2. Landfills

Summary

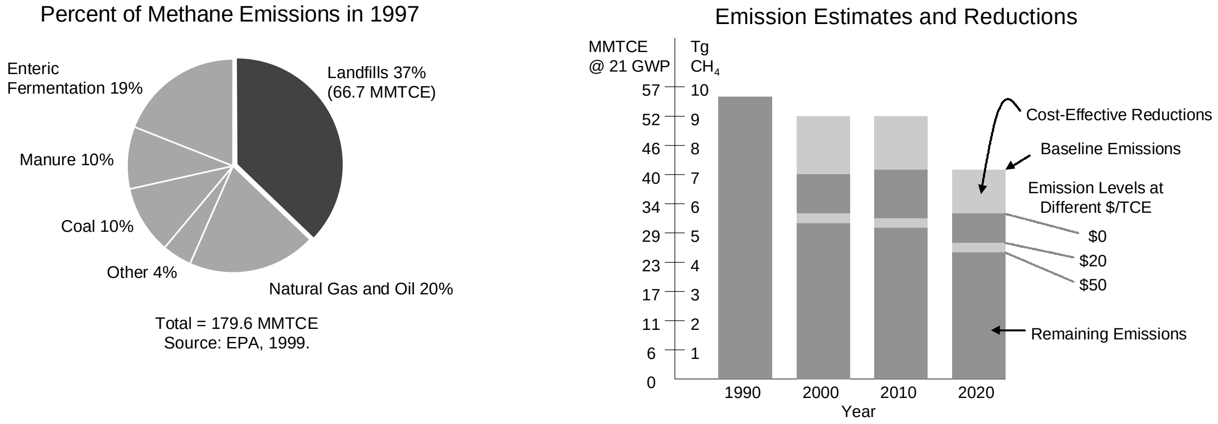
Landfills are the largest source of U.S. methane emissions and emitted approximately 66.7 MMTCE (11.6 Tg) of methane or 37 percent of total U.S. emissions in 1997 (EPA, 1999). Municipal solid waste landfills, which receive about 61 percent of U.S. solid waste, generate 93 percent of U.S. landfill emissions, while industrial landfills account for the remaining emissions. Over 2,500 landfills currently operate in the U.S. with a small number of the largest landfills receiving most of the waste and generating the majority of methane emissions (BioCycle, 1998).

EPA expects future landfill methane emissions to decline due to the Landfill Rule (New Source Performance Standards and Emissions Guidelines), which was promulgated under the Clean Air Act in March 1996 and amended in June 1998 (EPA, 1996, 1998). The Landfill Rule requires landfill gas to be collected and either flared or used at landfills that: (1) have a design capacity greater than 2.5 million metric tons (MMT) and 2.5 million cubic meters; and (2) emit at least 50 metric tons (MT) per year of non-methane organic compounds (NMOCs). Although the Landfill Rule controls NMOC emissions because they contribute to tropospheric ozone (smog) formation, the process of reducing them also reduces methane emissions. Under the Landfill Rule, EPA expects landfill methane emissions to decline to 52.0 MMTCE (9.1 Tg) in 2010, excluding possible additional Climate Change Action Plan and other reductions.[1]

Landfill methane emissions can be reduced through methane recovery and use projects, as well as flaring. Currently, over 250 U.S. landfills have methane utilization projects. The recovered methane is used as on-site fuel, used to generate electricity, or sold to energy end-users, such as factories. Recovering landfill methane also reduces odors and the risk of methane migration through soil.

Exhibit 2-1 shows baseline emissions decreasing between 1990-2020. Although not shown, baseline emissions increase between 1990-1997. After 1997, emissions decrease due to the Landfill Rule. In addition, Exhibit 2-1 shows that by implementing cost-effective technologies and practices, the U.S. could reduce methane emissions from landfills by up to 10.5 MMTCE (1.8 Tg) in 2010 at energy market prices (in 1996 US$) or $0/TCE. At higher emission reduction values, more methane reductions could be achieved. For example, EPA's analysis indicates that with a value of $20/TCE for abated methane added to the energy market price, baseline emissions could decrease to 31.8 MMTCE and U.S. reductions could reach 20.2 MMTCE (3.5 Tg) in 2010.

Exhibit 2-1: U.S. Methane Emissions from Landfills (MMTCE)



Percent of Methane Emissions in 1997

Emission Estimates and Reductions

1.0 Methane Emissions from Landfills

Solid waste landfills produce methane as bacteria decompose organic wastes under anaerobic conditions. Methane accounts for approximately 45 to 50 percent of landfill gas, while carbon dioxide and small quantities of other gases comprise the remaining 50 to 55 percent. Methane production begins six months to two years after waste disposal and may last for decades, depending on disposal site conditions, waste characteristics, and the amount of waste in the landfill. Methane migrates out of landfills and through zones of low pressure in soil, eventually reaching the atmosphere. During this process, the soil oxidizes approximately ten percent of the methane generated by a landfill, and the remaining 90 percent is emitted as methane unless captured by a gas recovery system and then used or flared (Liptay, et al., 1998).

This section presents background information on the factors influencing methane generation and the methods EPA uses to estimate both current and future emissions. A description of the five primary factors that influence landfill methane production are discussed first, followed by a discussion of the emission estimation method used for this analysis. Next, the current and projected emission estimates for U.S. landfills are presented. Lastly, the uncertainties associated with the emission estimates are discussed.

1.1 Emission Characteristics

The amount and rate of methane production over time at a landfill depends on five key characteristics of the landfilled material and surrounding environment. These characteristics are briefly summarized below.

Quantity of Organic Material. The most significant factor driving landfill methane generation is the quantity of organic material, such as paper and food and yard wastes, available to sustain methane-producing microorganisms. The methane production capacity of a landfill is directly proportional to its quantity of organic waste. Methane generation increases as the waste disposal site continues to receive waste and gradually declines after the site stops receiving waste. However, landfills may continue to generate methane for decades after closing.

Nutrients. Methane generating bacteria need nitrogen, phosphorus, sulfur, potassium, sodium, and calcium for cell growth. These nutrients are derived primarily from the waste placed in the landfill.

Moisture Content. The bacteria also need water for cell growth and metabolic reactions. Landfills receive water from incoming waste, surface water infiltration, groundwater infiltration, water produced by decomposition, and materials such as sludge. Another source of water is precipitation. In general, methane generation occurs at slower rates in arid climates than in non-arid climates.

Temperature. Warm temperatures in a landfill speed the growth of methane producing bacteria. The temperature of waste in the landfill depends on landfill depth, the number of layers covering the landfill, and climate.

pH. Methane is produced in a neutral environment (close to pH 7). The pH of most landfills is between 6.8 and 7.2. Above pH 8.0, methane production is negligible.

1.2 Emission Estimation Method

Estimating the quantity of municipal solid waste-in-place (WIP) that contributes to methane emissions requires a characterization of the current and expected future population of landfills. EPA characterizes each landfill in terms of its year of opening, waste acceptance during operation, year of closure, and design capacity. The landfill population as of 1990 is based on EPA's landfill survey (EPA, 1988). The future population of landfills is modeled by simulating the closure of existing landfills as they reach their design capacity and the opening of new landfills when a significant shortfall in disposal capacity is predicted. Simulated new landfills are assumed to be larger, on average, than the landfills they are replacing, reflecting the trend toward fewer and larger regional waste disposal facilities.

EPA simulates the opening and closing of landfills based on waste disposal estimates. For 1990 through 1997, waste disposal estimates are based on annual BioCycle data (BioCycle, 1998).[2] The uncertainty in predicting future waste disposal levels is due to significant shifts in waste disposal practices. Therefore, for the years after 1997, this analysis uses a constant overall disposal rate based on the average rate from 1990 to 1995. This simplification is based on the assumption that the total amount of municipal solid waste (MSW) generated will increase while the percentage of waste landfilled will decline due to rising recycling and composting rates (EPA, 1997a).

The current and future national quantity of waste disposed is apportioned across an assumed population of landfills. Exhibit 2-2 shows the landfill sizing assumptions for each category used in the population analysis. (See Appendix II, Exhibit II-3 for the distribution of waste disposal across the landfill categories). The analysis annually updates the landfill characteristics, i.e., the total WIP and years of operation. The result is a simulated population of landfills reflecting the national MSW disposal rates over time.

Exhibit 2-2: Landfill Capacity Assumptions

Landfill Category	Capacity (MT)
Small	500,000
Small-Medium	1,000,000
Medium	5,000,000
Large	15,000,000
Very Large	> 15,000,000

MT = metric tons

1.3 Emission Estimates

EPA uses the results of the landfill population analysis to calculate the methane emissions from MSW landfills. The quantity of waste in landfills over time drives methane generation. An emissions model uses this landfill-specific data to estimate the amount of methane produced by MSW landfills in a given year (EPA, 1993). The model is based on information from 85 landfills that represent the population of U.S. landfills and vary in terms of depth, age, regional distribution, and other factors.

As indicated in Exhibit 2-3, annual landfill methane emissions are calculated by summing annual methane generated from MSW landfills, subtracting methane recovered and oxidized, and adding methane emissions from industrial solid waste.

Exhibit 2-3: Components of Methane Emissions from Landfills

Total Landfill Methane Emissions

Equals

Methane Generated from Municipal Solid Waste
(MSW Landfills)

Less

Methane Recovered and Flared or Used for Energy

Less

Methane Oxidized from MSW Landfills

Plus

Methane Emissions from Industrial Waste Sites

Exhibit 2-4 presents estimates of the amount of municipal solid waste contributing to methane emissions for the years 1990 to 1997. Methane generation coefficients are applied to the WIP to determine total methane generated for individual landfills for the same period.[3]

The analysis also assesses the applicability of the Landfill Rule based on methane generated for each landfill. The Landfill Rule (New Source Performance Standards and Emissions Guidelines) was promulgated in March 1996 under the Clean Air Act and amended in June 1998. The Landfill Rule requires gas collection and flaring or other combustion at landfills whose design capacity exceeds 2.5 million metric tons (MMT) and 2.5 million cubic meters (million m^3), and that emit 50 metric tons per year (MT/yr) of non-methane organic compounds (NMOCs). EPA estimates that up to 350 existing and 50 new landfills will install gas control systems by 2000 under the Landfill Rule.[4] The emission model identifies which landfills are subject to the Landfill Rule and projects baseline emissions accordingly. Thus, for the purposes of the cost analysis presented in this chapter, EPA analyzes only landfills with emissions below the Landfill Rule threshold.

Although not explicitly modeled in this analysis, EPA has estimated methane reductions under the Climate Change Action Plan (CCAP). Under CCAP, the Landfill Methane Outreach Program (LMOP) has promoted methane recovery and utilization. LMOP/CCAP reductions reflect those landfills at which LMOP has provided assistance.

1.3.1 Current Emissions and Trends

The amount of MSW in landfills contributing to methane emissions increased from approximately 4,900 MMT in 1990 to approximately 5,800 MMT in 1997. Methane emissions also increased between 1990 and 1997, from 56.2 million metric tons of carbon equivalent (MMTCE) or 9.8 Teragrams (Tg) to 66.7 MMTCE or 11.6 Tg, respectively (EPA, 1999). Exhibit 2-5 shows this gradual increase of 1.5 MMTCE/yr (0.26 Tg/yr). Although emissions increased, methane collection and combustion by landfill operators also increased from an estimate of 8.6 MMTCE (1.5 Tg) in 1990 to 10.3 MMTCE (1.8 Tg) in 1992. Since 1992, the number of landfill gas recovery projects has increased substantially. EPA is developing annual recovery estimates for gas utilization projects for the period 1990-1998. These estimates will be published in 2000, and may result in a stable emissions trend over the period 1990-1998.

For purposes of electricity generation, the U.S. recovered 6.9 MMTCE (1.2 Tg) of landfill methane in 1990 and 8.1 MMTCE (1.4 Tg) in 1992 (GAA, 1994). To account for methane flared without energy recovery, the recovery estimate is increased by 25 percent to arrive at the total methane recovered (EPA, 1993). Due to a current lack of information on annual recovery rates, the 1990 estimate is used for 1991, and the 1992 estimate is used for 1993 through 1997.

1.3.2 Future Emissions and Trends

As previously stated, total emissions are based on a characterization of the surveyed U.S. landfill population. The surveyed population, however, excludes industrial landfills and landfills with a WIP less than 500,000 MT; therefore, the emissions from these landfills are estimated as a percentage of MSW emissions from the surveyed population. Emissions for the small landfills (containing less than 500,000 MT) are based on an estimate of the portion of total waste disposed in small landfills. This portion is estimated to decline from 12 percent of current MSW emissions to six percent of the MSW emissions by 2020. Industrial landfill emissions are as-

Exhibit 2-4: Municipal Solid Waste Contributing to Methane Emissions (MMT)

Description	1990	1991	1992	1993	1994	1995	1996	1997
Total MSW Generated[a]	267	255	265	279	293	297	297	309
Percent of MSW Landfilled[b]	77%	76%	72%	71%	67%	63%	62%	61%
Total MSW Landfilled	206	194	191	198	196	187	184	189
Cumulative MSW Contributing to Emissions[c]	4,926	5,027	5,162	5,292	5,428	5,560	5,677	5,791

MMT = million metric tons

[a,b] Source: BioCycle, 1998.

[c] The EPA emission model (EPA, 1993) assumes all waste that has been in place for less than 30 years emits methane.

Exhibit 2-5: Methane Emissions from Landfills (MMTCE)

Activity	1990	1991	1992	1993	1994	1995	1996	1997
MSW Landfilling	66.4	67.8	69.7	71.6	73.6	75.7	77.3	78.9
Recovery	(8.6)	(8.6)	(10.3)	(10.3)	(10.3)	(10.3)	(10.3)	(10.3)
Oxidation from MSW	(5.8)	(5.9)	(5.9)	(6.1)	(6.3)	(6.5)	(6.7)	(6.9)
Industrial Waste Landfilling	4.2	4.3	4.4	4.5	4.6	4.8	4.9	5.0
Total	**56.2**	**57.6**	**57.8**	**59.7**	**61.6**	**63.6**	**65.1**	**66.7**

MMTCE = million metric tons of carbon equivalent

Totals may not sum due to independent rounding.

sumed to equal seven percent of the total methane generated from MSW at all landfills, including those with less than 500,000 MT. The emissions from industrial and small landfills are added to the total MSW methane emissions and are included in baseline emissions. Excluding the small and industrial landfills, approximately 3,900 existing and future landfills are simulated in the U.S. landfill population. Of these, approximately 2,030 existed in 1990.

Future landfill methane emissions will decline due to the Landfill Rule and increased recycling and alternative waste disposal methods. Based on the annual quantity of waste disposed and the criteria for the Landfill Rule, EPA simulates candidate landfills for methane recovery. Since the analysis incorporates projected waste quantities, it reflects the fact that certain landfills will not be subject to the Landfill Rule, and others will not have enough waste to cost-effectively recover and use methane until some time in the future. Exhibit 2-6 shows estimated landfill methane emissions with and without the Landfill Rule for 2000 through 2020. Baseline emission projections include emission reductions achieved as a result of the Landfill Rule.

1.4 Emission Estimate Uncertainties

The primary source of uncertainty with the landfill emission estimates is the characterization of the current and future landfill population. The characterization is based on an EPA survey of a small number of landfills rather than landfill-specific information from the population of U.S. landfills. For example, the analysis simulates the opening and closing of landfills, waste disposal over time, and the installation of landfill gas-to-energy recovery systems. In addition, the baseline emission estimates do not include emission reductions associated with landfills that flare their gas and do not have landfill gas-to-energy recovery systems. Such data are not currently available, but EPA is working to develop it. Thus, the analysis underestimates current emission reductions.

2.0 Emission Reductions

Two approaches exist for reducing methane emissions from landfills: (1) recovering and either flaring or using landfill methane for energy; and (2) modifying waste management practices to reduce waste disposal in landfills, through recycling and other alternatives. The first approach is an increasingly common practice as demonstrated by the over 250 landfills that currently collect and use their gas for energy (Kruger, et al., 1999). This report focuses on evaluating the cost-effectiveness of methane recovery for energy. The second approach is not assessed, although expected changes in MSW disposal rates due to recycling are reflected in the emission projections.

The costs and benefits of emission reductions (through the implementation of gas recovery projects) at landfills not subject to the Landfill Rule are analyzed for the years 2000, 2010, and 2020. In addition, a marginal abatement curve (MAC) is constructed showing a schedule of emission reductions that could be obtained at increasing values for methane. The analysis considers the value of abated methane as the sum of its value as a source of energy, i.e., natural gas and electricity, and as an emission reduction of a greenhouse gas (GHG).

A description of the various technologies and practices that can reduce methane emissions is provided in this section. In addition, this section also presents the cost

Exhibit 2-6: Projected Baseline Methane Emissions from Landfills (MMTCE)

Activity	2000	2005	2010	2015	2020
MSW Landfilling	83.4	87.5	87.0	82.5	76.1
Oxidation from MSW	(8.3)	(8.8)	(8.7)	(8.2)	(7.6)
Industrial Waste Landfilling	5.3	5.5	5.5	5.2	4.8
Total Emissions (without the Landfill Rule)	**80.3**	**84.3**	**83.8**	**79.4**	**73.3**
Landfill Rule Emission Reductions	(28.8)	(30.3)	(31.8)	(32.0)	(32.2)
Projected Baseline Emissions	**51.4**	**54.0**	**52.0**	**47.4**	**41.1**

Totals may not sum due to independent rounding.

analysis for evaluating emission reductions as well as the MAC for emission reductions in 2010. Finally, the uncertainties and limitations associated with EPA's reduction estimates are described.

2.1 Technologies for Reducing Methane Emissions

Gas collection, by vertical wells and horizontal trenches, typically begins after a portion of a landfill, called a cell, is closed. Vertical wells are most commonly used for gas collection, while trenches are sometimes used in deeper landfills, and may be used in areas of active filling. The collected gas is routed through lateral piping to a main collection header. Ideally, the collection system should be designed so that an operator can monitor and adjust the gas flow if necessary. Once the landfill methane is collected, it can be used in a number of ways, including electricity generation, direct gas use (injection into natural gas pipelines), powering fuel cells, or compression to liquid fuel. EPA's analysis focuses on the first two options, summarized below.

Electricity Generation. Almost 80 percent of landfill electric power generation projects use reciprocating internal combustion (IC) engines (Kruger, et al., 1999). IC engines are relatively inexpensive, efficient, and appropriate for smaller landfills where gas flows are between 625 thousand cubic feet per day (Mcf/day) to 2,000 Mcf/day at 450 British thermal units per cubic feet (Btu/ft^3) (Jansen, 1992). This gas flow and energy content is sufficient to produce one to three megawatts (MW) of electricity per project (Thorneloe, 1992).

Direct Gas Use. Landfill gas is used as a medium-Btu fuel for boilers or industrial processes, such as drying operations, kiln operations, and cement and asphalt production. In these projects, the gas is piped directly to a nearby customer where it is used as a replacement or supplementary fuel. If medium-Btu fuel is sold to a customer that is in close proximity to the landfill, ideally within five miles, usually only minimal gas processing is required. Ideal gas customers have a steady, annual gas demand compatible with a landfill's gas flow.

The analysis does not assess the following technologies for reducing emissions because they are typically more costly than electricity generation or direct gas use projects and the extent of their use in the landfill gas-to-energy industry is difficult to predict.

- **Reduced Landfilling.** Landfilling is reduced through recycling, waste minimization, and waste diversion to alternative treatment and disposal methods, such as composting and incineration. The U.S. is making significant efforts at both the federal and state level to reduce landfilling. Although the analysis does not evaluate the cost-effectiveness of reduced landfilling, the baseline methane emission estimates include the anticipated impacts of changes in waste management practices.
- **Turbine Generators**. Similar to IC engines, turbine generators generate electricity. While turbines are often better for large projects in excess of three MW, IC engines are more cost-effective for the sizes of projects examined in this analysis. Because the largest landfills in the U.S. are expected to recover and combust their gas under the Landfill Rule by the year 2000, this analysis focuses on the smaller landfills for which IC engines are preferred.
- **Natural Gas Pipeline Injection.** Landfill gas can be sold to the natural gas pipeline system once it has met certain process and treatment standards. This option is appropriate in limited cases, such as when very large quantities of gas are available.
- **Liquid Vehicle Fuel.** Landfill gas is processed into liquid vehicle fuel for use in trucks hauling refuse to a landfill.
- **Flare-Only Option.** Several U.S. landfills have implemented flare systems without energy recovery systems. These landfills are either required to flare their landfill gas or they flare to control odor and gas migration. EPA's analysis did not address flaring as a stand-alone option.

2.2 Cost Analysis of Emission Reductions

EPA evaluates both electricity generation and direct gas use projects for landfills not subject to the Landfill Rule.

A project is considered cost-effective when the value for its abated methane (revenue) is equal to or greater than the project's cost. The analysis evaluates the cost-effectiveness over a range of comparable values for abated methane in terms of electricity prices (dollars per kilowatt-hour or $/kWh), gas prices (dollars per million Btu or $/MMBtu), and emission reduction values (dollars per metric ton of carbon equivalent or $/TCE).

EPA first evaluates electricity generation projects for each modeled landfill and determines if such a project is cost-effective. For those landfills where electricity generation projects are not cost-effective, the analysis then evaluates whether direct gas use projects are cost-effective at an equivalent value in gas-price terms, $/MMBtu. For landfills that cannot cost-effectively implement either project, methane emission reductions are zero. The analysis is repeated at a range of values for abated methane and the results of the analysis are used to construct a MAC.

Both electricity and direct gas use projects require a gas collection system and involve capital and operation and maintenance (O&M) costs for various project components. Capital costs for a collection system include the purchase and installation of extraction wells, lateral well connections, a header system, a gas mover system, and a condensate handling system. Annual O&M figures include labor costs of two to three person-years and indirect costs including overhead, insurance, and administration. The expected cost of replacing components of the collection system are small relative to the overall cost of the collection and recovery and utilization systems. Additional component costs for electricity and direct gas use are described in more detail below.[5]

2.2.1 *Electricity Generation*

The cost analysis for landfill gas-to-electricity projects consists of the following three steps.

Step 1: Define Project Components. Each project includes a collection system, flare system, and electricity production system. Appendix II, Exhibit II-5 details the factors used to estimate project costs.

- **Collection System.** As discussed above, all gas recovery projects start with a gas collection system. These costs are driven primarily by the amount of WIP. Gas collection efficiency is assumed to be 75 percent of emitted methane.
- **Flare System.** All gas recovery projects require a flare system because excess gas may need to be flared at any time. Peak gas flow from the collection system drives these costs.
- **Electricity Production.** Electricity production requires a variety of equipment including: compressors to move the gas, a prime mover (IC engines in this case), an electric generator, an interconnect with the local grid, and a monitoring and control system.

Total costs equal the sum of the components listed above. Exhibit 2-7 lists estimated costs for projects of various sizes as defined by a landfill's WIP and the electricity production capacity in MW. The size of each generator is based on the maximum gas flow rate during the life of the project. In most cases the gas produced is less than the maximum capacity of the engine generator. No downtime is assumed since the unit is modeled to run at less than capacity during most of the project's lifetime.

Step 2: Estimate Project Revenue. EPA estimates revenues for a range of electricity prices and values of abated methane. The rate at which landfill owners sell electricity depends on local and regional electric power market conditions, and often varies by time of day and season. This analysis uses a market price of $0.04/kWh (1996 US$) as a representative figure.[6] The analysis does not consider additional revenues from state and federal incentives for landfill gas-to-energy projects. EPA estimates the annual total electricity production from the project based on the amount of gas produced and collected each year.

For modeling purposes, electricity prices are converted to $/TCE using methane's Global Warming Potential (GWP) of 21 and the heat rate (10,000 Btu/kWh) of the engine-generator.[7]

Exhibit 2-7: Electricity Generation – Example Cost Estimates by Project Size

Size		Collect and Flare System		IC Engine/Generator		Total Costs	
WIP (MT 000)	(MW)	Capital ($000)	O&M ($000)	Capital ($000)	O&M ($000)	Capital ($000)	O&M ($000)
318	0.50	$272	$61	$693	$66	$965	$127
476	0.75	$353	$64	$1,011	$99	$1,364	$163
635	1.00	$428	$67	$1,322	$131	$1,749	$199
953	1.50	$568	$73	$1,927	$197	$2,495	$270
1,271	2.00	$699	$78	$2,517	$263	$3,216	$341
1,127	3.00	$654	$77	$3,957	$394	$4,611	$471
2,918	5.00	$1,310	$103	$6,000	$657	$7,310	$760

All estimates are in 1996 dollars.

Step 3: Evaluate Cost-Effectiveness. EPA assesses the cost-effectiveness of implementing a project at each landfill using a benefit-cost analysis with the costs and revenues described above, and the cost parameters listed in Exhibit 2-8. Electricity production is assumed to take place for 20 years, with an option at the end of that period to replace the engines and generate electricity for another 20 years. If the net present value (NPV) of the project is zero or positive, the project is considered cost-effective.

Exhibit 2-8: Financial Assumptions for Emission Reduction Analysis

Parameter	Value
Discount Rate	8 percent real
Depreciation Period	10 years
Marginal Tax Rate	40%
Duration of Project	Electricity: 20 years; Direct Gas Use: 15 years
Collection Efficiency	75%

2.2.2 Direct Gas Use

EPA evaluates the cost-effectiveness of direct gas use projects at landfills not subject to the Landfill Rule and for which electricity generation projects are not cost-effective. The evaluation is based on the three steps indicated below.

Step 1: Define "Model" Project Components. The costs of a model project include a gas collection and flare system, gas treatment, gas compression to 50 pounds per square inch (psi), and a five-mile gas pipeline to a customer. For each landfill size, EPA estimates the capital and O&M costs for each component using the unit costs presented in Appendix II, Exhibit II-6 and the cost parameters in Exhibit 2-8. The unit costs are taken from the Energy Project Landfill Gas Utilization Software (E-PLUS), an EPA-distributed software used to evaluate the cost-effectiveness and feasibility of landfill gas-to-energy projects (EPA, 1997b).[8] Exhibit 2-9 presents the costs and break-even gas prices as defined by a landfill's WIP.

EPA estimates the break-even gas prices ($/MMBtu) required to support a "model" direct gas use project for landfills with a WIP ranging from 50,000 to 11,000,000 MT. The break-even gas price is the value required to produce a zero NPV over the 15-year life of the project.

Step 2: Define Methane Abatement Values. A market price of gas of $2.74/MMBtu (1996 US$) is used in the analysis. This price is 80 percent of the national average industrial natural gas price of $3.42/MMBtu (EIA, 1997). The national average price is discounted by 20 percent to account for the fact that the landfill gas is a medium-grade gas. EPA converts gas prices, in $/MMBtu, to methane abatement values, in $/TCE, using methane's GWP of 21 and a Btu content of 1,000 Btu/ft^{3}for methane.[9]

In order to compare direct gas use with electricity generation projects and combine them on the same MAC, gas prices are aligned with the electricity prices based on equivalent emission reductions values. For example, 150 percent of the market electricity price or $0.06/kWh, is

Exhibit 2-9: Direct Gas Use Cost Estimates by Project Size

WIP (MT 000)	Collection and Flare		Compression		Gas Treatment		Pipeline		Total		Break-Even Gas Price ($/MMBtu)
	Capital ($000)	O&M ($000)	Capital ($000)	O&M ($000)	Capital ($000)	O&M ($000)	Capital ($000)	O&M ($000)	Capital ($000)	O&M ($000)	
50	$124	$52.0	$3.3	$12.6	$3.25	$10.0	$924	$18.5	$1,054	$93	$55.03
100	$156	$54.5	$6.6	$13.3	$3.31	$10.0	$924	$18.5	$1,090	$96	$27.72
200	$215	$56.0	$13.4	$14.6	$3.42	$10.0	$924	$18.5	$1,156	$99	$14.92
300	$269	$57.3	$20.1	$15.9	$3.53	$10.0	$924	$18.5	$1,216	$102	$10.36
400	$319	$59.8	$26.7	$17.2	$3.64	$10.0	$924	$18.5	$1,273	$105	$8.11
500	$364	$62.3	$33.4	$18.5	$3.74	$10.1	$924	$18.5	$1,325	$109	$6.74
600	$412	$64.6	$40.1	$19.8	$3.85	$10.1	$924	$18.5	$1,380	$113	$5.83
700	$458	$68.0	$46.8	$21.1	$3.96	$10.1	$924	$18.5	$1,432	$118	$5.20
800	$500	$68.6	$53.5	$22.3	$4.07	$10.1	$924	$18.5	$1,481	$120	$4.67
900	$540	$70.0	$60.2	$23.6	$4.18	$10.1	$924	$18.5	$1,529	$122	$4.27
1,000	$581	$70.8	$129.0	$37.0	$5.30	$10.2	$924	$18.5	$1,639	$136	$2.16
11,000	$3,522	$189.0	$603.0	$129.0	$19.00	$10.9	$924	$18.5	$5,068	$347	$1.35

Estimates are an average for arid and non-arid conditions and represent 1996 dollars.

Source: EPA, 1997b.

paired with 150 percent of the market gas price or $4.10/MMBtu.

Step 3: Evaluate Cost-Effectiveness. For direct use projects, EPA estimates the break-even WIP for each gas price by interpolation; as shown in Exhibit 2-9. The analysis categorizes a landfill as implementing a direct gas use project when its methane-producing WIP is equal to or greater than the break-even WIP for a given gas price.

Emission reductions from direct gas use projects equal the gas that is collected and combusted. EPA assumes that only 75 percent of these cost-effective direct gas use projects are implemented to account for the uncertainty in identifying an energy end-user.

As energy prices increase, the break-even WIP declines allowing smaller landfills to cost-effectively invest in direct gas use projects. This trend is important because while the Landfill Rule is reducing emissions from larger U.S. landfills, many small landfills exist where cost-effective reductions also can be achieved.

2.3 Achievable Emission Reductions and Marginal Abatement Curve

The result of this analysis is an assessment of the cost-effectiveness of two types of landfill gas recovery and use projects: electricity generation and direct gas use. For 2010, EPA estimates that U.S. landfills could reduce methane emissions by up to 10.5 MMTCE (1.8 Tg) through implementing these types of cost-effective projects at energy market prices (1996 US$). These potential reductions are without any additional value for abated methane in terms of $/TCE. If emission reduction values are added to the energy market prices, greater methane reductions are achieved. For example, EPA's analysis indicates that with a value of $20/TCE for abated methane added to the energy market price, U.S. reductions could reach 20.2 MMTCE (3.5 Tg) in 2010.

Exhibit 2-10 shows the amounts of abated methane incremental to the Landfill Rule that can be cost-effectively achieved for a range of comparable values of abated methane through $200/TCE. For some landfills, both electricity and direct gas use projects are cost-effective. However, for modeling purposes, EPA assumes that these landfills implement an electricity generation project. Consequently, the eligible landfills for direct use projects indicated in Exhibit 2-10 represent

Exhibit 2-10: Schedule of Emission Reductions Over and Above the Landfill Rule by Price in 2010

	Electricity Production[a]				Direct Gas Use				Total Emission Reductions		
Value of Carbon Equivalent ($/TCE)	Price ($/kWh)	Break-Even WIP (MT)	Eligible Landfills	Incremental Reductions (MMTCE)	Price ($/MMBtu)	Break-Even WIP (MT)	Eligible Landfills	Incremental Reductions (MMTCE)	Cumulative Reductions (MMTCE)	% of base-line	Label on MAC[b]
(10)	0.03	Infeasible	0	0.00	1.64	7,436,565	0	0.00	0.00	0%	N/A[c]
(6)[d]	0.03	Infeasible	0	0.00	2.05	2,330,467	114	3.48	3.48	7%	A
0	0.04	2,900,493	64	1.98	2.74	972,739	498	5.09	10.55	20%	B
10	0.05	538,232	773	11.25	3.84	920,668	106	(7.35)[e]	14.44	28%	C
20	0.06	273,860	1,919	6.96	4.94	749,467	7	(1.16)	20.23	39%	D
30	0.07	177,368	2,319	1.27	6.03	576,422	0	(0.05)	21.45	41%	E
40	0.08	129,583	2,505	0.29	7.13	468,324	0	0.00	21.75	42%	F
50	0.09	101,309	2,615	0.11	8.23	393,655	0	0.00	21.85	42%	G
75	0.12	66,064	2,685	0.05	10.98	283,477	0	0.00	21.90	42%	H
100	0.15	48,086	2,720	0.02	13.73	222,143	0	0.00	21.91	42%	I
125	0.18	Negligible	2,720	0.00	16.48	182,893	0	0.00	21.91	42%	J
150	0.20	Negligible	2,720	0.00	19.23	152,742	0	0.00	21.91	42%	K
175	0.23	Negligible	2,720	0.00	21.98	134,836	0	0.00	21.91	42%	L
200	0.26	Negligible	2,720	0.00	24.73	118,155	0	0.00	21.91	42%	M

[a] Includes emission reductions for landfills at which either a gas or an electricity project is modeled as cost-effective. By default, the analysis selects electricity projects over gas projects where both are cost-effective.

[b] Point on marginal abatement curve (see Exhibit 2-11) indicating minimum break-even WIP for electricity and direct gas use projects.

[c] Although cost-effective reductions at landfills of this size exist, they are subject to the Landfill Rule (over 2.5 MMT WIP), and thus, are not counted as emission reductions in this analysis.

[d] The potential emission reductions associated with the modeled prices of $2.05/MMBtu or -$6/TCE are "below the line" reductions in carbon equivalent terms.

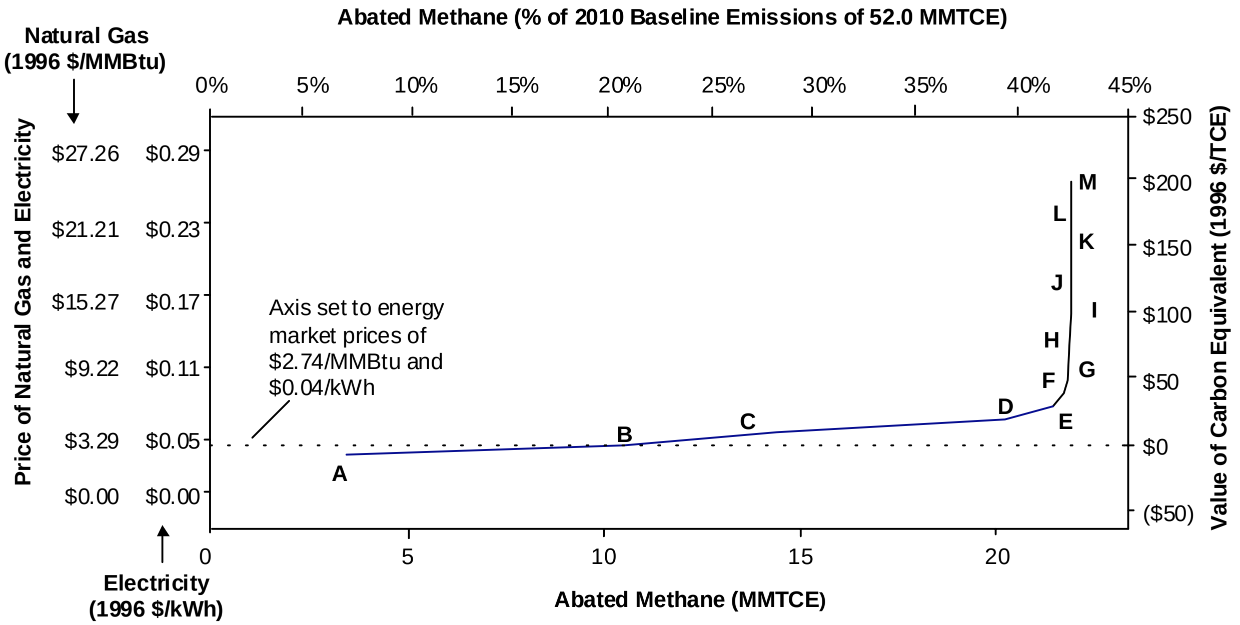
[e] Negative incremental reductions indicate that emission reductions attributed to gas projects at lower prices are modeled as electricity projects at higher prices because electricity projects become cost-effective as values increase above $0/TCE.

those landfills that find only direct gas use projects cost-effective. As indicated in the exhibit, above $20/TCE, no landfills find only direct gas use cost-effective. The negative incremental reductions under the direct gas option indicate the direct use projects for which electricity production also becomes cost-effective at the higher methane values.

Exhibit 2-11 illustrates the MAC for landfill electricity generation and direct gas use projects not subject to the Landfill Rule for 2010. Exhibit 2-12 presents the cumulative emission reductions for selected values of carbon equivalent in 2000, 2010, and 2020. The MAC can similarly be called a cost or supply curve since it shows the marginal cost per emission reduction amount. Energy market prices are aligned with $0/TCE given that this price represents no additional values for abated methane and where all price signals come only from the respective energy markets. The "below-the-line" reduction amounts, with respect to $0/TCE, illustrate this dual price-signal market, i.e., energy market prices and emission reduction values.

Each point on the MAC represents the quantity of methane that is cost-effectively abated at a given energy price combination and emission reduction value. In addition, each point on the graph reflects the minimum break-even WIP between electricity projects and direct gas use projects. The minimum break-even WIP for electricity generation and direct gas use projects determines the size of the smallest landfill for which a landfill gas-to-energy project is cost-effective. As shown in the exhibit, emis-

Exhibit 2-11: Marginal Abatement Curve for Methane Emissions from Landfills in 2010



sion reductions approach their maximum at approximately $36/TCE which is comparable to $0.08/kWh and $6.69/MMBtu.

The analysis indicates that at and below energy market prices, only direct gas use projects are cost-effective and electricity production projects do not contribute to emission reductions. This modeled result, however, underestimates the potential for emission reductions since many landfills are currently implementing electricity projects. Many of these landfills take advantage of state and federal incentives that are not reflected in this analysis.

Emission reductions from both landfills impacted by the Landfill Rule and "non-Rule" landfills reach approximately 65 percent of total MSW methane emissions, only 10 percent below the maximum possible given the estimated recovery efficiency of 75 percent. The analysis assumes that small and industrial landfills, which were not evaluated for purposes of the MAC, continue to emit methane. Therefore total emission reductions do not approach the 75 percent maximum.

Exhibit 2-12: Emission Reductions at Selected Values of Carbon Equivalent in 2000, 2010, and 2020 (MMTCE)

	2000	2010	2020
Baseline Emissions	51.4	52.0	41.1
Cumulative Reductions			
at $0/TCE	11.0	10.5	7.6
at $10/TCE	14.1	14.4	10.1
at $20/TCE	18.2	20.2	13.9
at $30/TCE	19.7	21.5	15.0
at $40/TCE	20.1	21.7	15.5
at $50/TCE	20.5	21.9	15.7
at $75/TCE	21.2	21.9	15.8
at $100/TCE	21.4	21.9	15.9
at $125/TCE	21.5	21.9	15.9
at $150/TCE	21.6	21.9	15.9
at $175/TCE	21.6	21.9	15.9
at $200/TCE	21.7	21.9	15.9
Remaining Emissions	29.8	30.1	25.2

2.4 Reduction Estimate Uncertainties and Limitations

Most of the uncertainties associated with emission reduction estimates relate to the landfill population uncertainties described in the first section. Additional data are needed to improve the basis for characterizing the landfill population and the potential to collect and use gas cost-effectively at each landfill.

Other uncertainties involve landfill gas recovery technologies and the costs for recovering landfill gas. For both electricity and direct gas use projects, EPA estimates the costs using aggregate cost factors and a relatively simple set of landfill characteristics. Costs vary depending on the depth, area, WIP, and waste materials for each landfill. Uncertainty is associated with the electricity analysis because EPA bases costs on a representative WIP. Although the costs for direct gas use projects account for depth, area, and WIP (along with unit costs), they are only representative of average costs.

The price at which landfills sell electricity also is an important driver in the analysis. At higher rates, more landfills find it cost-effective to implement electricity projects. In addition, efforts to reduce landfilling, including waste management policies that go beyond existing programs, are potentially cost-effective in further reducing future methane emissions. The costs and benefits of such alternative waste management policies are not included in this assessment.

Lastly, project revenues only reflect market prices of electricity and gas and do not reflect state and federal incentives or subsidies. Incorporating these currently available incentives in the analysis would result in additional cost-effective emission reductions.

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4.0 Explanatory Notes

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[1] Climate Change Action Plan or CCAP reductions are achieved as a result of voluntary industry actions. For example, under CCAP, EPA created the joint EPA-industry Landfill Methane Outreach Program (LMOP). Under this program, landfill industry partners undertake cost-effective efforts to reduce methane emissions from landfills. This analysis does not evaluate specific emission reductions associated with LMOP, rather, the analysis focuses on projected cost-effective emission reductions at landfills not impacted by the Landfill Rule. EPA expects that 40 percent of the cost-effective emission reductions available in 2010 will be taken as a result of LMOP.

[2] BioCycle includes construction and demolition (C&D) debris in their estimates of waste generation. However, the definition of municipal solid waste (MSW) is not uniform for each state in BioCycle's survey. Some states report C&D because many of their landfills accept waste from a variety of sources (BioCycle 1998). Although the waste estimates prior to 1990 exclude C&D waste, EPA did not adjust the BioCycle estimates due to the inconsistent definition of MSW for each state.

[3] Equations for calculating methane generation as a function of methane generating waste-in-place (WIP):

Methane Generating WIP	**Methane Emissions (MT/year)**
Less than or equal to 0.04 10^6 MT	0
Greater than 0.04 10^6 MT and less than or equal to 2.0 x 10^6 MT	7.43 x (WIP/10^6) x Conversion Factor[a] x Scale[b]
Greater than 2.0 x 10^6 MT	(8.22 + 5.27 x (WIP/10^6)) x Conversion Factor[a] x Scale[b]

[a] Conversion Factor (m^3/min to MT/year) = (365 days/yr) x (24 hrs/day) x (60 min/hr) x (662 g CH_4/m^3) x (MT/10^6g).

[b] The landfills in the landfill population data set are weighted in order to adjust the sample landfill population to the national level. The weighted numbers are 2, 3, and 7. Hence, a simulated landfill may account for 2, 3, or 7 landfills (Scale = 2, 3, or 7).

These equations are based on a survey of 85 landfills with a WIP ranging from 1.2 million MT to 30 million MT. The third equation is based on a regression analysis of the survey results. The second equation is based on the average rate of methane generation per unit of WIP.

[4] EPA conducts the emission analysis using a range of high and low average NMOC concentration values based on the number of landfills expected to trigger under the Landfill Rule by 2000. EPA calibrates the model by adjusting the average methane NMOC concentration to 500 parts per million by volume in order to simulate 350 existing and approximately 50 new landfills that will trigger under the Landfill Rule by 2000.

[5] EPA assumes that capital and O&M costs are constant for the 30-year time horizon and do not change due to development of more efficient and less costly technologies.

[6] The electricity rates in the U.S. that landfills are able to obtain for their generation, i.e., electric buyback rates, vary depending on several factors, including: the cost of system power on the grid (peak or off-peak), transmission (and in some cases distribution charges), region, and pricing. In addition, renewable power commands a premium that historically has been in the form of regulated buy-back rates or tax credits. More recently it has taken the form of green power premiums. Historically, under a regulated environment, landfill gas power projects have received electric buyback rates ranging from \$0.02/kWh to \$0.10/kWh, averaging about \$0.06/kWh (EPA, 1996). For this study, EPA assumes a price of \$0.04/kWh. This value represents the price of electricity close to distribution systems and receiving a renewable energy premium.

[7] Equation to calculate the equivalent electricity price for a given value of carbon equivalent:

$$\frac{\$}{TCE}\ x\ \frac{10^{6}\ TCE}{MMTCE}\ x\ \frac{5.73\,MMTCE}{Tg\ CH_4}\ x\ \frac{Tg}{10^{12}\ g}\ x\ \frac{19.2\ g\ CH_4}{ft^{3}\ CH_4}\ x\ \frac{ft^{3}}{1{,}000\ Btu}\ x\ \frac{10{,}000\ Btu}{kWh} = \frac{\$}{kWh}$$

Where: 5.73 MMTCE/Tg CH_4 = 21 CO_2/CH_4 x (12 C / 44 CO_2)
Density of CH_4 = 19.2 g/ft^3
Btu content of CH_4 = 1,000 Btu/ft^3
Heat rate of IC Engine = 10,000 Btu/kWh

[8] The costs for electricity production and direct gas use are based on different algorithms. Both options include collection and flare project components because some amount of gas will be flared. The landfill depth and area, and the collection system variable O&M costs are adjusted in E-PLUS so that the direct gas use collection capital and O&M costs are calibrated within five to ten percent of the electricity project collection system costs.

[9] Equation to calculate the equivalent gas price for a given value of carbon equivalent:

$$\frac{\$}{TCE}\ x\ \frac{10^{6}\ TCE}{MMTCE}\ x\ \frac{5.73\,MMTCE}{Tg\ CH_4}\ x\ \frac{Tg}{10^{12}\ g}\ x\ \frac{19.2\ g\ CH_4}{ft^{3}\ CH_4}\ x\ \frac{ft^{3}}{1{,}000\ Btu}\ x\ \frac{10^{6}\ Btu}{MMBtu} = \frac{\$}{MMBtu}$$

Where: 5.73 MMTCE/Tg CH_4 = 21 CO_2/CH_4 x (12 C / 44 CO_2)
Density of CH_4 = 19.2 g/ft^3
Btu content of CH_4 = 1,000 Btu/ft^3

Appendix II: Supporting Material for the Analysis of Landfills

In this appendix, EPA presents details on the methodologies to estimate the annual waste disposal rates and the costs for recovering methane from landfills. The appendix is comprised of six sections. The first section discusses the approach for projecting waste landfilled, and the second presents the assumptions used to evaluate costs and cost-effective emission reductions from landfill gas-to-energy projects (LFGTE). The third section describes the estimation method for the energy prices for which EPA conducts the analysis. The fourth section presents 84 break-even waste-in-place (WIP) and gas price combinations, a subset of which are used to construct a marginal abatement curve (MAC). The fifth section presents the cost-effective methane emission reductions for the energy prices and finally, the sixth section presents the uncertainties associated with the methods and analyses.

II.1 Waste Landfilled

This section provides an overview of the methods EPA uses to simulate waste in the population of U.S. landfills. EPA simulates waste disposal in U.S. landfills for the years 1990 through 2050. EPA bases the waste disposal data prior to 1990 on a 1988 landfill survey (EPA, 1988). For the years 1990 to 1997, EPA uses the BioCycle data presented in Exhibit II-1 (BioCycle, 1998). After 1997, waste disposal remains constant at 179,418 metric tons (MT). This estimate is the average of the BioCycle data from 1990 to 1995.

The analysis bases the total amount of waste disposed in each landfill on the design capacity and waste acceptance rate over time. Exhibit II-2 shows the design capacity for the categories of modeled landfills and Exhibit II-3 shows the percent of municipal solid waste (MSW) disposed in each landfill category from 1990 to 2050. Exhibit II-4 shows how EPA apportions total waste according to the waste disposal rates for each design capacity provided in Exhibit II-2.

Exhibit II-1: Landfill Waste Data

Year	Waste Generated[a] ('000 MT)	Percent Landfilled[b]	MSW Disposed in Landfills with Capacity < 500,000 MT[c]	Waste Landfilled for Categories 1-5[d]
1990	266,542	77%	10%	184,714
1991	254,797	76%	9%	175,443
1992	264,843	72%	9%	173,907
1993	278,573	71%	8%	181,568
1994	293,110	67%	8%	181,458
1995	296,586	63%	7%	173,770
1996	297,268	62%	7%	171,405
1997	309,075	61%	7%	175,338

[a, b] Source: BioCycle, 1998.

[c] These landfills are analyzed separately as they are excluded from EPA's 1988 landfill survey.

[d] The average between the beginning of 1990 to the beginning of 1995, is used to estimate total waste apportioned in each landfill category (see Exhibit II-4).

Exhibit II-2: Modeled Landfill Categories

Landfill Category	Capacity (MT)
1 - Small	500,000
2 - Small-Medium	1,000,000
3 - Medium	5,000,000
4 - Large	15,000,000
5 - Very Large	> 15,000,000

Exhibit II-3: MSW Landfill Waste Disposal Rates (Percent of Total MSW Landfill Disposed)

Category	Base ('90)	1990-95	1995-00	2000-05	2005-10	2010-15	2015-20	2020-25	2025-50
1	3.0%	2.0%	2.0%	1.5%	1.0%	1.0%	0.5%	0.5%	0.5%
2	9.6%	9.0%	8.0%	7.0%	6.0%	5.0%	4.0%	3.0%	2.0%
3	39.4%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%	40.0%
4	27.0%	29.0%	30.0%	30.5%	31.0%	31.5%	32.0%	32.0%	32.0%
5	21.0%	20.0%	20.0%	21.0%	22.0%	22.5%	23.5%	24.5%	25.5%
Total	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**	**100.0%**

Exhibit II-4: Total Waste Apportioned by Landfill Category (MT)

Category	Base('90)	1990-95	1995-00	2000-05	2005-10	2010-15	2015-20	2020-25	2025-50
1	5,541	3,588	3,588	2,691	1,794	1,794	897	897	897
2	17,732	16,148	14,353	12,559	10,765	8,971	7,177	5,383	3,588
3	72,777	71,767	71,767	71,767	71,767	71,767	71,767	71,767	71,767
4	49,873	52,031	53,825	54,722	55,620	56,517	57,414	57,414	57,414
5	38,790	35,884	35,884	37,678	39,472	40,369	42,163	43,957	45,752
Total:	**184,714**[a]	**179,418**[b]	**179,418**	**179,418**	**179,418**	**179,418**	**179,418**	**179,418**	**179,418**

[a, b] Source: BioCycle, 1998.

[b] 1995-2050 estimates are based on the average of the beginning of 1990 to the beginning of 1995.

II.2 Costs For Implementing Electricity And Direct Gas Use Projects

EPA uses different methods to estimate capital and operating and maintenance (O&M) costs for electricity generation and direct gas use. Exhibit II-5 presents the equations and assumptions used to calculate the total costs for electricity generation and Exhibit II-6 presents those used for direct gas use projects.

Exhibit II-5: Landfill Gas-to-Energy Project Cost Factors For Electricity Generation Projects

Cost Component	Cost Factors or Equation	Comments
Collection System Capital Cost	$[\text{WIP } (10^{6} \text{ MT})]^{0.8}$ x \$468,450	The maximum amount of waste-in-place (WIP) during the project lifetime is used to estimate the capital cost.
Collection System O&M Annual Costs	0.04 x Capital Cost + \$49,019	
Flare System Capital Costs	(Max Gas (ft^3/min) x \$31) + \$64,828	Max Gas is the peak gas flow rate during the anticipated operating lifetime from the collection system in cubic feet per minute.
Flare System O&M Costs	1.697 x Max Gas (ft^3/min) + \$3,497	

Exhibit II-5: (continued)

Cost Component	Cost Factors or Equation	Comments
Electric System Capacity in Megawatts (MW)	$\frac{\text{Max Gas (ft}^3\text{/min) x 500 Btu/ft}^3}{\text{10,000 Btu/kWh x 1,000 kW/MW}}$	Max Gas is the peak gas flow rate from the collection system in cubic feet per minute. The heat rate of the IC engine is 10,000 Btu/kWh. The landfill gas is 50% methane, with a Btu content of 500 Btu/ft^3.
Electric Generation System Capital Costs	Maximum of a) or b): a) $10^{0.903 \times \log(MW)}$ x 1,674,000 - Collection System Capital Costs; or b) 1,200,000 x MW	MW is the system capacity. Collection system costs are as estimated above from the landfill WIP. Option (a) developed from levelized costs and an 8% real discount rate over 20 years.
Electric Generation System O&M Costs	$0.015 kWh	

All estimates in 1996 dollars.

Sources: EPA, 1991a and 1991b.

Exhibit II-6: Unit Costs for Direct Use Projects

System	Capital		O&M	
	Component	Cost	Component	Cost
Collection	Wells	$80 / foot of depth	Collection System Variable O&M	$1,000 / acre[a]
	Wellheads	$750 / wellhead		
	Piping (main & branch)	$35 / foot		
	Blowers	$20 / ft^3 / min		
	Condensate Knockout	$8,000 / unit		
	Monitoring System	$1,000 / unit		
Flare	Flares	$75,000 / unit	Flare Fixed O&M	$2,000 / yr
Compression	Compressor System Capital	$1,350 / hp	Compressor System Variable O&M	Calculated[b]
Gas System	Scrubber	$15 / ft^3 / min	Gas Treatment Variable O&M	$2.50 / mill ft^3 / yr
	Dessicator	$10 / ft^3 / min	Gas Treatment Fixed O&M	$10,000 / yr
	Refrigeration	$60 / ft^3 / min		
	Filters	$3,220 / unit		
	Gas Treatment Installation	$15 / ft^3 / min		
Pipeline	Five-Mile Pipeline (12 inch diameter)	$35 / ft	Pipeline Variable O&M	2% of capital cost

[a] This number is calibrated in the Energy Project Landfill Gas Utilization Software (E-PLUS) so that the annual collection O&M cost for each landfill is consistent with the annual collection O&M cost for electricity projects, i.e., within five to ten percent.

[b] The fixed O&M used in this analysis is calculated using the following formula: compressor qty (hp) x 8,760 (hrs/yr) x 0.7457 (hp-hr to kWh) x $0.04 (price of electricity) + $12,000/unit/yr.

Source: E-PLUS, EPA, 1997.

II.3 Energy Prices

EPA translates a range of carbon equivalent values into energy prices to analyze how placing a value on reducing emissions affects the cost-effectiveness of emission reductions from electricity generation. The equivalent electricity prices ($/kilowatt-hour (kWh)) for each carbon equivalent value ($/ton of carbon equivalent (TCE)) are shown in Exhibit II-7. EPA calculates the electricity price at which landfill owners sell electricity by adding the equivalent electricity prices to the market price of $0.04/kWh. These prices are also shown in Exhibit II-7. EPA then evaluates each electricity price plus the additional value of carbon equivalent ($/TCE) to develop the MAC.

Exhibit II-7: Equivalent Electricity Prices for Carbon Equivalent Values

	Carbon Equivalent Value ($/TCE)											
	$0	$10	$20	$30	$40	$50	$75	$100	$125	$150	$175	$200
$/kWh	$0.00	$0.01	$0.02	$0.03	$0.04	$0.05	$0.08	$0.11	$0.14	$0.16	$0.19	$0.22
Base Prices	$0.04	$0.05	$0.06	$0.07	$0.08	$0.09	$0.12	$0.15	$0.18	$0.20	$0.23	$0.26

EPA uses a similar approach to calculate gas prices. A carbon equivalent value in $/TCE is converted into $/million British thermal units (MMBtu). The equivalent gas prices for each carbon equivalent value are shown in Exhibit II-8. EPA calculates the price at which landfill owners sell their gas by adding each equivalent gas price to the market gas price of $2.74/MMBtu. EPA uses these gas prices plus the additional value of carbon equivalent, shown in Exhibit II-8, to construct the MAC.

Exhibit II-8: Equivalent Gas Prices for Carbon Equivalent Values

	Carbon Equivalent Value ($/TCE)											
	$0	$10	$20	$30	$40	$50	$75	$100	$125	$150	$175	$200
$/MMBtu	$0.00	$1.10	$2.20	$3.30	$4.40	$5.50	$8.25	$11.00	$13.75	$16.49	$19.24	$21.99
Base Prices	$2.74	$3.84	$4.94	$6.03	$7.13	$8.23	$10.98	$13.73	$16.48	$19.23	$21.98	$24.73

II.4 Break-Even Waste-in-Place

In order to determine if direct gas use projects are cost-effective, EPA conducts a benefit-cost analysis and estimates the break-even WIP for 84 gas prices. Each WIP and gas price combination is presented in Exhibit II-9. A subset of these values is used to create the MAC presented in the Landfill Chapter (see Exhibit 2-11). These 84 gas prices reflect a range in energy values from 50 to 300 percent of base energy prices shown in Exhibit II-8.

Exhibit II-9: Gas Price and Equivalent Break-Even WIP

Gas Price ($/MMBtu)	Break-Even WIP (MT)	Gas Price ($/MMBtu)	Break-Even WIP (MT)	Gas Price ($/MMBtu)	Break-Even WIP (MT)
$1.37	10,733,415	$7.82	419,389	$16.47	183,036
$2.05	2,330,467	$8.21	394,982	$16.48	182,893
$2.47	985,447	$8.23	393,655	$17.17	175,391
$2.74	972,739	$8.50	380,051	$17.85	167,889
$3.15	953,057	$8.77	366,448	$17.86	167,746
$3.42	940,349	$8.92	358,983	$18.55	160,244
$3.57	933,376	$9.31	341,640	$19.20	153,030
$3.84	920,668	$9.60	330,039	$19.22	152,886
$4.10	907,960	$9.62	329,523	$19.23	152,742
$4.25	900,986	$9.87	319,468	$19.91	147,367
$4.52	837,428	$10.30	302,581	$20.60	143,216
$4.67	800,200	$10.41	298,865	$20.61	143,137
$4.94	749,467	$10.97	283,826	$21.30	138,986
$5.20	698,987	$10.98	283,477	$21.95	134,995
$5.35	675,817	$11.51	269,487	$21.97	134,915
$5.47	656,765	$11.67	265,202	$21.98	134,836
$5.62	633,595	$12.35	247,859	$22.66	130,685

Exhibit II-9: (continued)

Gas Price ($/MMBtu)	Break-Even WIP (MT)	Gas Price ($/MMBtu)	Break-Even WIP (MT)	Gas Price ($/MMBtu)	Break-Even WIP (MT)
$5.77	610,424	$12.36	247,615	$23.35	126,535
$6.03	576,422	$12.61	243,106	$23.36	126,456
$6.30	545,669	$13.05	234,879	$24.04	122,305
$6.45	530,436	$13.71	222,631	$24.70	118,313
$6.57	517,911	$13.72	222,387	$24.72	118,234
$6.72	502,678	$13.73	222,143	$24.73	118,155
$6.87	490,135	$14.42	209,407	$25.41	114,004
$7.13	468,324	$15.10	198,039	$26.10	109,854
$7.40	447,136	$15.11	197,896	$27.45	101,632
$7.55	437,304	$15.80	190,394	$27.46	101,553
$7.67	429,221	$16.46	183,180	$30.20	95,459

II.5 Marginal Abatement Curve

EPA evaluates the cost-effectiveness of LFGTE systems for the combinations of electricity and gas prices. The amounts of abated methane for 2000, 2010, and 2020 are displayed in Exhibit II-10 and Exhibit II-11. Exhibit II-10 shows the abated methane in million metric tons of carbon equivalent (MMTCE) and Exhibit II-11 shows the abated methane as a percent of the baseline. In each exhibit, the abated methane is incremental to methane abated as a result of the Landfill Rule. EPA estimates the percent abated methane as the emission reductions divided by the baseline emissions for the individual years. The baseline emissions are the emissions that would occur after the Landfill Rule emission reductions are taken into account. Each percent of abated methane represents cost-effective emission reductions for the combination of gas and electricity prices plus the added value of carbon equivalent. The market price, with no added value of carbon equivalent, is represented by $0/TCE.

An example of how percent abated methane is estimated at a combination of energy prices plus an additional carbon equivalent value is as follows. At $20/TCE in 2010, the emission reduction incremental to the Landfill Rule is 20.2 MMTCE and the electricity and gas prices are $0.06/kWh ($0.04/kWh + $0.02/kWh) and $4.94/MMBtu ($2.74/MMBtu + $2.20/MMBtu), respectively. The percent of abated methane at this combination of energy prices is 39%. This value is calculated as indicated in Exhibit II-12.

Exhibit II-10: Emission Reductions Incremental to the Landfill Rule by Year (MMTCE)

	Carbon Equivalent Value ($/TCE)											
	$0	**$10**	**$20**	**$30**	**$40**	**$50**	**$75**	**$100**	**$125**	**$150**	**$175**	**$200**
2000	11.03	14.08	18.21	19.74	20.13	20.55	21.23	21.41	21.49	21.56	21.61	21.66
2010	10.55	14.44	20.23	21.45	21.75	21.85	21.90	21.91	21.91	21.91	21.91	21.91
2020	7.62	10.12	13.88	15.00	15.46	15.69	15.84	15.88	15.88	15.90	15.90	15.92

Exhibit II-11: Emission Reductions Incremental to Landfill Rule by Year (Percent of Baseline Emissions)

	Carbon Equivalent Value ($/TCE)											
	$0	**$10**	**$20**	**$30**	**$40**	**$50**	**$75**	**$100**	**$125**	**$150**	**$175**	**$200**
2000	21%	27%	35%	38%	39%	40%	41%	42%	42%	42%	42%	42%
2010	20%	28%	39%	41%	42%	42%	42%	42%	42%	42%	42%	42%
2020	19%	25%	34%	37%	38%	38%	39%	39%	39%	39%	39%	39%

Exhibit II-12: Percent Reduction – Example Calculation

Total Emissions from Landfills in 2010[a]	52.0 MMTCE (see Exhibit 2-6 in Chapter 2)
Landfill Rule Reductions in 2010	31.8 MMTCE (see Exhibit 2-6 in Chapter 2)
Total reductions incremental to the Landfill Rule in 2010 at $20/TCE	20.2 MMTCE (See Exhibit II-10)
Percent reduction in 2010 at $20/TCE	(20.2 / 52.0) MMTCE = 39 %

[a] This value accounts for reductions associated with landfills that are impacted by the Landfill Rule.

The methane abatement potential for non-Rule landfills in 2020 is slightly less than in the previous years because the Landfill Rule plays an increasingly large role in reducing emissions in the future. New landfills simulated to open are estimated to be larger (on average) than existing landfills. These larger landfills are expected to trigger under the Landfill Rule and, consequently, emissions decline in the future.

The collection efficiency for all landfill methane recovery projects, whether required by the Landfill Rule or not, is 75 percent. However, the percent of abated methane, even at high carbon equivalent values, is lower than 75 percent (see Exhibit II-11) due to EPA's methodology for estimating the percent of abated methane beyond regulation requirements. As indicated in Exhibit II-11, even at high additional carbon equivalent values, further abatement is not achieved as methane emissions cannot be collected with 100 percent efficiency. The example in Exhibit II-13 illustrates this concept.

The analysis evaluates the percent of abated methane from non-impacted landfills against baseline emissions. Baseline emissions represent a conglomerate of four sources: (1) methane from landfills not impacted by the Landfill Rule; (2) residual methane not recovered from landfills that are impacted by the Landfill Rule, i.e., methane that is emitted due to 75 percent collection efficiency and not captured by the gas collection system; (3) methane from industrial landfills; and (4) methane from small landfills. Consequently, the baseline emission value includes emissions from landfills impacted by the Landfill Rule that cannot further reduce emissions.[1]

Exhibit II-13: Calculating Percent Reductions - Hypothetical Example

- Emissions from landfills not impacted by the Landfill Rule:
  - Base emissions = 10.0 MMTCE
  - After installing LFGTE system = 2.5 MMTCE
  - Emissions reduced = 7.5 MMTCE
- Emissions from landfills impacted by the Landfill Rule:
  - Prior to installing LFGTE system = 20.0 MMTCE
  - Base emissions (after installing LFGTE system) = 5.0 MMTCE
- Base:
  - Emissions from landfills not impacted by the Landfill Rule plus resulting emissions from landfills impacted by Landfill Rule = (10.0 + 5.0 = 15.0) MMTCE
- Percent emissions reduced due to implementing cost-effective LFGTE:
  - Emissions reduced from landfills not impacted by rule divided by base = (7.5/15.0) MMTCE = 50 %

II.6 Uncertainties

Exhibit II-14 outlines the uncertainties with the methane estimation approach and Exhibit II-15 describes the uncertainties with the MAC.

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[1] As the share of landfills impacted by the Rule increases over time, fewer emission reductions are achieved beyond the Landfill Rule requirements, i.e., the percent reduction approaches zero.

Exhibit II-14: Emission Estimate Uncertainties

	Basis
Characterization of landfills and total WIP	A simulation characterizes the entire U.S. landfill population based on characterizations of a subset of U.S. landfills, including size, waste acceptance rate, and opening year.
Future waste disposal	Future waste disposal is assumed to remain constant at the average rate from the beginning of 1990 to the beginning of 1995. This average is based on the assumption that waste generation increases along with population, but will subsequently be offset by increases in alternative disposal methods such as recycling and composting.
Gas equation used for estimating methane emissions	Emission factors are derived from data on 85 U.S. landfills and are applied based on landfill WIP.
Recovery prior to 1997	Recovery rates (after flared methane is accounted for) are assumed to remain constant at 1990 levels for 1991 and at 1992 levels for 1993 to 1997. In addition, the gas collected but not utilized is assumed to equal 25 percent of the methane recovery.
Flare-only option	For years following 1997, the analysis lacks sufficient information about the population of landfills that flare without recovering methane for energy use.
Industrial waste landfilled	Industrial methane production is assumed to equal approximately seven percent of MSW landfill methane production.
Methane oxidation rate	Ten percent of methane generated is assumed to oxidize in soil.

Exhibit II-15: Cost Analysis Uncertainties

	Basis
Cost estimate	Costs are estimated using aggregate cost factors and a relatively simple set of landfill characteristics. Electricity costs are estimated using representative WIP. Direct use costs are estimated using hypothetical landfills in terms of depth, area, and WIP.
Revenue	The rate at which electricity is sold from a landfill project depends on local and regional electric power market conditions and often varies by time of day and season of year. However, this analysis uses a representative figure that remains constant.
Potential for landfills to collect and use gas cost-effectively	The extent to which electricity production and direct gas use are cost-effective depends on the energy price and availability of end-users.
Methane recovery technologies	This analysis only focuses on internal combustion (IC) generators and direct gas use because they are the most cost-effective technologies for projects examined in this analysis. However, other technologies are available, e.g., electricity generation using turbine generators.
Equipment and engineering costs	Information is based on current projects and industry experts.

II.7 References

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