Potential for Reducing Global Methane Emissions From Landfills, 2000-2030

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SUMMARY. Global generation of municipal solid waste (MSW) is now ~1200 Tg/yr (1 Tg = 10^{12} g), >70% of which is landfilled. Landfilling of waste contributes ~30-35 Tg methane (CH_4) annually to the world's total CH_4 emission of ~550 Tg/yr. Recycling and thermal treatment of waste in waste-to-energy (WtE) facilities contribute equally to diverting MSW from the waste stream destined for landfills and to mitigating CH_4 emission. Waste generation is estimated to more than double by 2030 indicating that CH_4 emission from waste will rise substantially in the absence of strong policies to reduce landfilling rates. To investigate the potential for future mitigation of methane emission from landfills, we developed reference projections of waste generation, recycling and landfill-gas capture, together with four WtE scenarios ranging from very conservative to very aggressive. Based on these scenarios, global 2030 CH_4 emission, including reductions from recycling, range from 86 Tg (most conservative) to 27 Tg (most aggressive). WtE appears to provide the best option for limiting future waste-related emission.

1. INTRODUCTION

Global mean annual temperature is predicted to increase by several degrees by the end of the 21st century, if greenhouse-gas emissions continue unabated. Hansen et al. (2006) conclude that additional warming of more than 1°C relative to 2000 will produce "highly disruptive" impacts; this represents a total warming of 2˚C relative to pre-industrial climate. Several years ago, Hansen et al. (2000) argued that the rapid warming observed in recent decades was driven primarily by non-CO_2 greenhouse gases and that a climate target of 1˚C warming in the 21st century, considered to be below the dangerous level, could be achieved by controlling both CO_2 and non-CO_2 emissions of methane and black-carbon aerosols. Addressing only CO_2 emissions would require stabilizing atmospheric CO_2 at 450 ppm, not far above the current level of about 380 ppm; controlling both CO_2 and non-CO_2 greenhouse gases (GHG), would allow CO_2 concentrations to stabilize at a higher level (550 ppm) affording a better chance of success. This model-based "Alternative Scenario" quantified the magnitude of required reduction in non-CO_2 emissions but did not address specifics of how and which reductions of non-CO_2 greenhouse gas emissions would be achieved.

Many modeling studies involving numerous scenarios of economic, energy and population futures and of the corresponding emissions of greenhouse gases and climate-relevant particulates (sulfate, carbonaceous) have been undertaken during the last decade. The Intergovernmental Panel on Climate Change (IPCC) supported a major effort resulting in the Special Report

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Emissions Scenarios (SRES) (Nakicenovic et al., 2000) and follow-on scenario work has been continued within several groups and institutions including IIASA and the Energy Modeling Forum. The SRES scenarios are described as "alternative images of the future" and the emission results are widely used in climate and chemistry models. However, while much has been learned about potential ranges of future climate and chemistry responses to modeled emissions, the studies remain primarily sensitivity studies in that no scenarios are identified as more likely to occur than others. Thus, evaluating the effects of likely futures, of implementing plausible mitigation strategies and of identifying policies that will support such strategies has received much less attention. The study reported here is designed to address this major gap in the field. The study presented here is part of a larger project investigating climate implications of plausible trajectories of methane emission from all sources, with and without implementation of mitigation strategies. We will use these scenarios of methane emissions, together with others for carbonaceous aerosols and a suite of related gases (CO_2, SO_2, VOC, CO etc.) in the Global Climate/Chemistry Model of NASA's Goddard Institute for Space Studies to investigate the consequences of unmitigated and mitigated emissions on 21st century climate and to quantify the potential impact of various policy strategies on limiting climate change by century's end.

We report initial results for plausible future trends in waste generation, recycling, waste-to-energy capacity, and landfill-gas capture. The estimates are anchored with data for 2000-2005 and projected through 2030. We developed single reference scenarios for waste generation, recycling and gas capture that represent conservative development of these components. We developed four WtE scenarios based on these reference projections that investigate the potential for reduction in landfilling of MSW and in net methane emission; WtE assumptions range from extremely conservative WtE development (constant capacity between 2000 and 2030) to accelerated implementation of capacity (10%/year) from 2010-2030 requiring major governmental legislation and economic incentives.

2. BACKGROUND

2.1 The Role of Waste and Landfills in the Global Methane Budget

Bingemer and Crutzen (1987) published the first global estimate of methane emission from landfills reporting a high value of 70 Tg CH_4/yr which is the net effect of estimates for waste generation (low) and fraction of degradable organic carbon (DOC) anaerobically dissimilated to CO_2 or CH_4 (high); oxidation within the landfill and landfill gas capture, which both reduce methane emission, were not considered. Dissimilated DOC was assumed to be 0.77 corresponding to a methane yield of 0.10 kg CH_4/kg dry solid waste; later studies suggest that lower values may better represent field conditions. Using an energy proxy to estimate MSW generation, Bogner and Matthews (2003) estimated that landfilled MSW increased from ~475 Tg in 1980 to 625 Tg in 1996. Applying IPCC default methods for estimating CH_4 emission from landfills but using a lower value for dissimilated DOC (0.5), and incorporating oxidation within the landfill (0.1 of produced CH_4) and landfill-gas capture (3.8 Tg or 18% of produced methane in 1996), they report global net emissions of ~17 CH_4 in 1996 implying a CH_4 yield of 0.03 kg CH_4/kg dry solid waste. However, global CH_4 production and emission are likely underestimated. E.g., based on comparisons of measured and predicted waste generation for individual countries, waste generation is underestimated by ~35% for industrialized countries that constitute the bulk of generated waste. In this case, gross production and net emission of methane are underestimated, and the net emission for 1996 is probably closer to 26 Tg. USEPA (2006) estimates that global net CH_4 emission from landfills is ~36 Tg for 2000. They also used IPCC methods to estimate waste generation and methane production but included both oxidation and gas capture in their estimate. With the exception of the early study of Bingemer and Crutzen (1987), these studies indicate that landfills contribute between 5-10% of global methane emissions or about 10% of the anthropogenic fraction. However, none of them explicitly estimates the impact of thermal treatment of waste (waste-to-energy) (WtE) and recycling on landfilling rate and on subsequent CH_4 emission from landfills.

2.2 Approaches to Estimating Methane Emission From Landfills

Bogner and Matthews (2003) presented the IPCC method for estimating methane emission from landfills as follows (IPCC, 1996):

Methane emitted (Tg/yr) =

$$[MSW_t * MSW_f * MC_f * DOC * DOC_f * F * (16/12)] - R * (1- OX) \qquad (1)$$

where:
MSW_t = total municipal solid waste (MSW) generated (Tg/yr).
MSW_f = fraction MSW disposed in engineered landfill
MC_f = methane correction factor (fraction MSW decomposing anaerobically)
DOC = fraction biodegradable organic carbon in MSW
DOC_f = fraction DOC dissimilated (converted to methane or carbon dioxide)
F = methane fraction of landfill gas; default is 0.5
R = recovered methane (Tg/yr); assumes active extraction system
OX = methanotrophic oxidation factor (fraction); default is 0

The IPCC approach relies on country- or region-specific values for per capita production rates of municipal solid waste (MSW), trash-composition profiles, landfilling rates, oxidation rate within the landfill and other variables. As applied in estimating emissions, the default values for these terms remain constant over time. Due to the difficulty of obtaining data on changing solid-waste production, Bogner and Matthews (2003) developed a technique using per capita energy consumption as a proxy for per capita waste generation. In this historical study, developed countries expectedly exhibit low growth rates in waste generation and emission for 1980-1996 and an absolute decline between 1990-1996 while developing countries, with high population increases and rapid urbanization, show increasing emissions that are likely to continue without technological and/or legislative intervention. Since 1996, the last year reported by Bogner and Matthews (2003), substantial changes have occurred that impact waste generation, landfilling rates, and methane emission, and indicate alternative emission trends for future decades.

The new approach for estimating methane emission from landfills developed for this study relies on Bogner and Matthews' (2003) energy-based proxy to estimate waste generation by region for 2000-2030 but employs a substantially different technique to estimate the remaining components that determine landfilling rates and landfill-related methane emission. In particular, we explicitly calculate the amount of generated MSW that is recycled and that is thermally treated in waste-to-energy projects and thus diverted from landfills. This approach eliminates the use of default values for MSW_f and MC_f in the IPCC method (Eq. 1). Furthermore, we used analyses of waste composition and a global assumption for DOC to derive a direct estimate of CH_4 yield from landfilled MSW which replaces the default values of DOC_f, MC_f and OX from the calculation. Finally, as done by others, we estimate the extent of on-site methane recovery (R) updated to 2000 and projected to 2030. This new streamlined approach is written as follows:

Methane emitted (Tg/yr) =

$$[(MSW_t - MSW_{rc} - MSW_{WtE}) * Y] - R \qquad (2)$$

where:
MSW_t = total MSW generated (Tg/yr)
MSW_{rc} = recycled MSW (Tg/yr)
MSW_{WtE} = MSW thermally treated in waste-to-energy facilities (Tg/yr)
Y = methane yield in CH_4/landfilled MSW (w/w); 0.05 for DOC of 0.3
R = recovered methane (Tg/yr)

3. MSW: GENERATION, RECYCLING AND WASTE-TO-ENERGY

3.1 Waste Generation and Recycling

We developed the 2000-2030 reference time series of global annual waste generation by region using the energy-proxy approach of Bogner and Matthews (2003). We used current and projected population statistics from the UN Food and Agriculture Organization (UN FAO), and energy consumption statistics for the same period and regions from the International Energy Agency (IEA, 2006). We estimated per capita energy consumption by converting IEA's energy statistics from Mtoes (millions of tons of oil equivalent) to the unit used in Bogner and Matthews (2003) (millions of tons of coal equivalent or Mtce), and dividing by population. MSW generation was estimated from energy consumption using the 1500 kgce/capita threshold for determining which of two relationships of Bogner and Matthews (2003) to apply (high consumers > 1500 kgce/capita > low consumers); total population was used to calculate MSW for high consumers and urban population was used for low consumers. The advantage of this approach is that it captures the dual dependence of waste generation on population and living (consumer) standard and replaces the commonly-used IPCC (1996) method using default values of per capita waste generation specific to countries or regions which remain constant over time. Current rates of recycling materials from the mixed MSW stream (excluding source-separated materials) were assumed to be ~150 Tg MSW.

Fig. 1 shows annual MSW generated for 2000-2030 which is the baseline for all WtE scenarios. MSW generation more than doubles between 2000 and 2030, from about 1070 Tg/yr in 2000 to ~2300 Tg/yr thirty years later, while energy consumption (not shown) increases by 70% over the same period. Although per capita waste generation is related to per capita energy consumption, the largest absolute increase in population takes place in regions with lower per capita energy use while population growth is modest in regions where energy consumption and waste generation are both already high. Recycling, estimated at 150 Tg MSW or 14% of total waste generated in 2000, is assumed proportional to waste generation throughout the period. Thus, like waste generation, recycled MSW more than doubles by 2030, rising from 150 to 322 Tg/yr (Fig. 1). Post-recycling MSW, the maximum MSW that could be landfilled, increases from ~921 to 1980 Tg in this time period.

3.2 Waste-to-Energy: Thermal treatment of MSW

There are ~600 waste-to-energy facilities worldwide, most of them in the EU (~400), Japan (>100) and the U.S. (88). The dominant technology is combustion of as-received fuel (“mass burn”) and generation of steam that is used in steam turbines for electricity generation; in some EU nations turbine exhaust is used for district and industrial heating.

New capacity of WtE facilities for 2000-2007 by the two dominant technologies (Martin and Von Roll Inova) increased by 12.3 and 7.1 Tg, respectively. With additional construction by other technologies such as Mitsubishi Heavy Industries, Japan Steel, JFE, Ebara, Seghers-Koeppel, and the Zhejiang University fluidized bed process, total WtE capacity increased by ~28 Tg, or ~4 Tg MSW per year, between 2000 and 2007.

An estimated 140 million tons of post-recycling MSW is currently combusted in WtE facilities. Anchoring our estimates to WtE data for 2000-2005, we constructed several scenarios of waste-to-energy development through 2030. For the (conservative) reference scenario (WtERef), we assumed that WTE capacity increases by 4 Tg MSW/yr as it did during 2000-2007; for scenarios WtE5 and WtE 7.5, capacity increases by 5% and 7.5%/yr, respectively, between 2010 and 2030. The most optimistic scenario, in which the implementation of new WtE capacity rapidly accelerates to 10%/yr for 2010-2030, would require major interventions in the form of legislation and economic incentives. Since permitting and construction of WTE facilities requires 3-5 years, the WtE scenarios do not diverge until after 2010.

Fig. 1 shows the impact of multiple scenarios of WtE growth on reducing the flow of MSW to landfills. As noted above, recycling reduces MSW destined for landfills by a constant rate of 14% in all years but post-recycling MSW grows by 120% between 2000 and 2030. WtE scenarios (Fig. 1) indicate the powerful potential impact of increasing WtE capacity on lowering landfilling rates (and subsequent methane emissions). The most conservative WtE scenario (Ref) diverts 86% more MSW from landfilling in 2030 than in 2000 but landfilled MSW more than doubles. Increasingly aggressive establishment of WtE capacity slows the 2000-2030 growth of landfilled MSW to 84% (WtE5) and to 42% (WtE7.5) relative to 2000 while the most optimistic WtE10 scenario produces an absolute decline of 31% in landfilled MSW by 2030, dropping from 781 Tg in 2000 to 535 Tg in 2030. By 2030, the lower growth in landfilled MSW achievable with increased WtE capacity has the potential to reduce the global landfilling rate by a minimum of 13% (Ref) to a maximum of 73% (WtE10) relative to a recycle-only strategy in that year.

4. CH_4 PRODUCTION AND EMISSION FROM LANDFILLS

4.1 Methane Emission From Municipal Solid Waste

Methane is generated in landfills by the anaerobic bioreaction of organic matter (food and yard wastes, paper, wood, organic textiles, and leather). By using the ultimate (atomic) analysis of various types of wastes (Tchobanoglous et al., 1993) and the atomic weights of the respective elements, it is possible to derive the composite molecular formula corresponding to mixed food waste and paper:

Mixed food and green wastes: $C_6H_{9.6}O_{3.5}N_{0.28}S_{0.2}$

Mixed paper: $C_6H_{9.6}O_{4.6}N_{0.036}S_{0.01}$

Sulfur and nitrogen are relatively minor components and occur principally in mixed and green food waste and if one excludes nitrogen and sulfur, the molecular structure of mixed paper is very close to cellulose, $(C_6H_{10}O_5)_x$. Excluding minor elements and inorganic materials in MSW, the average molecular structure of the biomass in MSW can be approximated by the molecular composition $C_6H_{10}O_4$ (Themelis, 2002) which corresponds to the structural formula of at least ten organic compounds including ethyl butanedioic acid, succinic acid, adipic acid, ethylene glycol diacetate, and several others (HSC Chemistry, 2006). The maximum amount of methane generated during anaerobic decomposition can be determined from the approximate, structural formula presented above as:

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2 \quad (3)$$

According to Eq. (3), biogas produced in a landfill should consist of ~54% methane and 46% carbon dioxide. Assuming a 50-50 CH_4 to CO_2 ratio and 50% bioreaction of the biomass in landfilled MSW (Table 1), we determined the yield of methane and carbon dioxide from 1 ton of landfilled MSW for a range of potential biomass contents (30%, 40%, 50%, and 60%) with the balance consisting of moisture, petrochemicals, and inorganic materials such as metals and glass. Table 1 shows that 0.05-0.1 ton CH_4 is emitted per ton of landfilled MSW for these biomass classes. For all calculations reported here, we assume 30% biomass (DOC) and the corresponding methane yield of 0.05 t CH_4/t landfilled MSW.

4.2 Emission reduction from recycling and WtE

Recycling is estimated to avoid 8 Tg/yr in 2000 doubling to 16 Tg/yr in 2030 (Fig. 2). Under all WtE scenarios, between 4.7 and 6.4 Tg CH_4/yr of emissions are avoided between 2000 and 2010, but trends and emission vary substantially among the scenarios after 2010. Increasing waste-to-energy capacity can exert a major mitigating influence on potential future emissions from landfilled waste (Fig. 2 and 3). By 2030, WtE5 results in an 84% <u>increase</u> in emissions (from 34 to 63 Tg/yr) relative to 2000. However, despite this substantial increase, the 2030 emission is still 36% below that from the recycle-only strategy (Fig. 3). WtE7.5 expectedly produces lower emissions with a maximum of 52 Tg in 2020 declining to 49 Tg in 2030 as diversion of waste to WtE facilities overtakes increases n waste generation. These trends are equivalent to mitigation rates of 27% and 44%, respectively, relative to recycling alone in 2030. The most aggressive rate of WtE implementation—10%/yr annual increase between 2010 and 2030—would require major policy interventions and/or economic incentives to achieve. However, the results show that WtE10 produces an absolute decline of ~30% (12 Tg) in 2030 emissions relative to 2000 following a peak of 53 Tg in 2020. More striking is that the WtE10 methane emission in 2030 is 75% lower than that from a recycling-only strategy for that year.

4.3 Capture of landfill gas

The EPA Landfill Methane Outreach Project (LMOP, 2006) reports that in 2005 there were 400 LFG collection projects generating 9 billion kWh of electricity plus 74 billion standard cubic feet of biogas. On the basis of these numbers and assuming 35% thermal efficiency for conversion of biogas energy to electricity, we estimated that 2.6 Tg CH_4 was captured and utilized in the U.S. in 2005. LMOP does not provide an estimate of the LFG that is captured and then flared. Less than 1000 landfills in the world capture biogas (Themelis, 2006). For this study, we estimated that 4.7 Tg of CH_4 was captured in 2000 (Themelis, 2006) which is ~12% of the estimated CH_4 production from 780 Tg landfilled MSW in 2000. We assume this 12% capture rate of methane generated in landfills remains constant for 2000-2030. Thus, methane capture increases by 120%, from 4.7 Tg CH_4 in 2000 to 10.3 Tg in 2030 (Fig. 2).

4.4 Avoided CH_4 Emission: Recycling, WtE, and Gas Capture

Recycling is estimated to avoid 8 Tg/yr in 2000 doubling to 16 Tg/yr in 2030 (Fig. 4) assuming recycling remains a constant fraction of generated MSW. Similarly gas capture, assumed to be a constant fraction of *in situ* methane production, doubles from ~5 to 10 Tg/yr between 2000 and 2030. Avoided emissions in the WtE Ref scenario remain relatively flat, peaking at 13 Tg in 2030, while the other WtE scenarios provide substantial mitigation ranging from 27 Tg (WtE5) to 72 Tg (WtE10) in 2030 (Fig. 4). By 2030, WtE-related emission reductions lower methane emission globally by a minimum of 13% (Ref) to a maximum of 73% (WtE10) relative to emission for a recycle-only strategy.

5. DISCUSSION AND PROSPECTS

Current recycling of MSW diverts about 200 Tg/yr from the waste stream destined for landfills, thus avoiding the emission of 8 Tg CH_4/yr from landfills. The extent of recycling is difficult to determine, and may be underestimated here because informal reuse and recycling is extensively practiced in many countries. If recycling remains proportional to MSW generation as assumed here, avoided CH_4 emissions will approximately double by 2030. However, recycling will likely continue to increase particularly in EU countries and potentially in the US. The 1999 EU Landfill Directive requires that landfilling be limited to inert materials that are neither biodegradable nor combustible.

Waste-to-Energy facilities are relatively recent but capacity is increasing rapidly and is expected to continue in the coming decades despite substantial start-up costs. This strategy appears to hold the most promise for mitigation of methane emissions from MSW because the technology is developed and growth is expected to be greater than for recycling which is well established. Currently-operating waste-to-energy facilities incinerate ~150 Tg MSW/yr thereby avoiding emission of ~8 Tg CH_4/yr or ~15% of CH_4 production with a recycling-only approach. WtERef, a very conservative estimate assuming that today's annual increase in WtE capacity (4 Tg/yr) continues through 2030, results in rises in methane production and emission at landfills equal to 2.2 times 2000 levels (from 36 to 80 Tg/yr) avoiding only 13 Tg/yr in emissions in 2030 relative to recycling only. Two plausible scenarios of increasing WtE capacity—5% and 7.5%/yr between 2010 and 2030—would avoid emission of 27 and 48 Tg CH_4, respectively, in 2030 by reducing the amount of generated MSW that is landfilled. Globally, about 73% of generated MSW is currently landfilled; recycling and WtE contribute about equally to diverting MSW from the waste stream destined for landfills. Increasing WtE capacity by 5% and 7.5%/yr between 2010 and 2030 would reduce landfilling to 62% and 48%, respectively, of generated MSW by 2030 relative to recycling only. A 10%/yr increase in WtE capacity results in a decline to 27 Tg/yr in CH_4 emission which is ~30% below that in 2000. For WtE10, avoided CH_4 emission in 2030 is 72 Tg relative to no WtE capacity in that year. The substantial emissions avoided by increasing WtE capacity are augmented by those avoided through methane capture at landfills (3-10 Tg/yr by 2030).

Increasing waste-to-energy capacity appear to provide the greatest potential for controlling future methane emission from landfilled waste. Attaining the accelerated growth of WtE10 will require wide implementation of supportive policies (such as those enacted in E.U. and Japan where landfilling of decomposable material is banned) and provision of economic incentives for the recovery of energy from MSW. WtE development provides several additional benefits including avoiding the increasingly difficult and frequent necessity of building landfills near large population centers, and reducing primary fossil fuel use and associated greenhouse-gas emissions by providing energy from WtE facilities.

REFERENCES

Bingemer, H. G. and P. J. Crutzen, The production of methane from solid wastes, *J. Geophys. Res.*, 92, 2181-2188, 1987.

Bogner, J., and E. Matthews, Global methane emissions from landfills: New methodology and annual estimates 1980-1996, *Global Biogeochem. Cycles*, 17 (2), 1065, doi:10.1029/2002GB001913, 2003.

Hansen, J., Mki. Sato, R. Ruedy, A. Lacis, and V. Oinas, Global warming in the twenty-first century: An alternative scenario. *Proc. Natl. Acad. Sci.*, 97, 9875-9880, doi:10.1073/pnas.170278997, 2000.

Intergovernmental Panel on Climate Change (IPCC), *Revised 1996 Guidelines for National Greenhouse Gas Inventories,* Workbook and Reference Manual, 1996.

Intergovernmental Panel on Climate Change (IPCC), Chapter 5. Waste, *IPCC Good Practice Guidance and Uncertainty Management in National Greenhouse Gas Inventories*, Corrigendum (GPGAUM-Corr.2001.01, 15 June 2001), www.ipcc.nggip.iges.or.jp./public/ gp/pdf/5-waste.pdf, 2001.

International Energy Agency (IEA), *World Energy Outlook 2006*, IEA, Paris, 2006.

Landfill Methane Outreach Project (LMOP), www.epa.gov/lmop/docs/map.pdf, 2006.

Nakicenovic, N. et al., *Special Report on Emissions Scenarios*, IPCC, Paris, 2000.

Tchobanoglous, G., H. Theisen and S. Vigil, *Integrated Solid Waste Management*, NY, McGraw-Hill, 1993.

Themelis, N.J., Y. H. Kim, and M. H. Brady, Energy recovery from New York City municipal solid wastes, *Waste Manag. & Res.*, 20 (3), 223-233, 2002.

Themelis, N.J. and P. Ulloa, Methane generation in landfills, *Renewable Energy J.*, Elsevier, http://www.aseanenvironment.info/Abstract/41014160.pdf, 2006.

U. S. EPA, *Global Anthropogenic Non-CO2 Greenhouse Gas Emissions: 1990-2020*, USEPA, Washington, D.C., 2006.

Table 1. Waste characteristics and yield of CH_4 and CO_2 per landfilled ton of dry MSW.

fraction dry biomass in MSW	0.3	0.4	0.5	0.6
fraction C in biomass	0.148	0.197	0.247	0.296
t C/t MSW	0.148	0.197	0.247	0.296
t C reacted at 0.5 bioreaction	0.074	0.099	0.123	0.148
t C reacted to CH_4	0.0375	0.05	0.062	0.075
t CH_4 generated	0.05	0.067	0.083	0.1
t CO_2 eq. as CH_4 in biogas	1.046	1.394	1.743	2.092
t C reacted to CO_2	0.0375	0.049	0.061	0.073

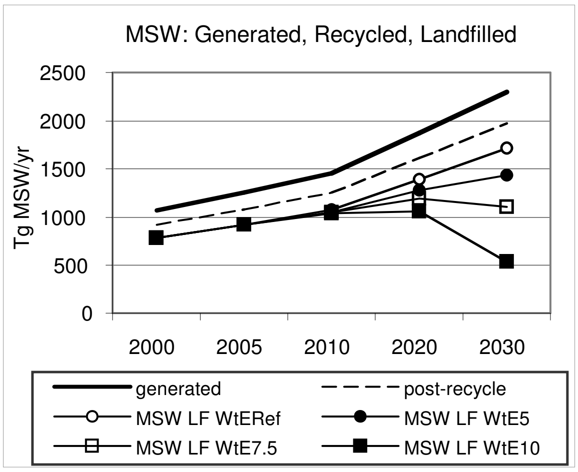

Fig. 1. Generated and post-recycle MSW (constant for all scenarios) and landfilled MSW under four WtE scenarios

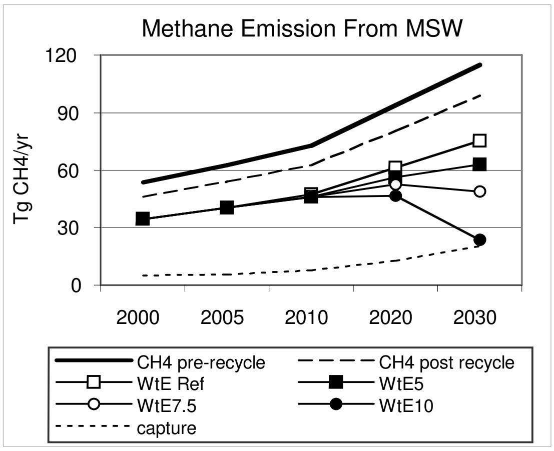

Fig. 2. Impact of WtE growth on net methane emission from MSW. The solid line, potential maximum, is included for reference only.

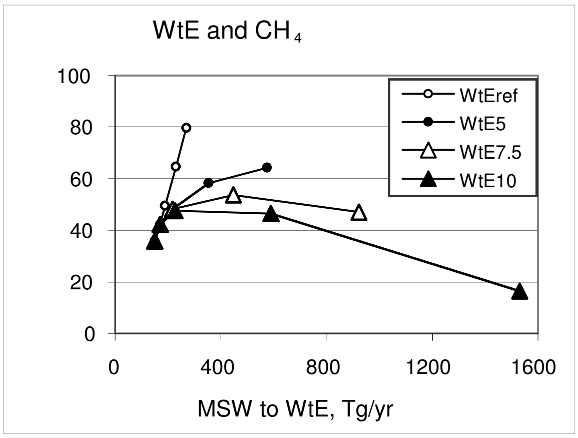

Fig. 3. Impact of WtE capacity on methane emission from landfills. Values plotted for 2000, 2005, 2010, 2020 and 2030 for each scenario.

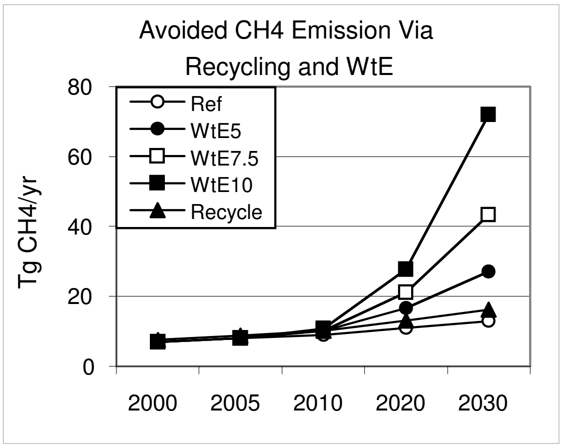

Fig. 4. Avoided CH_4 emission under four WtE growth scenarios.