduces additional uncertainty to the results.

Furthermore, estimates of waste generation and its relationship to GDP and population are not clear. The relationship between waste generation and GDP is different in each country, and especially in the long term it might change. However, the maximum annual waste generation of 900 kg/cap assumed in this study is smaller than current waste generation in some countries (IPCC, 2006). On the other hand, some countries with high GDP had much smaller waste generation rates in 2000 (e.g. Luxemburg 660 kg/cap, Switzerland 400kg/cap, Japan 470 kg/cap) (IPCC, 2006). The final result of scenarios is highly sensitive to this assumption.

For example, if it were assumed that maximum waste generation/cap is that of Switzerland in 2000 (400 kg/cap), global Baseline emissions in 2030 (2050) would be 38% (48%) lower. On the other hand, if max waste generation/cap were assumed 25% higher than in our calculations, emissions would be 19% (24%) higher, respectively. This shows the differences between the connection of GDP and waste generation in different countries. As waste generation rates are very uncertain and do not only depend on GDP but also on various other

issues which are difficult to quantify, these assumptions form a notable source of uncertainty in the calculations. Similar sensitivities could be found by varying the % of waste disposed to landfills. However, as the upper and lower bounds chosen for the sensitivity study are not likely to be realized, this result (from 40% lower to 20% higher emissions in 2030) can be assumed to represent the uncertainty range for both waste generation and % landfilled.

In the scenarios, country-specific or regional waste composition from the IPCC (IPCC, 2006) was used. These data are also uncertain, as statistics on waste composition are scarce. In addition, waste composition varies between different countries in the regions, and also within countries (urban and rural population, different income groups). Furthermore, waste composition may change with increasing GDP, but due to lack of data this could not be reflected in the scenarios.

The amount of LFG recovered can be accurately metered. However, estimates for the year 2002 recovery by Willumsen (2003) do not include collection of LFG without energy recovery. Therefore, LFG recovery may be underestimated in the BL scenario.

Total uncertainties in the scenario considerations are difficult to quantify due to numerous sources of uncertainty and propagation of uncertainty in the dynamic calculations of the FOD model. In a Finnish study, uncertainties were estimated for each calculation parameter, and uncertainties were combined with a Monte Carlo simulation of the FOD model. In that study, uncertainties in CH₄ emissions from landfills in specific years were estimated at $\pm 30\text{--}40\%$ for a 95% confidence interval relative to the mean (Monni et al., 2004a; Monni, 2004). In that study (Monni et al., 2004a; Monni, 2004), detailed country-specific data from the Finnish GHG inventory was used. As averaged data was used in the calculations presented in this report, uncertainties are larger than in the referenced study (Monni et al., 2004a; Monni, 2004). The uncertainties are estimated to be the largest for developing countries due to the most uncertain activity data. However, uncertainties in emission estimates of country groups (OECD, EIT and Non-OECD) are smaller than those of individual countries. Furthermore, due to correlations, uncertainties between scenarios and different points of time are smaller than uncertainties in emission estimates of individual years.

4. Discussion and conclusions

According to the *Baseline* scenario, global emissions from landfills are expected to increase from 340 Tg CO₂ eq in 1990 to 1500 Tg CO₂ eq by 2030 and to 2900 Tg CO₂ eq by 2050. The emission reduction scenarios, covering increased waste incineration, increased paper recycling and increased LFG recovery gave emissions reductions from 5% (9%) to 21% (27%) compared to the *Baseline* in 2030 (2050). As each scenario considered only one mitigation option, the results are largely additive and total mitigation potential can be assumed to be 30% in 2030 and 50% in 2050. The scenarios took into account political decision making, market penetration of technology and changes in waste management systems.

Another approach presented in this study considered the economic emission reduction potential at different marginal emission abatement cost levels by using a systems approach. At very high marginal cost levels (up to 100 USD/t CO₂ eq), a 75% emission reduction compared to *Baseline* could be achieved in 2030. This result is comparable to result from similar studies (USEPA 2003; Delhotal 2005 and others). However, due to slow degradation of waste in landfills, the high cost abatement measures reducing waste disposed in landfills should be implemented by 2010 in order to achieve the 75% reduction in 2030.

The largest emissions reductions in 2030 and 2050 were achieved in the *High LFG recovery (HR) scenario* where it was assumed that LFG recovery increases annually by 15% in all country groups. In developing countries, it was assumed that this development could be achieved as a result of CDM type of activities. In the HR scenario, global emissions from landfills were 310 Tg CO₂ eq (21%) lower than in the *Baseline* in 2030 and 800 Tg (27%) lower in 2050. In scenarios where the amount of landfilled waste was assumed to be reduced, the reduction in emissions will take place over longer time scales. The *Increased paper recycling* scenario yielded 10% (19%) lower global emissions in 2030 (2050) than the *Baseline*. The *Increased incineration* scenario had the smallest emissions of all scenarios in OECD countries (20% lower in 2030 and nearly 40% lower in 2050), but global emission reductions were smaller (5% and 9%, respectively), because waste incineration was assumed to be too costly to be widely used in developing countries before 2030.

LFG recovery and waste incineration have potential to replace other fuels. Emissions savings assuming substitution of natural gas or coal in electricity generation were estimated. For LFG, estimated savings were 1–11% in 2030 and up to 12% in 2050 depending on the scenario, when compared to emissions from landfills in respective scenarios without energy substitution. As LFG is of biogenic origin, its combustion does not emit fossil CO₂. In case of waste incineration, substitution of coal in electricity generation yielded emissions savings up to 12% in II scenario in 2030 and 2050 when compared with emissions from landfills and waste incineration without energy recovery. However, substitution of natural gas did not result in emission savings, due to fossil CO₂ emissions from waste incineration and relatively low efficiency of waste incineration. According to the calculations based on high marginal emission reduction costs, net emissions were negative when waste incineration was assumed to be widely applied replacing coal combustion in electricity generation. However, these calculations are exemplary only. The estimates are highly dependent on the assumptions used for the fossil fuel replaced and efficiency of combustion, which may change in the future. Furthermore, the energy content of waste was estimated roughly in emissions savings calculations.

Energy recovery in waste incineration or LFG recovery is not very significant for the global energy economy in the near future. However, energy recovery provides locally significant energy, improves the cost-efficiency of waste management measures, and can therefore be important for the economic potentials of waste management operations.

In the long term, with the scenario assumptions of this report, the energy contained in the waste would represent a higher fraction of the primary energy used in 2050, up to several percent. This is because waste generation is assumed to increase at a higher rate with increasing GDP than energy consumption.

As there are numerous measures to limit greenhouse gas emissions from the waste sector, and the potentials overlap, the market penetration of the measures was estimated by using the TIMES systems model. These measures included e.g. increased combustion, mechanical-biological treatment, composting, anaerobic digestion and landfill gas recovery. As the penetration of these measures will increase at least in many developed countries, the potential estimates for the year

2030 were assessed using 15 geographic regions. The data describing the characteristic features of waste, as well as the operating costs of the measures, were given by region. The technologies used are, however, considered more from an average global viewpoint. More accurate assessment of the potentials would need quite detailed consideration of regional and even local conditions.

According to the results from the TIMES model, the total economic potential for reducing global methane emissions from landfills is relatively large. At zero or negative costs, the potential was found to be 35%. At the cost level of 20 USD/t, it increased to over 60%, and at 100 USD/t it reached over 90%. The TIMES model does not include the time lag for waste decay in the landfill. If the measures were implemented in 2010 so that only 15% of generated waste would be landfilled from 2010 onwards, about 80% of the emission reductions indicated by the model results would take place by 2030. The remaining emission reductions would be realized after 2030.

At high marginal cost levels considerable changes would take place in the energy production and consumption sectors. These changes would likely dominate the changes in the waste sector. However, to achieve the maximum emission reductions, the measures should be implemented as early as in 2010. It is not likely that mitigation at the cost levels of 50–100 USD/t CO₂ eq would be achieved before 2010, and it is also unlikely that mitigation measures with the highest cost levels would take place in developing countries by 2030.

Furthermore, according to a sensitivity study, if the interest rate used in the calculations is decreased from the used 7% to 4%, some measures with relatively high investment cost, e.g. anaerobic digestion, would have a higher share in the emission reduction.

The systems approach used to estimate the potential of a set of emission reduction measures at various marginal emission reduction cost levels gives technical penetrations for the measures. In reality, these penetrations might be smaller due to local conditions which are not considered in the calculations.

Although the results indicate a substantial economic potential for the use of waste for energy, one should bear in mind that waste recycling was not included as an option in the analysis of the TIMES model. Whenever economically

feasible, increased recycling should obviously have a priority over the other options. Furthermore, none of the approaches used in this study included measures that aim at reducing waste generation, which could be an efficient measure in the long term.

Even though uncertainties in estimates of future emissions and mitigation potentials of solid waste disposal are large, the scenarios were compiled in a systematic way, and are therefore comparable between different regions and different points of time.

The two different approaches used in this study – one estimating potential by assuming inertia in technology penetration and changes in waste management systems, and the other estimating maximum economic potential using marginal cost levels – give a wide perspective for the possible future emission mitigation in the solid waste disposal. The mitigation potential by 2030 given by the two approaches varied between 30% and 75% for the *Baseline* emissions. The future mitigation potential may realistically lie somewhere between these two numbers. The highest mitigation potentials can be reached in 2030 and 2050 with early implementation of measures reducing waste disposal in landfills combined with increased landfill gas recovery.

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Title Global climate change mitigation scenarios for solid waste management			
Abstract The waste sector is an important contributor to climate change. CH ₄ produced at solid waste disposal sites contributes approximately 3–4 percent to the annual global anthropogenic greenhouse gas emissions. Emissions from solid waste disposal are expected to increase with increasing global population and GDP. On the other hand, many cost-efficient emission reduction options are available. The rate of waste degradation in landfills depends on waste composition, climate and conditions in the landfill. Because the duration of CH ₄ generation is several decades, estimation of emissions from landfills requires modelling of waste disposal prior to the year whose emissions are of interest. In this study, country- or region-specific first-order decay (FOD) models based on the 2006 IPCC Guidelines are used to estimate emissions from municipal solid waste disposal in landfills. In addition, IPCC methodology is used to estimate emissions from waste incineration. Five global scenarios are compiled from 1990 to 2050. These scenarios take into account political decision making and changes in the waste management system. In the Baseline scenario, waste generation is assumed to follow past and current trends using population and GDP as drivers. In the other scenarios, effects of increased incineration, increased recycling and increased landfill gas recovery on greenhouse gas (GHG) emissions are assessed. Economic maximum emission reduction potentials for these waste management options are estimated at different marginal cost levels for the year 2030 by using the Global TIMES model. Global emissions from landfills are projected to increase from 340 Tg CO ₂ eq in 1990 to 1500 Tg CO ₂ eq by 2030 and 2900 Tg CO ₂ eq by 2050 in the Baseline scenario. The emission reduction scenarios give emissions reductions from 5% (9%) to 21% (27%) compared to the Baseline in 2030 (2050). As each scenario considered one mitigation option, the results are largely additive, and the total mitigation potential can be assumed to be up to 30% in 2030 and 50% in 2050. The most favourable mitigation scenario was High landfill gas recovery scenario where increased rates of landfill gas recovery were assumed in developed and developing countries. In developing countries CDM type activities have appeared to be favourable mechanisms to stimulate this development. Due to the time lag in the emissions from landfills, the impact of increased recycling and incineration in mitigating the emissions from the waste sector is seen more slowly than that of landfill gas recovery. According to the calculations of economic potentials, one third of global CH ₄ emissions from landfills could be reduced at zero to negative costs in 2030. Below 10–20 USD/t CO ₂ eq, more than half of the emissions could be reduced. The economic maximum potential would be approximately 75% in 2030 when compared with the Baseline, but due to the time lag between waste disposal and emissions, this would be reached only if measures with very high marginal cost levels could be implemented in 2010. These assessments of potentials based on specific assumptions are appropriate for generalized global comparisons; however, more accurate assessment of the potentials would need more detailed consideration of regional and local conditions.			
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The waste sector is an important contributor to climate change. CH₄ produced at solid waste disposal sites contributes approximately 3–4 percent to the annual global anthropogenic greenhouse gas emissions. Emissions from solid waste disposal are expected to increase with increasing global population and GDP. On the other hand, many cost-efficient emission reduction options are available. In this study, global emissions scenarios for the waste sector are compiled from 1990 to 2050. These scenarios take into account the time lag in emission generation in landfills, political decision making and changes in the waste management system. In addition, maximum economic potentials of mitigation measures at different marginal cost levels are calculated using linear optimisation at the global scale for the year 2030.

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