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LANDFILL GAS RECOVERY/UTILIZATION - OPTIONS AND ECONOMICS

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ABSTRACT

The decomposition of landfilled waste results in a gas which can be a source of pollution as well as a resource. Of the more than 6,000 active municipal solid waste landfills in the United States (U.S.), there are 114 landfill gas (LFG) energy projects. This paper describes the options and economics for LFG utilization, as well as ongoing research associated with encouraging/facilitating energy recovery from LFG. The health and environmental concerns are described as well as the economic, environmental, and energy benefits associated with LFG utilization. Six case studies are also provided to illustrate the options for LFG utilization. In addition, the results of a recent EPA survey of U.S. LFG utilization are provided.

The Environmental Protection Agency (EPA) research that is described in this paper was conducted as part of EPA's Global Climate Change Program on emissions from landfills and other waste facilities that contribute to global climate change (Thomeloe, 1991). EPA's Air and Energy Engineering Research Laboratory (AEERL) has responsibility for EPA's research on emissions and mitigation for the major sources contributing to global climate change.

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INTRODUCTION

LFG is generated from the anaerobic decomposition of landfilled biodegradable waste. The composition of the gas is typically 50 to 55% methane, 45 to 50% carbon dioxide, and <1% nonmethane organic compounds (NMOCs). The concentration of NMOCs can range from 240 to 14,300 ppm (EPA, 3/91). LFG can also contain chlorinated and fluorinated compounds, particulate, water vapor, and occasionally air. Air is present from air intrusion into the landfill (i.e., it does not result from the anaerobic decomposition of wastes). There are economic incentives as well as safety considerations to operate the gas extraction wells so that air intrusion is minimized. Air intrusion can (1) kill the anaerobic bacteria that are needed to decompose organic refuse and (2) cause a landfill fire. Air infiltration is also minimized because it dilutes the gas and increases the cost of recovering energy from the gas.

The average heat content of LFG ranges from 17 to 20 MJ/dscm (450 to 550 Btu/dscf). Laidlaw Technologies, Inc., with responsibility for 12 LFG energy recovery projects, estimates that between 1,250 and 1,600 kW_e of energy is generated from 28,000 scmd (1 million scfd) of LFG at 17 MJ/scm (450 Btu/scf) (Jansen, 1992). Consequently LFG is recovered to take advantage of the energy potential. This results in reducing emissions of methane, NMOCs, and toxics. In addition, emissions are reduced at coal-fired power plants, and global resources of fossil fuel are conserved.

The environmental and health concerns associated with municipal solid waste (MSW) landfills have been well documented. In the U.S., EPA has documented 40 cases of gas migration resulting in explosions and fires. Of these 40 cases, 10 resulted in injuries and death (EPA, 3/91). The methane is also a concern because of its contribution to global warming. Landfills are a significant source of methane, ranking third in anthropogenic sources after rice paddies and ruminants (Peer et al., 1992, Khalil and Rasmussen, 1990). A third concern with LFG emissions is the contribution of NMOCs to tropospheric ozone which affects human health and vegetation. The EPA has estimated that roughly 1% (i.e., 260,000 Mg/yr) of the NMOC emissions from stationary sources in the U.S. are emitted by MSW landfills. Toxic constituents typically found in LFG include vinyl chloride, toluene, and benzene. The toxic constituents may contribute to possible cancer and non-cancer health effects. A fifth concern is the odor nuisance associated with LFG. Because of the health and environmental concerns, the EPA has designated "MSW landfill emissions" as a pollutant. The EPA has proposed Emission Guidelines for existing landfills and New Source Performance Standards for new landfills (F.R., 5/91). The regulations are scheduled to be promulgated this Fall.

The regulatory alternative proposed by the Clean Air Act regulations would result in requiring 621 landfills to collect and control MSW landfill air emissions. (p. 24480, F.R., 5/91). It is hoped that the sites affected by these regulations will utilize the gas as opposed to flaring the gas. The use of energy recovery for the control of MSW landfill air emissions will result in decreased emissions of methane, NMOC, and toxics. In addition, there are benefits associated with the development of an alternative source of energy which results in decreased emissions at coal-fired power plants and a decreased use of fossil fuels. The focus of this paper is to identify the options for LFG gas utilization and provide an overview of the economics associated with each option. Case studies are presented to illustrate the options for LFG utilization.

Energy Utilization Options

A recent EPA survey identified 114 LFG energy recovery projects in the U.S. The results from this survey are summarized in Table 1. Detailed results of this EPA survey are scheduled to be published this summer. This survey was conducted in coordination with the Solid Waste Association of North America and used the results of recent U.S. LFG surveys (Berenyi and Gould, 1991, Waste Age, 1990). Only sites that are actually operating LFG energy projects are included in Table 1.

Figure 1 provides a breakdown of the type of energy projects in the U.S. Most of the projects (i.e., ~75%) generate electricity which is either used on-site or sold to a local utility. Of the projects generating electricity, approximately 344 MW_e of power is being produced with 61 projects using internal combustion (IC) engines, 21 projects using gas-fed turbines, and 3 projects using steam-fed turbines. Pipeline quality gas is produced at 6 sites, and 1 site is processing LFG to produce diesel fuel. The most economical options for LFG utilization tend to be direct uses such as for process heat and as boiler fuel. Direct use of LFG as medium-heating value fuel is occurring at 21 sites.

Figure 2 provides a breakdown of the U.S. LFG projects by state indicating the number of projects for states where there are at least three active LFG utilization projects. California has the largest number of LFG projects partially due to state and local requirements resulting in the collection and control of gas. However, many LFG energy projects have been initiated because of attractive economics particularly in the early 1980s when the price of energy helped make this more economical. Waste Management of North America has installed gas collection and controls as part of their operating policy. Waste Management has LFG energy recovery projects at 25 sites with plans to start new projects at 5 additional sites. The Clean Air Act regulations proposed May 30, 1991, are expected to result in additional LFG utilization projects.

Direct-Gas Use (Medium-Heating Value). The options for medium-heating value LFG [i.e., ~19 MJ/dscm (~500 Btu/dscf)] include use as boiler fuel, space heating and cooling, and industrial heating/cofiring applications. The most typical use is as boiler fuel to produce steam. The majority of the 21 sites selling LFG for direct use are supplying fuel for boilers. This is a particularly attractive option since conventional equipment can be used with relatively little modification. In addition, boilers tend to be less sensitive to LFG trace constituents and consequently less gas cleanup is required compared to the other alternatives. A limitation in the selection of this option is that a LFG customer must be relatively near, typically less than 1,600 to 3,200 meters (1 to 2 miles) is considered desirable.

The other options for medium-heating value gas include industrial applications such as lumber drying, kiln operations, and cement manufacturing. An advantage of many industrial applications is that fuel is required continuously, 24 hours per day. LFG can also be used as a supplemental fuel that meets a portion of the total demand. LFG to produce space heating is in limited use primarily due to piping costs and difficulty in matching up the LFG energy output with nearby user needs. Depending on climate and other factors, heat energy supplied by 14,000 scmd (500,000 scfd) LFG corresponds to heating needs of a 18,600-93,000 m^2 (200,000 to 1,000,000 sq ft) facility. The main difficulty with space heating is that loads tend to be variable over time, both during the day and by season. One of the case studies, however, demonstrates the successful use of LFG for producing space heating.

Electricity Generation. Of the 114 U.S. LFG energy recovery projects, 61 projects generate electricity using IC engines and 24 projects generate electricity using turbines. Of the 344 MW_e of energy produced at these sites, 50% is generated using turbines and 50% is generated using IC engines. The type of equipment is generally determined by the volume of gas available and the air pollution requirements of the area in which the project

TABLE 1. U.S. LANDFILL GAS ENERGY PROJECTS

USEPA, Thorneloe, 5/7/92

	Landfill Name	Location (City)	Location (State)	Use of Landfill Gas	Date Gas Recovery Began	LFG Recov'd (millions) (scfd)	Gross Energy Recov'd (MW)	Total Land-fill (acres)	Devoted Methane Recovery (acres)	Refuse Buried On-Site (mil. T)	LFG Developer/Operator
1	Northside	Birmingham	AL	Pipeline Quality Gas	Apr-88	2.7	NA	100	80	5.8	Birmingham Gas Resources
2	Huntsville	Huntsville	AL	Direct Gas User - Boiler	May-90	2.3	NA	45	12	0.5	The Maguire Group Inc.
3	Olinda	Brea	CA	Electricity Gen - IC Engines	Nov-84	3.0	5.7	135	135	12.0	GSF Energy
4	Burbank	Burbank	CA	Electricity Gen - IC Engines	Aug-88	4.4	0.8	86	24	1.4	J.W. Operating Co.
5	Temescal Road	Corona	CA	Electricity Gen - IC Engines	Jan-86	1.0	2.3	90	90	4.0	O'Brien Energy Systems
6	Duarte (*)	Duarte	CA	Electricity Gen - IC Engines	Oct-87	0.5	1.6*	33	33	1.6	O'Brien Energy Systems
7	Southeast Regional	Fresno	CA	Electricity Gen - IC Engines	Feb-89	0.7	0.7	70	70	2.0	Monterey Landfill Gas Corp./J.W. Oper. Co.
8	Industry Hills	Industry	CA	Direct Gas User - Med Btu	Feb-81	0.5	NA	150	150	1.5	City of Industry
9	Altamont	Livermore	CA	Electricity Gen - Gas Turbine (2)	May-89	2.0	6.0	225	225	14.3	Waste Mgmt of North America
10	Mountain Gate	Los Angeles	CA	Direct Gas User - Boiler	Nov-84	5.0	NA	80	80	10.0	GSF Energy
11	Toyon Canyon	Los Angeles	CA	Electricity Gen - IC Engines	Dec-85	4.0	10.0	90	90	16.0	Pacific Energy
12	Monterey Regional	Marina	CA	Electricity Gen - IC Engines	Dec-83	0.9	1.2	478	60	3.7	Monterey Regional Waste Mgmt
13	Acme	Martinez	CA	Direct Gas User - Med Btu	Apr-82	1.7	NA	270	270	5.0	GSF Energy
14	Marsh Road	Menlo Park	CA	Electricity Gen - IC Engines	Jan-83	1.4	2.0	160	100	4.0	Laidlaw Gas Recovery Systems
15	Mountain View	Mountain View	CA	Electricity Gen - IC Engines	Dec-85	2.2	3.5	300	200	3.0	Laidlaw Gas Recovery Systems
16	American Canyon	Napa County	CA	Electricity Gen - IC Engines	Dec-85	0.8	1.5	122	70	?	Laidlaw Gas Recovery Systems
17	Coyote Canyon	Orange County	CA	Electricity Gen - IC Engines	Feb-89	14.4	20.0	300	300	50.0	Laidlaw Gas Recovery Systems
18	Oxnard Power Station (**)	Oxnard	CA	Electricity Gen - IC Engines	Mar-85	3.5	5.1	140	140	2.7	Pacific Energy
19	Palo Alto	Palo Alto	CA	Electricity Gen - IC Engines	Apr-90	0.8	1.1	80	60	2.5	Monterey Landfill Gas Corp.
20	Spadra	Pomona	CA	Electricity Gen - Steam Fed Turbine/Direct Use in Boiler	Feb-90	4.3	5.0	210	210	9.0	LA County Sanitation Districts
21	Palos Verdes	Rolling Hills Estates	CA	Electricity Gen - Steam Fed Turbine/Direct Use in Boiler	Mar-88	11.0	9.0	173	173	18.0	LA County Sanitation Districts
22	Sacramento	Sacramento	CA	Direct Gas User - Boiler	90	1.0	NA	113	40	2.6	Laidlaw Gas Recovery Systems

1 ft^3 = 0.028 m^3; 1 acre = 4046.9 m^2; 1 ton = 907 kg
NA = Not Applicable, ? = Not Available

(Continued)

TABLE 1. U.S. LANDFILL GAS ENERGY PROJECTS (Continued) *USEPA, Thorneloe, 5/7/92*

	Landfill Name	Location (City)	Location (State)	Use of Landfill Gas	Date Gas Recovery Began	LFG Recov'd (millions) (scfd)	Gross Energy Recov'd (MW)	Total Landfill (acres)	Devoted Methane Recovery (acres)	Refuse Buried On-Site (mill. T)	LFG Developer/Operator
23	Crazy Horse Canyon	Salinas	CA	Electricity Gen - IC Engines	Dec-86	0.8	1.1	125	125	1.8	Pacific Energy
24	Otay Landfill (#)	San Diego	CA	Electricity Gen - IC Engines	Dec-86	1.9	3.4	525	400	6.1	Pacific Energy
25	Sycamore Canyon	San Diego	CA	Electricity Gen - Gas Turbine	Dec-88	1.2	1.7	532	100	4.5	Laidlaw Gas Recovery Systems
26	Newby Island	San Jose	CA	Electricity Gen - IC Engines	Aug-84	3.0	5.0	342	170	?	Laidlaw Gas Recovery Systems
27	Davis Street	San Leandro	CA	Direct Gas User - Med Btu	Jul-81	1.9	NA	100	100	9.7	GSF Energy
28	San Marcos	San Marcos	CA	Electricity Gen - Gas Turbine	Dec-88	1.2	1.7	95	95	3.8	Laidlaw Gas Recovery Systems
29	Santa Clara	Santa Clara	CA	Electricity Gen - IC Engines	Dec-86	0.9	1.1	165	125	3.5	Pacific Energy
30	Guadalupe	Santa Clara Co.	CA	Electricity Gen - IC Engines	Apr-84	1.1	2.6	115	65	3.5	Laidlaw Gas Recovery Systems
31	Santa Cruz	Santa Cruz	CA	Electricity Gen - Gas Turbine	Nov-88	0.6	0.9	100	30	4.5	Laidlaw Gas Recovery Systems
32	Austin Road	Stockton	CA	Electricity Gen - IC Engines	Dec-85	0.4	0.8	171	140	1.9	Pacific Energy
33	Bradley	Sun Valley	CA	Direct Gas User - Med Btu	Jun-89	3.0	NA	209	209	13.4	Waste Mgmt of North America
34	Penrose (##)	Sun Valley-LA	CA	Electricity Gen - IC Engines	Dec-85	4.9	10.0	72	72	9.0	Pacific Energy
35	Sheldon-Arleta	Sun Valley-LA	CA	Direct Gas User - Med Btu	Jan-88	0.8	NA	40	40	3.0	Pacific Energy
36	BKK	West Covina	CA	Electricity Gen - IC Engines	86	23.0	5.0	500	500	25.0	Douglas Energy
37	Puente Hills- Rio Hondo (###)	Whittier	CA	Direct Use - Boiler & Cogen Engine	Mar-84	0.5	0.55*	570	570	60.0	LA County Sanitation Districts
38	Puente Hills-Gas Turbines (###)	Whittier	CA	Electricity Gen - Gas Turbine	Dec-83	4.0	4.0	570	570	60.0	LA County Sanitation Districts
39	Puente Hills-PERG (###)	Whittier	CA	Electricity Gen - Steam Fed Turbine/Direct Use in Boiler	Nov-86	33.0	50.0	570	570	60.0	LA County Sanitation Districts
40	Yolo County	Yolo County	CA	Electricity Gen - IC Engines	Nov-89	1.3	1.5	700	116	3.1	Monterey Landfill Gas Corp.
41	Templeton Gap	Colorado Springs	CO	Pipeline Quality Gas	Jun-91	2.4	NA	40	33	2.0	Fuel Resources Development Co.
42	County Line	Littleton	CO	Electricity Gen - IC Engines (1)	Dec-86	0.3	0.8	90	90	3.1	Waste Mgmt of North America
43	Synhitech	Pueblo	CO	Upgrading Gas into Diesel Fuel	Jul-91	2.0	NA	114	114	3.5	Fuel Resources Development Co.
44	New Milford	New Milford	CT	Electricity Gen - Gas Turbines (1)	Jun-91	2.0	3.3	90	90	3.6	Waste Mgmt of North America

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45	Kenilworth Park	Washington	DC	Direct Gas User- Med Btu	Nov-82	0.3	NA	145	12	2.7	National Park Service
46	Cherry Island	Wilmington	DE	Direct Gas User - Med Btu	Oct-90	0.9	NA	30	17	0.8	Delaware Solid Waste Authority
47	Central Disposal (CDSL)	Pompano Beach	FL	Electricity Gen - Gas Turbines (5)	May-89	10.0	15.0	210	210	15.3	Waste Mgmt of North America
48	Watts Rd Landfill	Atlanta	GA	Pipeline Quality Gas	Apr-86	1.1	NA	55	55	3.0	Browning Ferris Industries
49	Macon	Macon	GA	Direct User - Brick Kiln	Jan-85	1.1	NA	120	69	3.5	Gas Resources Corp.
50	Kapaa	Kailua, Oahu	HI	Electricity Gen - Gas Turbines	May-89	2.1	3.3	42	42	1.2	Laidlaw Gas Recovery Systems
51	Settler's Hill	Batavia	IL	Electricity Gen - Gas Turbines (2)	Oct-88	2.5	3.9	179	179	7.7	Waste Mgmt of North America
52	Blue Island	Blue Island	IL	Direct Gas User - Med Btu	Nov-83	1.0	NA	130	130	5.0	GSF Energy
53	CID	Chicago	IL	Electricity Gen - Gas Turbines (3)	May-89	6.0	9.0	173	173	20.0	Waste Mgmt of North America
54	Tazewell	East Peoria	IL	Electricity Gen - IC Engines (2)	Jul-89	0.8	1.6	125	110	2.2	Waste Mgmt of North America
55	Milam	Madison	IL	Electricity Gen - IC Engines (2)	Apr-91	0.9	1.6	110	110	4.3	Waste Mgmt of North America
56	Lake Landfill	Northbrook	IL	Electricity Gen - Gas Turbines (2)	Jul-88	4.0	6.0	187	187	12.6	Waste Mgmt of North America
57	Pennington Ave	Baltimore	MD	Direct Gas User - Med Btu	Apr-84	0.9	NA	60	50	2.0	Maryland Recycling & Rehandling
58	Brown Station Rd	Prince George's County	MD	Electricity Gen - IC Engines & Direct Use	Jun-87	1.0	2.6	40	20	4.0	The Maguire Group Inc.
59	Gude Southlawn	Rockville	MD	Electricity Gen - IC Engines	Dec-85	1.4	2.5	91	91	4.8	Pacific Energy
60	Wayne Disposal	Belleville	MI	Electricity Gen - IC Engines & Direct Use	Jun-84	0.8	1.4	300	300	12.0	Wayne Energy Recovery, Inc.
61	Wood Street	Lansing	MI	Electricity Gen - IC Engines	Oct-85	0.7	?	200	55	1.6	Granger Renewable Resources, Inc.
62	Riverview	Riverview	MI	Electricity Gen - Gas Turbines	Dec-87	3.8	6.1	250	145	10.0	Riverview Energy Systems, Inc.

1 ft³ = 0.028 m³; 1 acre = 4046.9 m²; 1 ton = 907 kg
NA = Not Applicable, ? = Not Available

(Continued)

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63	Grand Ledge	Watertown	MI	Electricity Gen - IC Engines	Apr-91	1.2	2.4	200	60	?	Granger Renewable Resources, Inc.
64	Woodland Meadows	Wayne	MI	Direct Gas User - Boilers	Jan-91	2.1	NA	203	175	7.0	Waste Mgmt of North America
65	Anoka	Anoka	MN	Direct Gas User - Med Btu	Nov-89	0.8	NA	100	100	3.8	Waste Mgmt of North America
66	North Sanitary	Maryland Hts	MO	Direct Gas User - Med Btu	Jun-81	0.3	NA	50	30	?	Fred Weber Company
67	Little Dixie	Jackson	MS	Direct Gas User - Med Btu	Sep-90	1.6	NA	30	30	1.8	Browning Ferris Industries
68	Rowland	Raleigh	NC	Electricity Gen - IC Engines	Jun-84	0.0	0.1	25	4	0.1	Natural Power
69	Wilder's Grove	Raleigh	NC	Direct Gas User (Boiler Fuel) - Med Btu	Dec-89	1.5	NA	125	90	3.5	Natural Power
70	Manchester	Manchester	NH	Electricity Gen - IC Engines	Jul-88	0.5	0.8	30	30	1.2	Energy Tactics
71	Turnkey	Rochester	NH	Electricity Gen - IC Engines	Feb-92	1.3	2.4	96	50	3.1	Waste Mgmt of North America
72	Kinsley	Deptford Township	NJ	Electricity Gen - IC Engines	Jun-85	1.3	2.4	136	70	6.0	United Environmental Services, Inc.
73	Edison	Edison	NJ	Electricity Gen - IC Engines	Sep-90	3.0	4.4	30	30	2.5	O'Brien Energy Systems
74	Hackensack Meadowlands	Kearny	NJ	Pipeline Quality Gas	Dec-89	7.2	NA	350	300	30.0	GSF Energy
75	H.S.L.	Lafayette	NJ	Electricity Gen - IC Engines	Aug-90	0.7	1.0	30	30	1.5	O'Brien Energy Systems
76	L & D	Mount Holly	NJ	Electricity Gen - Gas Turbines (2)	Mar-90	2.5	3.9	175	175	3.3	Waste Mgmt of North America
77	High Acres	Fairport	NY	Electricity Gen - IC Engines (2)	Apr-91	0.5	1.6	92	92	3.4	Waste Mgmt of North America
78	Mohawk Valley	Frankfort	NY	Electricity Gen - IC Engines (1)	Oct-91	0.4	0.8	80	50	1.7	Waste Mgmt of North America
79	Orange County	Goshen	NY	Electricity Gen - Gas Turbines	Dec-88	2.1	3.3	70	70	4.0	Laidlaw Gas Recovery Systems
80	Blydenburg Road	Hauppauge	NY	Electricity Gen - IC Engines	Dec-88	2.3	4.0	70	40	2.0	JWP, Inc.
81	East Northport	Huntington	NY	Electricity Gen - IC Engines	Apr-84	0.8	1.2	44	37	4.0	H. O. Penn Machinery, Inc.
82	Al Turi	Middletown	NY	Electricity Gen - IC Engines	Jun-87	2.5	4.1	72	72	2.8	J.W. Operating Co.
83	Hempstead	Oceanside	NY	Electricity Gen - IC Engines	Dec-90	2.9	4.0	180	110	6.5	Energy Tactics

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84	Oyster Bay	Oyster Bay	NY	Electricity Gen - IC Engines	Dec-85	1.4	2.6	120	60	2.8	Energy Tactics
85	Riverhead	Riverhead	NY	Electricity Gen - IC Engines	Jan-85	0.4	0.6	40	40	3.0	United Environmental Services, Inc.
86	Monroe Livingston	Scottsville	NY	Electricity Gen - IC Engines (4)	Dec-88	1.7	3.2	90	90	2.9	Waste Mgmt of North America
87	Smithtown	Smithtown	NY	Electricity Gen - IC Engines	Jan-85	0.7	1.0	30	20	1.4	Energy Tactics
88	Fresh Kills	Staten Island	NY	Pipeline Quality Gas	Aug-82	9.5	NA	3,000	400	28.0	GSF Energy
89	Onondaga County	Syracuse	NY	Electricity Gen - IC Engines	Dec-87	0.7	1.0	60	60	1.3	Energy Tactics
90	Horse Block Road	Yaphank	NY	Electricity Gen - IC Engines	Jan-84	1.9	2.8	100	60	6.8	H. O. Penn Machinery, Inc.
91	Elda Landfill	Cincinnati	OH	Direct Gas User - Boilers	Apr-86	2.6	NA	106	106	5.8	Waste Mgmt of North America
92	Rumpke	Colerain	OH	Pipeline Quality Gas	Sep-86	5.4	NA	200	150	14.0	GSF Energy
93	Short Mountain	Lane County	OR	Electricity Gen - IC Engines	Jan-92	0.9	1.6	275	50	2.6	Emerald People's Utility District
94	F. R. & S.	Birdsboro	PA	Electricity Gen - IC Engines	Jul-87	0.5	0.8	25	25	1.6	O'Brien Energy Systems
95	East Pennsboro	Enola	PA	Electricity Gen - IC Engines	Sep-85	0.1	0.1	20	14	0.4	East Pennsboro Township
96	Mazzaro	Finley Township	PA	Electricity Gen - IC Engines	May-89	2.0	2.4	90	30	3.0	O'Brien Energy Systems
97	GROWS	Morrisville	PA	Electricity Gen - Gas Turbines (2)	Dec-87	4.0	6.0	434	100	11.6	Waste Mgmt of North America
98	Greater Lebanon	N. Lebanon Township	PA	Electricity Gen - IC Engines	Nov-85	0.9	1.2	75	40	1.0	Lebanon Methane Recovery, Inc.
99	Pottstown	Pottstown	PA	Electricity Gen - Gas Turbines (2)	Apr-89	4.0	6.0	178	90	9.9	Waste Mgmt of North America
100	Consho-hocken	Swedeland	PA	Electricity Gen - IC Engines	Mar-86	2.0	2.8	25	25	3.6	O'Brien Energy Systems
101	Taylor	Taylor	PA	Electricity Gen - IC Engines	May-88	0.7	2.0	45	40	2.0	O'Brien Energy Systems
102	Central	Johnston	RI	Electricity Gen - IC Engines	Nov-89	6.9	12.3	150	100	11.3	Palmer Capital
103	Chestnut Ridge	Heiskell	TN	Electricity Gen - IC Engines (3)	Jan-92	1.0	2.4	108	75	2.8	Waste Mgmt of North America
104	McCarty Road	Houston	TX	Pipeline Quality Gas	Feb-87	8.0	NA	270	270	14.0	GSF Energy
105	DFW	Lewisville	TX	Electricity Gen - Gas Turbine (1)	May-88	2.0	3.0	416	120	7.3	Waste Mgmt of North America

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	Landfill Name	Location (City)	Location (State)	Use of Landfill Gas	Date Gas Recovery Began	LFG Recov'd (millions) (scfd)	Gross Energy Recov'd (MW)	Total Land-fill (acres)	Devoted Methane Recovery (acres)	Refuse Buried On-Site (mil. T)	LFG Developer/Operator
106	Lorton (I-95)	Fairfax County	VA	Electricity Gen - IC Engines	Nov-91	2.0	3.0	290	25	17.5	MI Co-Gen
107	Mount Trashmore	Virginia Beach	VA	Electricity Gen - Gas Turbines	Apr-90	Temp. Shutdown	9.0	350	70	7.0	City of Virginia Beach
108	Brattleboro	Brattleboro	VT	Electricity Gen - IC Engines	Aug-82	0.4	0.7	30	15	0.6	Vermont Energy Recovery, Inc.
109	Pheasant Run	Bristol	WI	Electricity Gen - IC Engines (2)	Feb-92	0.8	1.6	80	80	· 2.1	Waste Mgmt of North America
110	Metro	Franklin	WI	Electricity Gen - Gas Turbines (2)	Jan-86	3.0	6.0	108	108	8.3	Waste Mgmt of North America
111	Omega Hills	Menomonee Falls	WI	Electricity Gen - Gas Turbines (3)	Dec-85	4.0	9.0	83	83	8.2	Waste Mgmt of North America
112	Winnebago	Oshkosh	WI	Electricity Gen - Gas Turbines	Jun-90	2.0	3.2	111	105	5.0	Winnebago County
113	Appleton	Outagamie County	WI	Electricity Gen - IC Engines & Direct Use	May-91	1.4	2.5	460	77	3.0	Outagamie County
114	Land Reclamation	Racine	WI	Direct Gas User - Med Btu	87	1.2	NA	61	45	?	Land Reclamation Co.

• Supplemented with natural gas.

•• Includes 1850 kW project expansion in 1991; receives gas from Ventura Coastal LF estimated at 28 hectares (70 acres) and 2.3 million tonnes of refuse (2/3 gas Ventura Coastal, 1/3 Santa Clara).

Includes 1850 kW project expansion in 1991.

Receives gas from 3 landfills -- Penrose, Sheldon-Arleta, and Bradley.

This landfill has 3 separate energy recovery projects.

1 ft^3 = 0.028 m^3; 1 acre = 4046.9 m^2; 1 ton = 907 kg
NA = Not Applicable, ? = Not Available

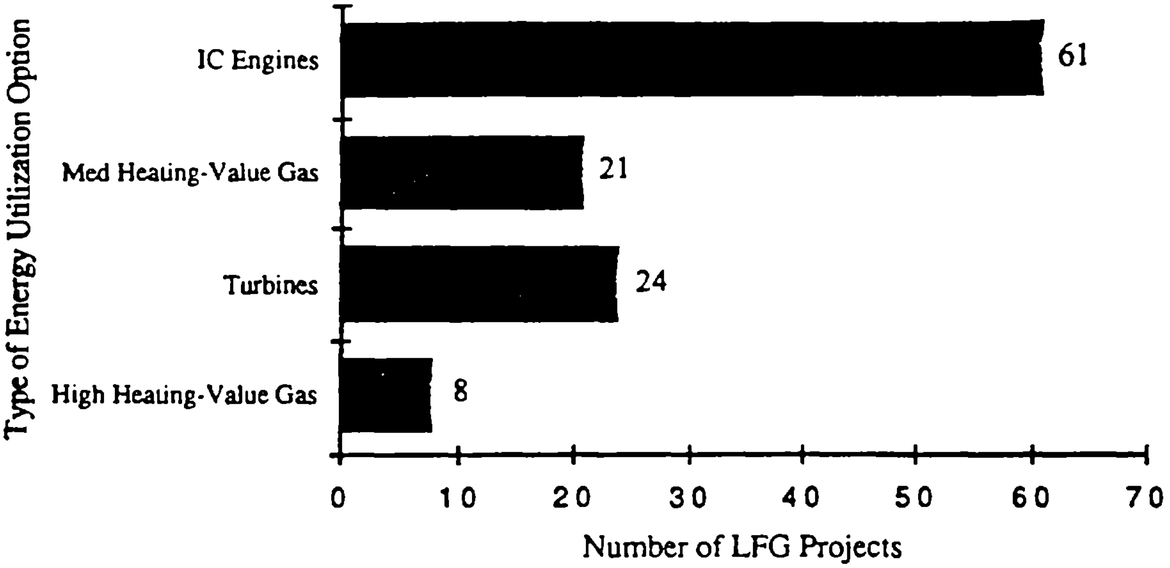

Figure 1. Number of U.S. Landfill Gas Projects by Energy Utilization Option

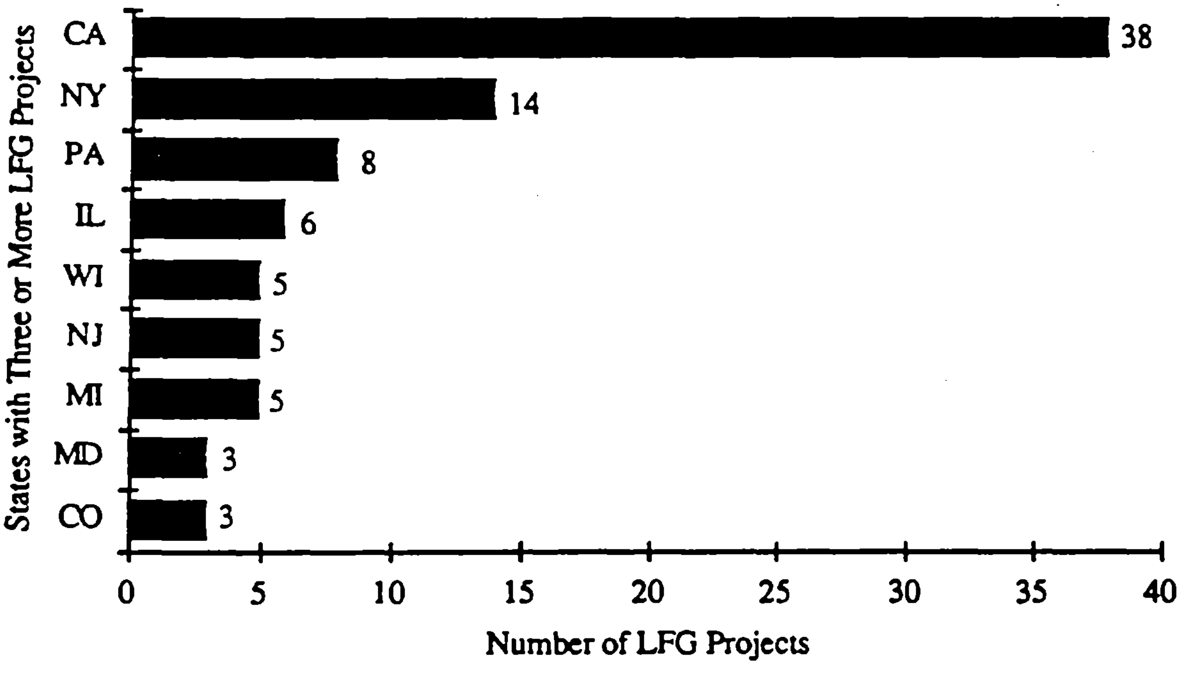

Figure 2. Number of U.S. Landfill Gas Projects by State
for those States with Three or More Projects

is located. Engines are typically used at sites where gas quantity is capable of producing 1 to 3 MW_e. Turbines are typically used at sites producing more than 3 MW_e.

Reciprocating IC engines drive electrical generators to produce electrical power which is typically sold to the local electric utility. Engines used in this application are sold by three manufacturers - Caterpillar, Cooper-Superior, and Waukesha. Each of the 3 manufacturers has in place more than 20 engines at U.S. landfill sites (GRCDA, 1989). These manufacturers design engines that are specific to LFG applications (i.e., corrosion resistant). Typically, warranties that guarantee engine performance require the operator to agree to certain conditions regarding engine operation and maintenance.

Reciprocating engines used for LFG applications may be stoichiometric combustion or lean combustion engines. The "lean-burn" engines are turbocharged and burn fuel with excess air. The stoichiometrically carbureted or "naturally aspirated" engines have air in the fuel/air mix just sufficient to burn the fuel. The case studies provide four examples--three LFG projects using lean-burn engines and one LFG project using naturally aspirated engines.

The lean-burn engines are typically used where NO_x and CO emissions are of concern. Stoichiometric combustion can result in relatively high NO_x emissions which can vary widely due to carburetor setting and other variables. Waukesha suggested that 2.2 to 6.7 µg/J (6 to 18 g/hp-hr) is a typical range of NO_x emission from stoichiometric engines (Stachowicz, 1989). Lean-burn engines are available that minimize (1) the production of NO_x and (2) fuel consumption. At landfill sites with gas flows below ~5,700 scmd (~200,000 scfd), an operator could use one or two naturally aspirated engines. The NO_x emissions would be less than 230 tonnes/yr (250 tons/yr), and the source would not be subject to new source review. At sites over ~5,700 scmd (~200,000 scfd), lean-burn engines are used to avoid new source review. The destruction performance of a lean-burn engine manufactured by Caterpillar (i.e., the Caterpillar 3516 SI Engine) at various NO_x emissions levels reported by the manufacturer is (Chadwick, 1989):

NO_x (µg/J)	NO_x (g/hp-hr)	NMOCDestruction Efficiency (%)
0.7	2.0	98.3
1.9	5.0	98.7
3.7	10.0	99.1

Note that there is a trade-off between low NO_x emissions and the reduction of NMOCs.

Data from 15 IC engines fueled with LFG were collected by the EPA. The range (at 15% O_2) of NO_x was 50 to 225 ppmvd (0.6 to 3.3 g/hp-hr). The range (at 15% O_2) of CO is 43 to 550 ppmvd (0.6 to 7.2 g/hp-hr). Emissions of SO_2 were measured for only one IC engine: the concentration of SO_2 (at 15% O_2) was 1.5 ppmvd (Thorneloe and Evans, 1989; EPA, 3/91).

Gas-fed turbines are also used at landfills to generate electricity. Gas turbines take large amounts of air from the atmosphere, compress it, burn fuel to heat it, then expand it in the power turbine to develop shaft horsepower. This horsepower can be used to drive pumps, compressors, or electrical generators (McGee and Esbeck, 1988). Gas turbines are used at 21 U.S. landfills to produce 108 MW_e of power. Waste Management of North America, Inc. has found that gas-fed turbines typically have parasitic energy losses of 17% of gross output as compared to 7% for IC engines. A factor to consider is that turndown performance is poor in comparison to IC engines. Turbines perform best when operated at full load, and difficulties can occur when operated at less than full load. In addition, trace constituents have been reported to cause corrosion, combustion chamber melting, and deposits on blades. However, these difficulties can be overcome as demonstrated by

Waste Management of North America (Schlotthauer, 1991). A major advantage reported by sites using gas turbines is that generally less day-to-day maintenance is required as compared to the lean-burn engines.

Emissions of NO_x for seven gas turbines fueled with LFG ranged from 11 to 174 ppmvd at 15% O_2. Emissions of CO ranged from 15 to 1,300 ppmvd at 15% O_2, and emissions of SO_2 ranged from 2 to 18 ppmvd at 15% O_2 (Thomeloe and Evans, 1989; EPA, 3/91). Emissions of SO_2 are not expected to be significant since landfill gas typically contains relatively low amounts of sulfur compounds as compared to fossil fuels. The new source performance standard for gas turbines with a power output of 2.93 to 29.3 MW_e is 150 ppmvd of NO_x at 15% O_2 (EPA, 1977). Although the units tested were below this cutoff, six of the seven turbines did have less than 150 ppmvd of NO_x at 15% O_2. Data for four gas turbine facilities were presented by Waste Management at the Air and Waste Management Association's 82nd Annual Meeting in June 1989 (Maxwell, 1989). The data for NO_x emissions from the Solar Centaur T-4500 LFG turbine ranged from 22 to 37 ppmv at 15% O_2, with a median of 30 ppmv.

Steam-fed turbines are in use at three sites to produce 64 MW_e of power. The largest landfill-gas-to-energy plant is the Puente Hills Energy Recovery from Gas facility (PERG), located at the Puente Hills Landfill in Whittier, California. This site began recovering LFG for energy utilization in November 1986. It is operated by the Los Angeles County Sanitation Districts. The facility consists of twin Zurn Industries, Inc. gas-fired steam generators. Each of the units fires 420,000 scmd (10,300 scfm) of LFG, producing 95,340 kg (210,000 lb) of steam per hour at 9.3 MPa (1350 psig), heated to 540°C (1000°F). This steam drives a Fuji Electric Co. Ltd. turbine that generates approximately 50 MW_e net, that is sold to Southern California Edison (Valenti, 1992).

High-Heating Value Gas. Seven sites in the U.S. upgrade LFG to pipeline quality. This option was considered more attractive in the early 1980s when the price of oil and natural gas helped make this more economical. The sites that are producing pipeline quality gas were initiated in the early 1980s when gas prices on a heating-value basis were comparable with oil. These sites have an average LFG flow rate of 142,000 scmd (5 million scfd) with the lowest gas flow rate being 31,150 scmd (1.1 million scfd) and the highest being 269,000 scmd (9.5 million scfd). Stringent cleanup technology is applied to purify the gas to pipeline quality by removing the trace constituents and CO_2. Similar to the medium-heating value applications, a nearby natural gas pipeline is needed. The largest operator of facilities producing pipeline quality gas from LFG is Air Products and Chemicals, Inc. Low natural gas prices in the late 1980s forced several previous projects to shut down, and continue to inhibit the development of new high-heating value projects in the U.S. However, sites in the Netherlands are finding more favorable economics (Scheepers, 1991).

A site that began operation last year in Pueblo, Colorado, is producing liquid diesel fuel from LFG. This site is operated by Fuel Resources Development, Inc. and began producing commercial product in January. A second site in the U.S. may be used to produce vehicular fuel from LFG. The South Coast Air Quality Management District has awarded a contract to demonstrate a process for producing methanol from LFG. The site selected for this demonstration is the BKK landfill, where there was co-disposal of hazardous and municipal waste. TeraMeth Industries is responsible for the demonstration and research is being coordinated with the EPA. The demonstration is anticipated to begin in 1993.

Other Options for Landfill Gas. Fuel cells are a potentially attractive option for LFG because of higher energy efficiency, availability to smaller as well as larger landfills, and recognition for minimal byproduct emissions. Other advantages include minimal labor and maintenance, and (because there are no moving parts) the noise impact is minimal. Hydrogen from the landfill gas is combined electrochemically with oxygen from the air to produce dc electricity and by-product water. The fuel cell is designed for automatic, unattended operation, and can be remotely monitored. The EPA's Air and Energy Engineering Research Laboratory initiated a project in 1991 to demonstrate the use of fuel cells for LFG application. The type of fuel cell being demonstrated is a commercially available 200 kW_e phosphoric acid fuel cell power plant. The 1-year full-scale demonstration is scheduled for 1993.

The major issue associated with this demonstration is designing a LFG cleanup process that will remove the trace constituents from the LFG and at the same time not be cost prohibitive. Since the composition of LFG varies over time, designing a process that can allow for this variability is difficult. A cleanup process has been proposed and is to be evaluated later this year. The fuel pretreatment system incorporates two stages of refrigeration combined with three regenerable adsorbent steps (Sandelli, 1992). It is hoped that, if the EPA demonstration of the use of fuel cells is successful, more landfill owner/operators will consider fuel cells as an option for LFG utilization. Given the higher energy efficiency and potential for minimal byproduct emissions, fuel cells may be the most attractive option for areas where there are stringent requirements for NO_x and CO emissions.

Economics

A major factor in helping to encourage LFG energy projects is the Public Utility Regulatory Policy Act (PURPA). It guarantees that utilities purchase power that was generated from landfills at a price related to the costs that utility would experience to produce the same amount of power. Although this guarantees a purchaser for the power, the power sale revenues may be low if the utilities' own generating costs are low. In addition, tax credits have been available that also help to encourage renewable energy projects, such as LFG utilization.

The major capital costs of a LFG energy recovery project are identified in Table 2 as estimated in a recent paper by George Jansen of Laidlaw Technologies, Inc. Laidlaw's experience suggests that LFG projects need to be over 1 MW_e and have an electrical price of at least $0.06-0.07/kWh including any capacity payments. Royalties should not exceed 12.5% at this energy pricing (Jansen, 1992). Laidlaw suggests that, if higher royalties are offered, the percentage should be a function of energy pricing over and above the base energy rate as inflation occurs. A range in the variability of the cost for each major component is also provided in Table 2.

The major cost and revenue components include (1) administration and development costs, (2) capital costs, (3) operating and maintenance costs, (4) royalty payments, (5) tax credits, and (6) energy-related revenues. A brief description is provided of each of these components.

- Administrative costs include legal fees, permit applications, and contract negotiations including gas lease agreements and power purchase agreements. These costs may vary widely depending upon the environmental issues, development considerations, and regulatory requirements.
- Capital costs include the cost of gas extraction and cleanup, energy conversion equipment, building, flares, and site modifications for construction.
- Operating and maintenance costs include the costs associated with the operation and maintenance of the energy project, labor, utilities, taxes, and insurance.

TABLE 2. CAPITAL COST ESTIMATE
Estimate of Capital Costs for a 1 MW_e Landfill Gas Energy Utilization Project

Item	Cost[1] ($\$10^3$)	Percent[1]	Range of Value ($\$10^3$/kWh)
Collection System[2]	200	13	200-1000
Fees-Planning/Environment/Legal[3]	30	2	30-1000
Interconnect Cost	76	5	20-500
Generating Equipment	970	65	500-2000
Contingency	225	15	--
Total	1500	100	850-4500

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[1] These costs were provided by Laidlaw Technologies, Inc. (Jansen, 1992)

[2] The range in cost of gas cleanup systems is \$10,000-\$500,000 ($\$10^3$/kWh)

[3] Legal fees are approximately 50% of the total (i.e., ~\$15,000-\$500,000)

- Royalty payments are proportional to energy output (or net or gross revenue) and are defined by the contract. Royalties are negotiated and may be paid to the landfill owner, owner of the gas extraction or delivery rights, or initial project developer. Royalties can range from 5 to 20% of gross energy sales.
- Tax credits are benefits proportional to gas energy delivery which were legislated by Congress (Section 20 of the IRS Code). These credits are a direct offset to taxes and can only be used to offset a profit. The tax credits will extend through the year 2002 and are allowable for extraction systems installed prior to the end of the year 1992. However, the most recent version of the tax bill being considered by Congress does not include a tax credit for non-fossil fuel projects.
- Revenues for energy sales are usually based on prices of the "competition" of equivalent energy sources (i.e., petroleum products). Since the value of the energy base commodity can fluctuate, this can impact profit. The early LFG projects were based on an established firm price for net energy which provided a substantial degree of security to developers.

Case Studies

The EPA's Air and Energy Engineering Research Laboratory initiated a project in 1991 to document the options for LFG utilization. This work included gathering data on the operating and maintenance requirements, the financing and contractual arrangements, and "lessons learned" from the six sites included in the case studies. This paper provides a brief summary of the case studies with emphasis on identifying the different utilization options in use. The final report will contain more detailed information for these sites including capital and operating costs, process flow diagrams, and data regarding the environmental benefits of LFG utilization.

Sites were selected to provide insight on the kinds of issues associated with LFG utilization and actions taken by operators and equipment manufacturers to ensure successful projects. Many companies have been successful in finding innovative solutions to difficulties arising from LFG utilization. Several firms have found that gas cleanup is critical to the performance of both engines and turbines. The design of the gas cleanup must be specific to the composition of the gas being recovered and allow for the variability which occurs over time. The EPA has initiated a follow-up project which will focus on the issues of gas cleanup, equipment design, and operational modifications. The focus of this initial project is to identify the different approaches for LFG utilization using six case studies to illustrate the different options. Provided below is a brief summary of the information gathered at the six LFG energy projects.

Site 1. Brown Station Landfill, Prince George's County, Maryland. LFG is used to supply both the electrical and heating needs of a county building in addition to producing electricity for sale to the local utility. The energy equipment includes a gas cleanup and pumping station, a 3,230 m (2-mile) pipeline transmission system, three engine generators, and a boiler which supports the heating and hot water system of the 21,800 m^2 (235,000 sq ft) county correctional facility. The three engines are lean-burn turbocharged. Approximately 28,320 scmd (1 million scfd) of gas is recovered from 3.6 million tonnes (4 million tons) of landfilled waste. This site began operation in June 1987 and produces about 2.6 MW_e of power.

This site experienced atypical difficulties during start-up, resulting in one of the three engines seizing after less than 500 hours of operation. Modifications have been made to the engine to make it "corrosive resistant" including hardened valve guides, chrome valve stems, modified piston rings, and elevated coolant temperatures. Operations were also modified including more frequent oil checks and changes. Since this occurrence, the site has had successful operation. Speculation about what contributed to the engine seizing suggests that higher levels of chlorinated organics (than is typical for landfills) may have caused the corrosion. Inspection of the engine showed evidence of extensive corrosion including deposit buildups which reduced piston clearances.

Site 2. Central Landfill, Yolo County, California. Gas from this landfill is used to fuel three IC engines to generate 1.5 MW_e. The generated power is delivered via an interconnect 1,200 m (0.75 mile) to nearby PG&E high voltage power lines. Yolo County, the owner of the landfill, receives royalties based on net power and capacity sales. This energy recovery project began operation in November 1989. Approximately 36,800 scmd (1.3 million scfd) of LFG is recovered from 2.8 million tonnes (3.1 million tons) of refuse. This project has experienced a number of difficulties including equipment problems. The types of engines were of an earlier design lacking newer adaptations to lean-burn operation on LFG. Modifications to the engines are being considered to make them more corrosive resistant for LFG applications. Because of the difficulties experienced at this site, the revenue from the royalties has dropped.

Site 3. Otay Landfill, San Diego County, California. This site is recovering 53,800 scmd (1.9 million scfd) of LFG to generate 3.4 MW_e using a lean-burn engine/generator set. The electricity is sold to the local utility. The Otay landfill contains approximately 5 million tonnes (~6.1 million tons) of refuse. The energy recovery project began operating in December 1986. The facility exports a net output of about 3400 kW at an average sale price of ~$0.09 kWh, and typically obtains more than $2 million per year in gross power sale revenue. The LFG energy recovery project is operated by Pacific Energy who are responsible for the operation of 10 LFG energy projects, nine in California and one in Maryland.

Site 4. Monterey Landfill, Marina, California. This site produces 1.2 MW_e from 23,300 scmd (0.9 million scfd) of LFG. This project is one of the first in the U.S., beginning operation in December 1983. The installation is the result of persistence by participants who were aware of the potential benefits of energy recovery from LFG. Approximately 3.4 million tonnes (3.7 million tons) of refuse is buried at this site as of 1992. The Monterey Regional Waste Management District owns and operates the engines, receiving the profit from engine operation. This site uses naturally aspirated engines and catalysts for the outlet exhaust to reduce NO_x and CO. This site has demonstrated exhaust catalyst use and has found that the oil type and alkalinity are critical to the engines' performance. Technical success is good despite that gas cleanup is less stringent than is typical for other sites. This site can be considered one of the pioneers in energy recovery from LFG.

Site 5. Sycamore Canyon Landfill, San Diego, California. This site is producing 1.7 MW_e from 34,000 scmd (1.2 million scfd) of LFG. This project began operating in December 1988 using two gas-fed turbines fueled with LFG to generate electricity which is sold to the San Diego Gas and Electric grid. This energy project was owned by Solar prior to being sold to Laidlaw Technologies, Inc. Solar reported that efficiency is reduced by 13% from the efficiency that would be obtained with the same turbine on more conventional pipeline gas or distillate fuels, due to the greater parasitic compression load. The equipment is occasionally limited due to inadequate quantities of LFG. This difficulty has occurred at other sites and gas projections for newer projects tend to be more conservative.

Site 6. Wilder's Grove Landfill, Raleigh, North Carolina. This site is an excellent example of how LFG can be used directly by an industrial client as medium-heating value fuel. The gas from the Raleigh landfill is piped 1,600 meters (1 mile)to a pharmaceutical facility for use as boiler fuel to produce 11,000 kg (24,000 lb) of steam per hour. This project began operating in December 1989 and is expanding. A second boiler is being added this year. Approximately 42,500 scmd (1.5 million scfd) of gas is recovered from approximately 3.2 million tonnes (3.5 million tons) of refuse. Natural Power initiated this project and is responsible for its operation.

Natural Power pays royalties to the City of Raleigh based on a percentage of steam sales. This project also receives tax credits on the extracted gas. All participants in this project appear satisfied with the performance of this project to date. However, Natural Power, who was the prime motivator in getting this project initiated, provided many years of work on the project during which there was no financial return.

This site was prone to off-site gas migration prior to the installation of the gas collection and recovery project. Since the installation of the energy project, gas migration off-site has not been detected. In addition, other environmental benefits are realized including the reduction from emissions of NMOCs, toxics, and methane, which is a contributor to global climate change.

Natural Power, the developer for this project, is presently negotiating a contract with a landfill in Kiev, in the Ukraine. This site has over 9 million tonnes (10 million tons) of waste. The gas is to be used to generate electricity for the Ukrainian capital.

CONCLUSIONS

The utilization of LFG is sensible in terms of economics, the environment, and energy usage. The utilization of alternative energy sources such as LFG extends our global fossil fuel resources. Not only are emissions directly reduced when LFG is collected and recovered for utilization, but emissions are also indirectly reduced when secondary air/emission impacts associated with fossil fuel use are considered. U.S. landfills are currently recovering ~1.2 million tonnes of methane and producing 344 MW_e of power. The proposed Clean Air Act regulations for MSW landfill air emissions are expected to result in additional emission reductions ranging from 5 to 7 million tonnes of methane. Hopefully, utilization of LFG will be considered and encouraged for those sites affected by the proposed Clean Air Act regulations. This would result in increased benefits to our economy, energy resources, and global environment.

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16. ABSTRACT

The paper describes the options and economics for landfill gas utilization. (NOTE: The decomposition of landfilled waste results in a gas that can be either a source of pollution or a resource. Of the more than 6000 active municipal solid waste landfills in the U.S., there are 114 landfill gas energy projects.) The health and environmental concerns are described, as well as the economic, environmental, and energy benefits associated with landfill gas utilization. In addition, the results of a recent EPA survey of U.S. landfill gas utilization are provided.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS		b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group	
Pollution	Climate Changes	Pollution Control	13B	04B
Gases		Stationary Sources	07D	
Earth Fills		Landfill Gas	13M	
Economics		Global Climate	05C	
Wastes			14G	
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