Highlights – Understanding of Biodegradation

- Over 60% of respondents claimed they understand the meaning of “biodegradable” quite well*.
  - Of all the venues in which respondents were asked where products labelled biodegradable would decompose, “landfills” received the highest score (72%) followed by “open environment” (51%) and “commercial composting” (51%)
  - 4 out of 5 (80%) respondents believe biodegradation in landfills is dissimilar to biodegradation in a composting environment
  - More than half of the respondents (55%) were unaware that landfills currently capture gases generated as a result of biodegradation and convert them to energy

*When asked to rate their understanding of the word biodegradable on a 5-point scale where 5 = I know it very well and can explain it to someone, 64% of respondents rated their understanding as being a 4 or 5.

“What are the differences between biodegradation in landfills vs. biodegradation in composting environments?”

- Many respondents attributed the differences to composition (27%), degradation process (26%), and/or duration of degradation (23%).
  - Respondents defined composition as what exactly goes into each environment and their levels of aeration
  - For the degradation process, respondents cited the end product of landfills as garbage and as soil for compost piles. Also they compared the ability of one over another to biodegrade matter, and referenced a presence of additives
  - Of those who mentioned factors related to the duration of degradation, the majority said landfills take longer to biodegrade

Highlights – Biodegradation of Plastics

- A good majority of respondents (72%) believe traditional plastics will not biodegrade on their own.
  - Those who think plastics do biodegrade on their own think it mainly happens in landfills or commercial composting sites
- A large number of respondents (84%) believe biodegradable plastic products will be beneficial to landfills.
  - 74% believe biodegradable plastics will reduce the burden on landfills
- 7 out of 10 (70%) respondents were okay with a 5 year or less window for duration of the biodegradation of biodegradable plastic packages.
  - 25% of respondents believe plastics should biodegrade in less than one year

Highlights – Package Labeling

- An overwhelming number of respondents (93%) think it is okay to label a package “biodegradable” if it decomposes in a landfill.
- A majority of respondents (63%) think it is not okay to label a package “biodegradable” if it only decomposes in a commercial composting facility and not in their back yards.

"What information would you like to see on a package labeled biodegradable?"

- Most respondents would like to know how long it takes a package to biodegrade (39%), where it biodegrades (27%), the conditions under which it biodegrades (18%), and/or what to do with the package when they're done with it (10%).

- A handful of respondents also want to know if the product was safe to use and not harmful once disposed of.
  - Examples: "Will biodegrade in less than 5 years in any environment. But, none of the chemicals used to make this new biodegradable product harmful to our health as we drink or eat from it."
  - "Safety of the by-products and the time to completely biodegrade."

Highlight – Attitude towards "green"

- Less than 2 out of 5 (38%) respondents claimed they often or always check for green aspects on a product label.

- Of the 6 attributes that contribute toward lowering a product's burden on the environment, respondents believe "biodegradable" and "recyclable" are the most important.

- Over 6 out of 10 (62%) respondents stated they are willing to pay a higher price for products that are less burdensome on the environment.

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Methane generation in landfills

Nickolas J. Themelis*, Priscilla A. Ulloa

Earth Engineering Center and Department of Earth and Environmental Engineering, Columbia University, New York, NY 10027, USA

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Abstract

Methane gas is a by-product of landfilling municipal solid wastes (MSW). Most of the global MSW is dumped in non-regulated landfills and the generated methane is emitted to the atmosphere. Some of the modern regulated landfills attempt to capture and utilize landfill biogas, a renewable energy source, to generate electricity or heat. As of 2001, there were about one thousand landfills collecting landfill biogas worldwide. The landfills that capture biogas in the US collect about 2.6 million tonnes of methane annually, 70% of which is used to generate heat and/or electricity. The landfill gas situation in the US was used to estimate the potential for additional collection and utilization of landfill gas in the US and worldwide. Theoretical and experimental studies indicate that complete anaerobic biodegradation of MSW generates about 200 Nm^3 of methane per dry tonne of contained biomass. However, the reported rate of generation of methane in industrial anaerobic digestion reactors ranges from 40 to 80 Nm^3 per tonne of organic wastes. Several US landfills report capturing as much as 100 Nm^3 of methane per ton of MSW landfilled in a given year. These findings led to a conservative estimate of methane generation of about 50 Nm^3 of methane per ton of MSW landfilled. Therefore, for the estimated global landfilling of 1.5 billion tones annually, the corresponding rate of methane generation at landfills is 75 billion Nm^3. Less than 10% of this potential is captured and utilized at this time.

Keywords: Landfill gas; Renewable energy; Municipal solid waste; Biogas; Methane emissions

*Corresponding author. Tel.: 1 212 854 2138; fax: 1 212 854 5213.
E-mail addresses: njt1@columbia.edu (N.J. Themelis), pau2102@columbia.edu (P.A. Ulloa).

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1. Introduction

Part of the methane generated in landfills can be captured and used as a renewable energy source. In contrast, when methane is allowed to escape to the atmosphere, it has a global warming potential that IPPC [1] estimates to be 23 times greater than that of the same volume of carbon dioxide. In his 2003 review of energy recovery from landfill gas, Willumsen [2,3] reported that as of 2001 there were about 955 landfills that recovered biogas or landfill gas. The largest number existed in the US followed by Germany and United Kingdom (Table 1). The capacity of most landfill gas-fuelled generators ranged from 0.3 to 4 MW. While the largest biogas plant in the world is at the Puente Hills landfill, close to Los Angeles California; the biogas is combusted in a steam boiler that powers a 50-MW turbine generator [4].

Willumsen also provided detailed information on 21 landfills in Denmark that in total captured about 5800 Nm^3 of biogas/h, equivalent to 27.4 MW of contained thermal energy. For comparison purposes, Denmark captures 20,000 tonnes of methane/y, while the US captures 2,600,000 tonnes.

1.1. US landfilling

In 2002, the Earth Engineering Center of Columbia University collaborated with BioCycle journal in a US-wide survey of the amount of municipal solid wastes (MSW) generated in the US and how they were disposed [5,6]. The results are summarized and compared with USEPA values [7] in Table 2 below.

Table 1
Energy recovering landfills [3]

Country	Number of plants
United States	325
Germany	150
United Kingdom	135
Sweden	70
Holland	60
Italy	40
Canada	25
Australia	25
Denmark	21
Norway	20
Austria	15
France	10
Spain	10
Switzerland	10
Finland	10
Poland	10
Brazil	6
Czech Republic	5
Hungary	5
China	3
Total	955

Table 2
Generation and fate of MSW in the US [5–7]

	14th SOG survey [3,4]		USEPA 2001 survey [5]	
	Million tonnes/yr	(%)	Million tonnes/yr	(%)
Amount generated	336	100	211	100
Amount recycled and composted	90	26.7	65	30.8
Amount to waste-to-energy	26	7.7	27	12.8
Amount landfilled	220	65.6	119	56.4

1.2. Global landfilling

The per capita generation of MSW in the US of 1.19 tonnes is twice as large as the total generation (i.e. before any recycling) of MSW per capita in the affluent nations of E.U. and Japan. This is expected because the consumption of materials and fossil fuels in the US, with 5% of the world population, amounts to 20–25% of the total global consumption.

To arrive at a rough estimate of global landfilling, we started with the known rate of landfilling in the US (220 million tonnes). The European Union (EU), and the rest of the ‘‘golden billion’’ who enjoy a high standard of living generate an estimated 420 million tonnes of MSW of which at least 210 million tonnes (50%) are landfilled. Waste management studies in developing nations, including some in Africa, have shown that the MSW generation is always higher than 0.2 tonnes per capita, most of which is food and yard wastes and is landfilled. This results in the estimate of 1080 million tonnes for the 5.4 billion people in the developing world. Adding up these estimates indicates that the global MSW landfilled is somewhere close to 1.5 billion tonnes of MSW.

2. Landfill dumps and regulated landfills

Broadly, landfills can be classified into two types. The most common ones, still used throughout the developing world, consist of dumps where the MSW is deposited until it reaches a height that for esthetic or technical reasons is considered to be the desirable maximum. After closing a landfill, some soil is deposited on top.

In October 1988, the US Environmental Protection Agency (USEPA) reported to the Congress that municipal solid wastes were landfilled in nearly 6,500 landfills. Although these landfills used a wide variety of environmental controls, they posed significant threats to groundwater and surface water resources, as well as health effects due a threat to air and water. To address these concerns, and standardize the technical requirements for MSW landfills, USEPA promulgated revised minimum federal criteria for MSWLFs on October 9, 1991 [8]. As a result of these more stringent regulations, many of the smaller landfills were closed and at the present time there are only 1767 landfills EPA [7]. Large landfill operations have taken advantage of economies of scale by serving large geographic areas and accepting other types of wastes, such as commercial solid waste, non-hazardous sludge, and industrial non-hazardous solid wastes. In 2000, an estimated 75% of the US municipal solid waste was deposited in 500 large landfills [9].

Regulated landfills are provided with impermeable liners and caps, and leachate collection and treatment systems. Also, a system of gas wells and pipes collects as much as possible of the landfill gas (LFG) and conveys it to a boiler or turbine where it is combusted to generate heat or electricity, or is simply flared. When the landfilled area reaches its maximum height, it is covered with an impervious layer so as to minimize entry of rainwater and, thus, continuation of the bioreactions within the landfill. Also, US landfill operators are required to continue collecting and treating gas and liquid effluents for a period of 30 years after closure of the landfill.

A variation of the regulated landfill that is being tested in the US with some measure of success is the "bioreactor" landfill. In this case, instead of preventing water from entering, the aqueous effluent is recirculated and distributed throughout the landfill. The objective is to accelerate the rate of biochemical degradation of the MSW, thus increasing the generation of methane gas and, because of increased settling, the storage capacity of the landfill.

The European requirements for non-hazardous, Class II landfills are similar to the US and are based on the standards established by French regulations in January 1996. However, the EU Landfill Directive of 1999 [10] requires that in the near future, landfilling be limited to inert materials that are not biodegradable or combustible. Nevertheless, it may take decades before this directive is applied in the new nations joining the EU, so the generation of landfill gas will continue for the foreseeable future. In contrast to the EU and Japan, landfilling remains the preferred means of MSW disposal in the US.

3. Composition of biomass in MSW

Table 3 is based on the characterization of US MSW [7]. Biomass materials, i.e. paper, food and yard wastes, wood, leather, cotton and wool, constitute 69.5% of the MSW and petrochemicals another 15%. The rest are inorganic materials such as metals, glass, gypsum, and other minerals.

By using the ultimate (atomic) analysis of various types [11] of wastes and the atomic weights of the respective elements, it was possible [12] to derive the composite molecular formulae corresponding to mixed food wastes and paper:

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

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

It can be seen that sulfur and nitrogen are relatively minor components and occur principally in mixed and green food wastes. Also, if one excludes nitrogen and sulfur, the molecular structure of mixed paper is very close to cellulose, $(C_6H_{10}O_5)_x$. If one excludes

Table 3
Characterization of US MSW by USEPA [7]

Biomass components	(%)	Petrochemical components	(%)
Paper/board	36.2	Plastics	11.3
Wood	5.8	Rubber, nylon, etc.[a]	3.7
Yard trimmings	12.1		
Food scraps	11.7		
Cotton, wool, leather[a]	3.7		
Total biomass	69.5%	Total man-made	15.0%

[a]Rubber, leather and textiles category of USEPA was assumed to be divided equally between natural and man-made products.

the minor elements, the average molecular structure of organic compounds in MSW can be approximated by the molecular composition $C_6H_{10}O_4$ [12]. It is interesting to note that this composition corresponds to the structural formula of at least ten organic compounds, such as ethyl butanedioic acid, succinic acid, adipic acid, ethylene glycol diacetate, and others. The thermodynamic heat of formation of most of these compounds is about −960 MJ per kmol.

Landfill gas is a product of biodegradation of refuse in landfills, and it contains primarily methane (CH_4) and carbon dioxide (CO_2), with trace amounts of non-methane organic compounds (NMOC) that include air pollutants and volatile organic compounds [13]. Table 4 shows the main compounds and their proportion of LFG.

3.1. Anaerobic biodegradation of MSW in landfills

Shortly after MSW is landfilled, the organic components start to undergo biochemical reactions. In the presence of atmospheric air, that is near the surface of the landfill, the natural organic compounds are oxidized aerobically, a reaction that is similar to combustion because the products are carbon dioxide and water vapor. However, the principal bioreaction in landfills is anaerobic digestion that takes place in three stages. In the first, fermentative bacteria hydrolyze the complex organic matter into soluble molecules. In the second, these molecules are converted by acid forming bacteria to simple organic acids, carbon dioxide and hydrogen; the principal acids produced are acetic acid, propionic acid, butyric acid and ethanol. Finally, in the third stage, methane is formed by methanogenic bacteria, either by breaking down the acids to methane and carbon dioxide, or by reducing carbon dioxide with hydrogen. Two of the representative reactions are shown below.

Acetogenesis

$$C_6H_{12}O_6 \rightarrow 2C_2H_5OH + 2CO_2. \tag{1}$$

Methanogenesis

$$CH_3COOH \rightarrow CH_4 + CO \tag{2}$$

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O. \tag{3}$$

The maximum amount of natural gas that may be generated during anaerobic decomposition can be determined from the approximate, simplified molecular formula that was, presented above:

$$C_6H_{10}O_4 + 1.5H_2O = 3.25CH_4 + 2.75CO_2. \tag{4}$$

Table 4
Composition of landfill gas [13]

Compound	Average concentration (%)
Methane (CH_4)	50
Carbon dioxide (CO_2)	45
Nitrogen (N_2)	5
Hydrogen sulphide (H_2S)	<1
Non-methane organic compounds (NMOC)	2700ppmv

This reaction releases a very small amount of heat and the product gas contains about 54% methane and 46% carbon dioxide. The biogas, or landfill gas, also contains water vapor near the saturation point corresponding to the cell temperature, plus small amounts of ammonia, hydrogen sulfide and other minor constituents. Therefore, in order for anaerobic reaction to continue, it is necessary to supply the principal reagent, water.

The ratio of the molecular weights of the composite organic compound (MW = 146) and water (MW = 18) in Eq. (4) indicates that each kilogram of water can react biochemically with 5.4 kg of organics. Since on the average, MSW contains at least 20% moisture, there is just about sufficient moisture to react the contained biomass. However, the anaerobic bacteria thrive at water concentrations above 40%, so continuous addition of water is required.

3.2. Generation of methane per tonne of MSW

The typical MSW of Table 3 contains 69.5% of biomass materials. This includes the contained moisture and inorganic dirt particles. Assuming that the dry organics amount to 60% of the biomass results in the estimate of 417 kg (2.86 kmol) of $C_6H_{10}O_4$ /tonne of total MSW. A simple material balance based on Eq. (4) shows that complete reaction of one tonne of MSW would generate 208 standard cubic meters of methane biogas or 0.149 tonnes of methane (1 kmol of CH_4 is equal to 22.4 Nm^3).

We shall now compare the above theoretical numbers with reported data of anaerobic digestion in the literature. The rate of biodegradation of MSW in landfills was studied by Barlaz et al. [14] in small pilot plant columns that provided ideal temperature and concentration conditions for bioreaction. As shown in Fig. 1, the reaction peaked at less than one hundred days and was nearly complete after about 320 days. Barlaz [15] estimated that the total amount of gas generated during this period was 213 Nm^3

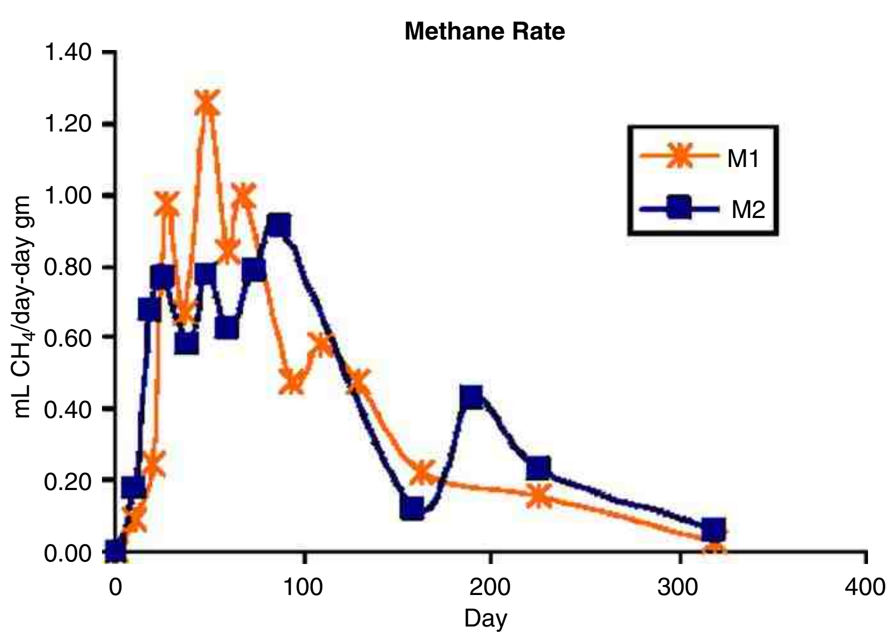

Fig. 1. Generation of methane in experimental apparatus simulating landfill bioreactions (M1 and M2 denote two different tests; [14]).

methane /dry tonne of biomass reacted (i.e. 0.153 tonnes methane /tonne of biomass). This number is in good agreement with the theoretical calculation presented above.

An analysis of several anaerobic digestion operations by Verma [16] showed that the reported rate of generation of biogas ranged from 100 to 200 Nm^3 of biogas (54–108 Nm^3 CH_4) per tonne of wastes digested (estimated 60% biomass content). These numbers correspond to generation rates from 73 to 135 Nm^3 methane per tonne of dry biomass. Therefore, during the two weeks or so of digestion in the anaerobic digestion reactor, the degree of bioreaction ranges from 35% to 65% of that projected by Eq. (4).

In an earlier publication, Barlaz et al. [17] reported that methane generation rates at a landfill receiving 286,000 tonnes /y ranged from 0 to 90 Nm^3 /min. Assuming the mid-range rate of generation of 45 Nm^3 per minute and that most of the gas is generated during the first year after the MSW is landfilled, indicates that about 83 Nm^3 or 0.12 tonnes of methane were generated /tonne of MSW.

It is interesting to note that the maximum capacity of landfilled MSW to produce methane was reported by Franklin [18] to be 62 standard m^3 of methane per tonne of MSW.

4. Estimates of global generation of methane from landfilling

USEPA estimated that the total anthropogenic emissions of methane were 282.6 million tonnes in 2000 [19], of which 13% or 36.7 million tonnes were due to landfill emissions (Fig. 2). We will now attempt to assess the accuracy of this number.

As shown earlier, the global MSW landfilled was estimated at about 1.5 billion tonnes of MSW. If it is assumed, on the basis of the data presented above, that on the average the methane generation is at least 50 Nm^3 of methane per tonne of MSW (i.e., at the low level of reported anaerobic digestion rates), the global generation of methane from landfilled MSW is in the order of 75 billion standard cubic meters or 54 million tonnes of methane.

Stern and Kaufman [20] extrapolated the 1985 estimate of Subak et al. [21] of 36 million tonnes of CH_4 to earlier years, by assuming that MSW generation and landfilling were

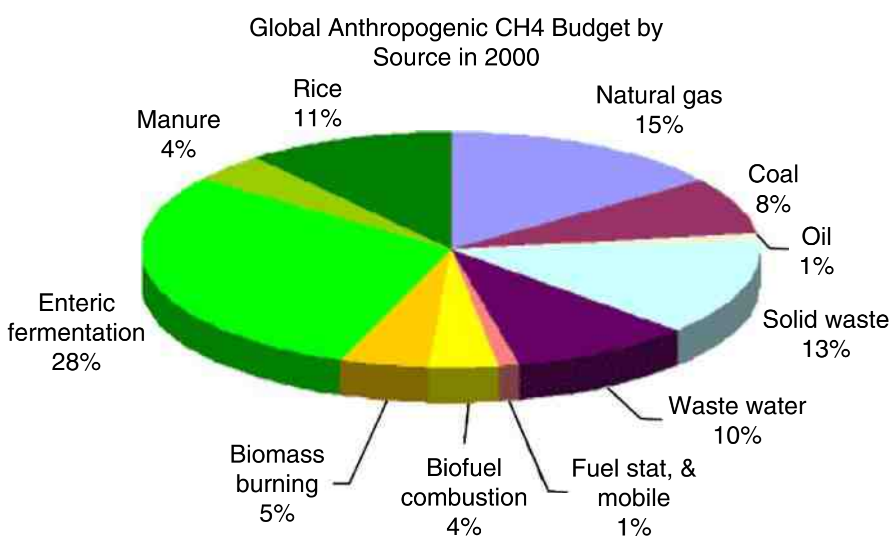

Fig. 2. Global anthropogenic methane [19].

proportional to economic growth. On the basis of this assumption, and considering that the global economic growth from 1985 to 2000 was 58% [22], the 36 million tonnes of methane in 1985 extrapolate to 57 million tonnes in 2000. This number is in fairly good agreement with the 54 million tonnes estimated by the present authors and is substantially higher than the 36.7 million tonnes estimated by USEPA.

5. Capture of landfill gas

As mentioned earlier, modern landfills try to collect the biogas produced by anaerobic digestion. However, the number of gas wells provided is limited (US average: about 1 well / 4000 m^2 of landfill [18]), so that only part of the biogas is actually captured.

Table 5 presents reported captured and estimated loss of methane for 25 landfills in California. The landfilled MSW is reported by California Integrated Waste Management Board [23] and the captured biogas was reported by Berenyi [24] and converted to methane by multiplying by 54%. On the average, the captured methane amounted to 43 Nm^3 per tonne of MSW and the estimated methane loss to 82 Nm^3 per tonne of MSW.

Table 5
Landfill methane in California [23,24]

Landfill name	MSW (Tonnes/yr)	Captured CH_4 (Nm3/yr)	Captured CH_4 (Nm^3/t MSW)	Assumed generation (Nm^3/t MSW)	Estimated loss CH_4 (Nm^3/ t MSW)
Altamont	1,157,312	24,001,656	21	122	101
Scholl Canyon	412,429	50,237,893	122	122	
Azusa	157,445	17,056,769	108	122	14
Puente Hills #6	3,377,867	200,549,669	59	122	63
Bradley Avenue West	418,341	40,190,314	96	122	26
Crazy Horse	151,258	4,822,838	32	122	90
Monterey Peninsula	197,797	3,351,872	17	122	105
Prima Deshecha	703,051	11,253,288	16	122	106
Olinda Alpha	1,877,620	17,862,362	10	122	112
Frank Bowerman	1,991,666	20,095,157	10	122	112
Sacramento Co (Kiefer)	615,702	16,076,126	26	122	96
Colton Refuse Disposal Site	305,682	13,664,707	45	122	77
San Timoteo	158,405	2,154,647	14	122	108
Otay Annex	1,267,641	11,164,869	9	122	113
Miramar	1,289,295	28,334,172	22	122	100
Sycamore	817,255	6,695,706	8	122	114
Tajiguas	200,084	9,766,246	49	122	73
Newby Island	592,877	17,683,738	30	122	92
Kirby Canyon	246,902	3,633,204	15	122	107
Guadalupe Disposal Site	166,915	8,038,063	48	122	74
Santa Cruz City	51,191	3,351,872	65	122	57
Buena Vista Disposal Site	131,775	4,420,935	34	122	88
Woodville Disposal Site	61,368	4,822,838	79	122	43
Visalia Disposal Site	108,327	8,038,063	74	122	48
Yolo County Central	163,841	10,449,482	64	122	58
Average			43		82

6. Generation and utilization of landfill gas in the US

Berenyi reported that as of 1999, there were 327 LFG-to-energy plants in the US [24]. Table 6 summarizes the different uses of landfill gas. Fig. 3 shows that slightly less than three-fourths (71%) or 231 LFG-to-energy plants produce electricity. About one-fifth (21%) sell their gas to a direct user, approximately 4% of the plants produce pipeline—quality gas, and approximately 3% use the gas to produce synthetic fuels or for other uses. (Fig. 3).

Table 6
Utilization of landfill gas [13]

Direct heating applications	✓ Use for industrial boilers
	✓ Space heating and cooling (e.g.greenhouses)
	✓ Industrial heating/cofiring
Electricity generation applications	✓ Processing and use in reciprocating internal combustion (RIC) engines (stoichoimetric or lean combustion)
	✓ Processing and use in microturbines, gas, and steam turbines
	✓ Processing and use in fuel cells
Feedstock in chemical manufacturing processes	✓ Conversion to methanol (industrial or vehicular use)
	✓ Conversion to diesel fuel (vehicular fuel)
Purification to pipeline quality gas	✓ Utilization as vehicular fuel
	✓ Incorporation into local natural gas network
Soil remediation	✓ Leachate evaporation system.
Heat recovery from landfill flares	✓ Using organic Rankine cycle
	✓ Using Stirling cycle engines

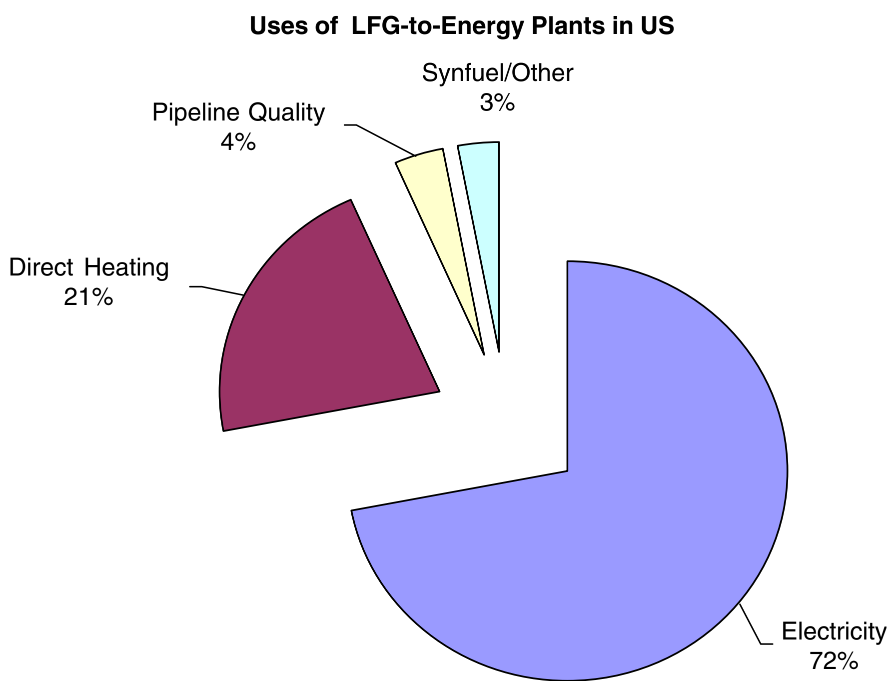

Fig. 3. Types of landfill gas utilization in the United States [24].

Fig. 4 provides a breakdown of the US landfill gas used for energy generation in each state. California has the largest number of landfill gas facilities, with 65 plants, because of state and local requirements resulting in the collection and control gas. Other states with significant number of plants include Illinois (43), Michigan (22), New York (20) and Pennsylvania (19).

Table 7 provides some characteristics of the landfill gas projects by each state. The total active area of landfills provided with landfill gas collection is around 21,000 ha, while a little more than the half of this area is devoted to methane recovery (12,000 ha). The states of California, Illinois, Michigan, New York and Pennsylvania represent approximately 50% of total of devoted area to methane recovery. On the other hand, California, New York, Illinois, Texas and Michigan represent about 60% of total of refuse buried in landfills with gas collection.

The average landfill depth in the gas-collecting landfills ranges from 14–53 m; the nation-wide average depth is 28 m. The density of the MSW buried in these landfills ranges from 594 to 832 kg/m^3, while the national average is estimated at 732 kg /m^3.

Table 8 provides data related with landfill gas collection by state, and also considers the amount of municipal solid waste landfilled annually in each state (Solid Waste Digest [25]). The largest amount of MSW landfilled is landfilled in California, with around 35 million tonnes /y. Other significant landfillers are Pennsylvania, Texas, Illinois, Michigan, and Ohio.

The total landfill gas collected is around 7 billion Nm^3 annually, while the landfill gas processed (i.e. excluding flaring) is 5 billion Nm^3 annually and represents about 70% of the biogas collected. The states of California, Illinois, Michigan, Pennsylvania and New York represent 60% of total of landfill gas processed to generate energy (heat, electricity or fuel).

The heating value of untreated landfill gas ranges from 464 to 591 kJ /Nm^3(average: 540 kJ Nm^{-3}).

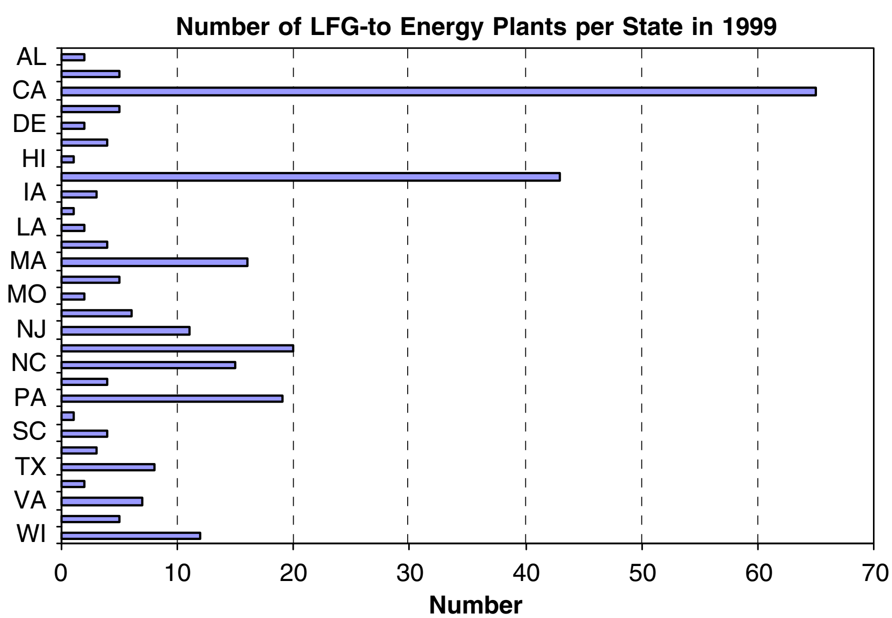

Fig. 4. Number of landfill gas to energy plants per state [24].

Table 7
Characteristics of LFG projects by state [24]

State	Number of LFG projects	Active area (ha)	Devoted area CH_4 recovery (ha)	Refuse buried (tonnes)	Average depth (m)	Average density refuse (kg/m^3)
Alabama	2	236	16	1,306,359	14	653
Arizona	5	285	254	17,418,126	29	693
Arkansas	1	57	57	4,717,409	18	772
California	65	5,746	3,570	546,179,234	36	730
Colorado	1	36	36	27,215,821	26	
Connecticut	5	147	109	12,655,357	32	733
Delaware	2	146	53	8,527,624	23	653
Florida	12	697	530	69,971,877	25	731
Georgia	4	160	68	15,694,457	24	698
Hawaii	1	17	17	1,195,500	23	594
Illinois	43	1,743	1,087	117,968,430	26	814
Indiana	4	163	93	10,886,329	22	832
Iowa	3	210	62	11,974,961	23	761
Kansas	3	482	77	19,958,269	18	713
Kentucky	1	304	122	n/a	46	891
Louisiana	2	209	122	n/a	53	
Maryland	4	233	128	14,424,385	21	624
Massachusetts	16	345	267	20,638,665	25	752
Michigan	22	1,038	697	67,676,676	24	744
Minnesota	5	190	158	20,303,003	25	743
Missouri	2	100	37	12,185,430	46	594
New Hampshire	6	158	151	10,646,829	28	713
New Jersey	11	770	492	62,367,776	23	790
New York	20	1,050	619	152,041,187	38	812
North Carolina	15	723	435	31,942,937	24	695
Ohio	6	383	245	47,718,407	23	792
Oregon	5	531	139	14,116,847	29	812
Pennsylvania	19	1,496	572	64,773,655	32	736
Rhode Island	1	62	47	10,886,329	46	653
South Carolina	4	84	37	5,663,612	18	653
Tennessee	3	181	116	12,428,558	35	793
Texas	8	865	475	117,730,352	22	730
Vermont	2	24	13	1,327,225	25	653
Virginia	7	347	190	29,393,087	26	754
Washington	5	663	364	35,017,690	34	817
Wisconsin	12	546	289	39,335,934	25	759
Total	327	20,426	11,742	1,636,288,340		

The reported data corresponds to 36 states (modified from Berenyi).
Note: n/a: no available.

7. Electricity generation

The US Environmental Protection Agency(USEPA), operates a Landfill Methane Outreach Program that encourages landfill owners to develop gas recovery projects wherever it is feasible.USEPA estimates that over 700 landfills across the United States could install economically viable landfill gas energy recovery systems, but only 380 energy recovery facilities were in place in 2004 [26]. Currently, 295 of these facilities generate electricity; the rest use landfill gas for heating, reducing volume of leachate, etc.

Table 8
Landfill gas capture by state [24,25]

State	MSW landfilled (solid wastes digest) (tonnes/yr)	Landfill gas captured (Berenyi) (Nm^3/yr)	Landfill gas used (Berenyi) (Nm^3/yr)	LFG processed (%)	Heating value untreated gas (KJ)
Alabama	5,110,224	446,559	446,559	100	580
Arizona	6,460,129	8,186,916	n/a	n/a	531
California	35,188,243	1,952,168,440	1,408,295,409	72	500
Colorado	6,269,618	3,096,143	3,096,143	100	514
Connecticut	257,643	55,819,881	20,497,060	37	543
Delaware	1,587,590	38,538,046	20,675,684	54	501
Florida	16,248,753	245,796,024	189,780,153	77	550
Georgia	10,827,361	33,581,240	33,581,240	100	563
Hawaii	595,119	21,702,770	21,702,770	100	528
Illinois	17,972,421	635,117,780	486,899,870	77	547
Indiana	6,097,251	66,983,857	21,137,128	32	522
Iowa	1,835,254	20,675,684	20,675,684	100	554
Kansas	2,835,889	36,179,553	36,179,553	100	528
Kentucky	4,486,075	21,434,834	n/a	n/a	n/a
Maryland	2,849,497	53,333,829	31,005,877	58	543
Massachusetts	1,406,151	203,407,647	111,848,156	55	535
Michigan	16,686,020	455,795,378	417,920,820	92	559
Minnesota	1,978,590	135,977,230	131,065,081	96	513
Missouri	4,066,951	56,564,146	37,213,254	66	580
New Hampshire	1,629,321	72,238,369	72,238,369	100	574
New Jersey	3,594,303	350,548,853	223,279,524	64	534
New York	6,647,011	445,472,421	336,958,573	76	543
North Carolina	6,630,681	113,296,992	85,221,081	75	552
Ohio	12,572,802	182,970,127	124,566,158	68	563
Oregon	4,870,725	16,954,359	16,954,359	100	520
Pennsylvania	22,458,496	556,625,930	363,379,983	65	545
Rhode Island	1,375,306	86,334,749	86,334,749	100	570
South Carolina	5,271,705	14,260,119	11,163,976	78	563
Tennessee	5,877,710	79,963,840	35,665,183	45	591
Texas	21,501,406	312,839,422	278,768,621	89	547
Vermont	410,052	6,981,206	6,981,206	100	475
Virginia	12,157,307	104,078,029	77,403,568	74	563
Washington	4,692,008	253,050,127	13,099,065	5	464
Wisconsin	6,263,268	199,492,812	184,160,952	92	540
Total reporting	253,814,753	6,811,497,272	4,901,214,602		

Through the Outreach Program, USEPA is working with municipal solid waste landfill owners and operators, states, utilities, industry and other federal agencies to lower the barriers to economic landfill gas energy recovery.

Table 9 compares the electricity generated by landfill gas to energy plants in each state according to Berenyi [24] and USEPA [26]. The amount of landfill gas processed is around 5 billion Nm^3 (Table 8), and generates about 912,000 kW, equivalent to 8 billion kWh / annum (Table 9).

Table 9
Electricity generation by using LFG [24,26]

State	Electricity produced (kW)		State	Electricity produced (kW)	
	Berenyi 1999	USEPA 2005		Berenyi 1999	USEPA 2005
Alabama	4,000	n/a	Missouri	800	n/a
Arizona	18,425	10,350	Nebraska	n/a	3,200
California	237,570	255,935	New Hampshire	15,700	13,800
Colorado	800	n/a	New Jersey	48,900	45,700
Connecticut	9,840	5,000	New York	46,047	48,300
Delaware	1,500	n/a	North Carolina	10,350	11,600
Florida	19,800	39,830	Ohio	8,500	36,200
Georgia	5,400	7,400	Oregon	5,660	5,600
Hawaii	3,000	n/a	Pennsylvania	46,350	68,400
Illinois	177,766	153,934	Rhode Island	12,000	17,000
Indiana	7,525	21,585	South Carolina	n/a	8,400
Iowa	8,500	6,400	Tennessee	7,000	7,200
Kansas	3,000	n/a	Texas	15,600	57,656
Kentucky	n/a	10,400	Vermont	1,500	1,200
Maryland	7,250	8,050	Virginia	14,600	31,800
Massachusetts	27,650	37,744	Washington	15,700	15,200
Michigan	79,900	72,300	Wisconsin	29,000	47,375
Minnesota	25,800	24,200	Total	911,433	1,071,759

In the more recent survey by USEPA [24] the amount of electricity generated from landfill gas was estimated at 1.07 GW.

8. Conclusions

On the basis of the theoretical and experimental information presented above, it can be assumed that, under the right conditions, at least 50% of the "latent" methane in MSW can be generated within one year of residence time in a landfill, while the landfilled area is not capped and rainfall can penetrate into the landfilled mass. This would correspond to about 50 Nm^3 of methane /tonne of a typical MSW. However, the 25 California landfills that we examined in detail captured only 43 Nm^3 of methane per tonne landfilled. Of course, conventional landfills are far from perfect bioreactors. Also, we have no information as to the effectiveness of the gas collection of these landfills.

Nearly three hundred eighty landfills in the US capture 3.7 billion Nm^3 of methane (2.6 million tonnes) of which 70% is used to generate thermal or electrical energy. The rest is flared, because it is not considered to be of economic use. There are nearly 1400 landfills that do not capture any biogas.

If it were possible to build and operate bioreactor landfills, where water is added and nearly all the generated methane is captured, the methane collected in the US, at an assumed average rate of 50 Nm^3 of methane per tonne of MSW, would amount to 11 billion Nm^3 of methane, i.e. three times the amount that is presently captured.

With regard to the global picture, an ongoing study [27] estimated the global disposition of MSW in landfills to be 1.5 billion tons of MSW. The corresponding generation of methane is estimated to about 50 million tonnes, of which only a total of 5 million tonnes are captured at this time. Therefore, methane emissions to the atmosphere are in the order of 45 million tonnes. Since methane has 23 times the global warming potential of carbon dioxide (CO_2), global landfill emissions correspond to about one billion tonnes of CO_2.

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Hanson Landfill Services / City of Whittlesea

Comparative Greenhouse Gas Life Cycle Assessment of Wollert Landfill

Final report

Hyder Consulting Pty Ltd
ABN 76 104 485 289
Level 16, 31 Queen Street
Melbourne VIC 3000
Australia
Tel: +61 3 8623 4000
Fax: +61 3 8623 4111
www.hyderconsulting.com

Hanson Landfill Services / City of Whittlesea

Comparative Greenhouse Gas Life Cycle Assessment of Wollert Landfill

Final report

Author	Joe Pickin
Modellers	Kyle O'Farrell, Joe Pickin
Internal review	Jessica North
External peer review	Hannes Partl
Approver	John Nolan
Date	1 February 2010
Version	3

Front cover picture: Wollert Renewable Energy Facility

Summary

Hanson Landfill Services (HLS) and the City of Whittlesea commissioned Hyder to undertake a robust, credible and holistic assessment of the greenhouse performance of the HLS Wollert landfill compared with four alternative waste management scenarios. The agreed method was life cycle assessment. As the study is restricted to greenhouse gas implications, it represents only a partial environmental assessment of the scenarios.

The wastes to be assessed were 144,000 tonnes of household garbage and 96,000 tonnes of commercial and industrial garbage sent to Wollert landfill in 2008, and also source-separated organic waste generated in 2008 from households that used Wollert landfill for their garbage disposal. The organics waste comprised 33,000 tonnes of material in the base case.

The scenarios compared are outlined in Table S1. The scenarios were considered as 'alternative worlds' in which the 2008 waste streams enter fully-developed management arrangements without any phase-in period. In two of the scenarios, garbage was processed through mechanical biological treatment (MBT), which involves separation of waste into fractions and treatment of the organic fraction by aerobic composting (in Scenario 1) or anaerobic digestion (in Scenario 2).

Table S1 Description of the scenarios modelled

<table>
<tr><th rowspan="2">Scenario no. & name
Waste type</th><th>Base case</th><th>Scenario 1</th><th>Scenario 2</th><th>Scenario 3a</th><th>Scenario 3b</th></tr>
<tr><th>Landfill</th><th>Aerobic MBT</th><th>Anaerobic MBT</th><th colspan="2">Food separation with garbage collection
fortnightly | weekly</th></tr>
<tr><td>Household organics – garden waste (all councils) + food waste (Nillumbik only)*</td><td colspan="3">Enclosed composting</td><td colspan="2" rowspan="2">Enclosed composting</td></tr>
<tr><td>Household organics – food waste (other councils) **</td><td rowspan="4">Landfill (Wollert)</td><td rowspan="3">Aerobic MBT</td><td rowspan="3">Anaerobic MBT</td></tr>
<tr><td>Household garbage – non-food</td><td colspan="2" rowspan="3">Landfill (Wollert)</td></tr>
<tr><td>Commercial and industrial garbage</td></tr>
<tr><td>Residuals from waste processing operations</td><td colspan="2">Landfill (Wollert)</td></tr>
</table>

Notes * Source-separated
** Source-separated for Scenario 3 only

As shown above, the residuals from waste processing facilities are all disposed to landfill, and hence this activity is considered in the assessment.

The most important greenhouse gas issue associated with landfill is the generation of methane from the anaerobic degradation of organic materials. Methane emissions were assessed using the Intergovernmental Panel on Climate Change's first-order decay model and the corresponding instantaneous emissions model. The model parameters were populated using data from Wollert landfill and values from reviewed literature. Of the methane potential of the 2008 waste deposited at the landfill, an estimated 56% derived from food waste and 22% from paper and cardboard.

Like most large modern landfill operations, methane generated at Wollert landfill is collected and burned to produce electricity for the grid. The recovered proportion of methane generated from the 2008 waste deposits is estimated at 60% to 88%, based upon a range of sources including direct measurement. The model credited carbon in the waste that is not emitted as equivalent to carbon dioxide (CO_2) removal from the atmosphere. It also provided credits for recovered metals and electricity generated using recovered methane.

There is significant uncertainty about the net energy yield from anaerobic MBT. For this parameter Hyder has relied on overseas data as these technologies have not been applied and operated in Australia for sufficient time to produce a representative range of local data.

Other emission sources in the various scenarios included: transport; facility construction; energy use and energy yields in waste processing; offsets for recovered recyclables; and organics degradation and storage.

The results are presented in Figure S1 using mid-range estimated values and a standard 100 year assessment timeframe. This assessment method assigns a relative warming value to methane on the basis that warming effects over the next century are equally important and those thereafter are not important. The base case and Scenarios 2, 3a and 3b produced similar outcomes, resulting in net savings of between 66,000 and 72,000 tonnes of carbon dioxide equivalent (CO_2-e). Aerobic MBT (Scenario 1) had lower net savings estimated at 33,000 tonnes CO_2-e. The savings (avoided emissions) mostly arose from carbon storage (in the landfill and compost) and product offsets (metals, plastics and especially electricity). The avoided emissions outweighed the actual emissions, which were mostly associated with landfill methane and process inputs.

The base case and Scenario 2 were shown to outperform Scenarios 1, 3a and 3b when the values for two critical parameters (the methane recovery rate at the landfill and net energy yield from anaerobic MBT) were fixed to the mid-point values. When the methane recovery rate was put at the high end of its range, the base case (Wollert landfill) was the best performing scenario (see Figure S2). At the low end of the methane recovery rate, the base case outperformed only Scenario 1 (aerobic MBT). Similarly, over the range of potential values for net energy yield from anaerobic MBT, Scenario 2 ranged from the best to the second worst option.

When the warming effects of methane and CO_2 are assessed over different timeframes the results change significantly (see Figure S3). When only warming over the next 20 years is considered, the base case (Wollert landfill) performs worst and the other scenarios are relatively equal. When warming effects over the next 500 years are included, the base case is best and Scenarios 1 and 2 (MBTs) are worst.

While there was no clear ‘winner’ amongst the scenarios and technologies assessed, all of them – including the current base case involving disposal at Wollert landfill – resulted in net savings of greenhouse gases. The key elements that determined the extent of the savings from each scenario were landfill methane emissions, carbon storage and recovery of energy.

The following conclusions can be drawn:

- Best practice landfill with good performance management is a potentially sound option from a greenhouse gas management perspective.
- Anaerobic MBT appears to be a better greenhouse option than aerobic MBT. This suggests that from a greenhouse gas perspective it is better to focus on maximising energy recovery from biological material rather than to generate stabilised organic products. The low-range estimate of net electricity output from Wollert landfill (around 150 kWh/t) greatly exceeded the high-range estimate for anaerobic MBT (68 kWh/t).
- Diversion of household food organics to the compost stream has a similar performance (but usually slightly worse) to disposal at Wollert landfill, from a greenhouse gas perspective.
- When food is diverted it makes little difference from a greenhouse perspective whether garbage is collected weekly or fortnightly.

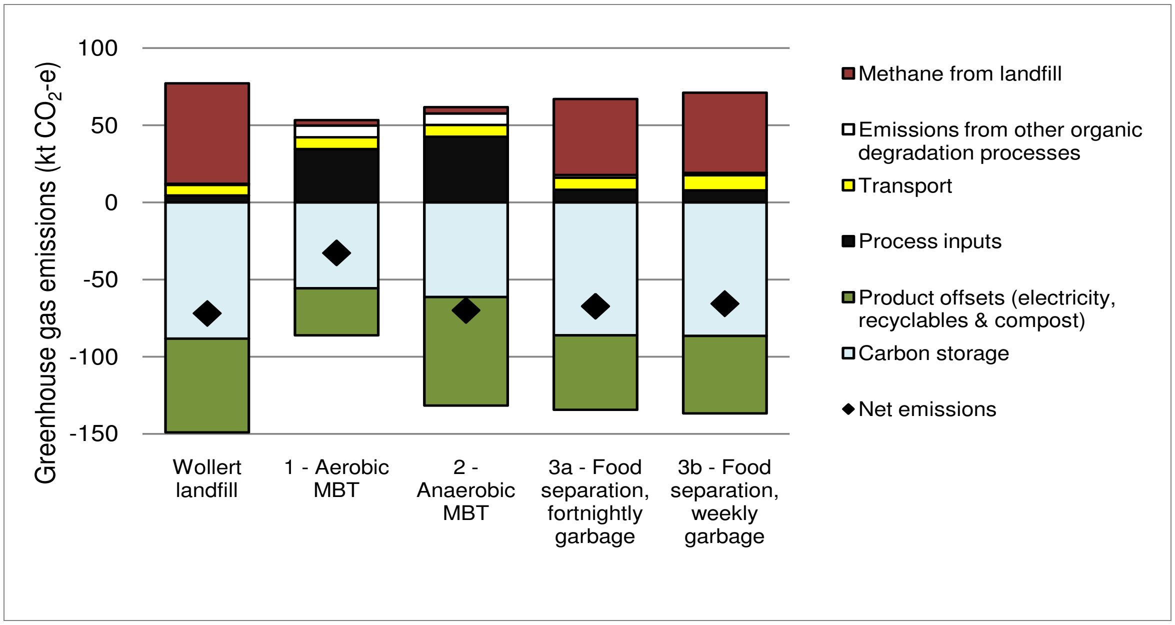

Figure S1 Results using mid-range parameter values assessed over a 100 year instantaneous emission basis

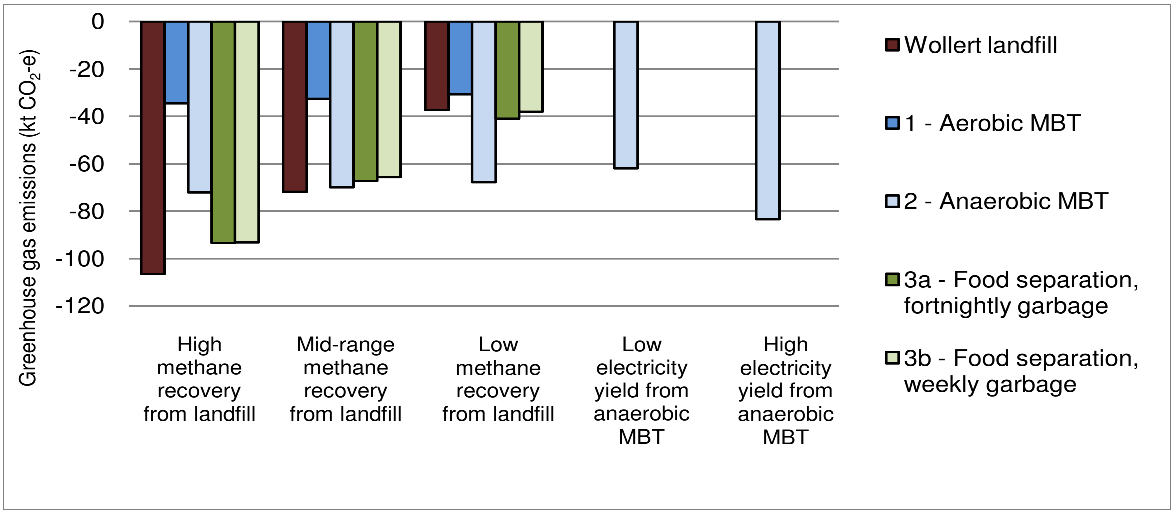

Figure S2 Results with high (88%), mid (74%) and low (60%) values for methane recovery from landfill, and high (68 kWh/t) and low (0 kWh/t) net electricity yield from anaerobic MBT. The charts use mid-range values for other parameters and a 100 year instantaneous emission assessment. Only Scenario 2 is affected by changes to the anaerobic MBT energy yield so the results for the other scenarios are not shown.

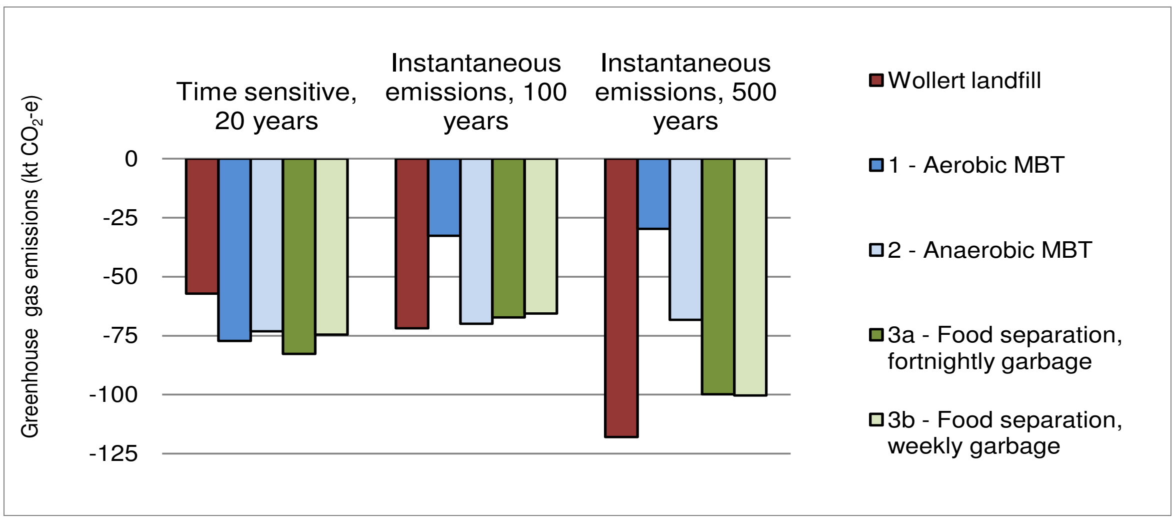

Figure S3 Results using different approaches in relation to time (mid-range parameter values)

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