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ELECTRICITY FROM BIOGAS

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ABSTRACT

Biogas is a medium-Btu methane and carbon dioxide mix produced by bacterial decomposition of organic matter. Its sources include landfills, waste water sludges, and animal wastes. It can fuel energy applications, of which electricity generation is a frequently-preferred option. The greatest current U. S. biogas recovery and energy use is at landfills, where biogas at about 80 landfill sites fuels a total of approximately 300 MWe. Wastewater treatment plants and confined animal waste management systems support additional electric power production. Generation of electricity from biogas can present difficulties due to the generally small scale of the generating facility, variable energy content of the gas, fluctuating availability, contaminant problems, and often-demanding control needs. However such difficulties are being successfully addressed, and economics for electricity generation are often favorable as biogas can be essentially "free" fuel. Biogas recovery and use has the additional advantage of mitigating a potent greenhouse gas. Biogas from U. S. landfills alone could fuel about 1% of U. S. electrical generation while giving climate change benefit equivalent to reducing CO_2 emissions in the electricity sector by more than 10%. Growth in landfill gas use will be facilitated by recent regulations, advances in equipment, and improved management techniques such as "controlled landfilling". The potential for biogas recovery and electricity production from sewage sludges, animal wastes and other organic resources such as agricultural residues is uncertain but probably exceeds the estimate for landfills.

1. INTRODUCTION

Bacteria are able to convert the organic fractions of many biomass feedstock materials--from municipal wastes, and much plant material--to a mix of methane and carbon dioxide in a process termed anaerobic digestion (digestion). Digestion occurs in nature in swamps, sediments, animal guts, and wherever organic material is present in the absence of oxygen (or other terminal electron acceptors such as nitrate and sulfate). For cellulose, the principal component of most plant material, the conversion reaction is:

$$\underset{\text{cellulose monomer}}{(C_6H_{10}O_5)_n} + n\,H_2O \xrightarrow[\text{bacteria}]{} 3n\,CH_4 + 3n\,CO_2$$

In this idealized equation complete reaction is assumed and microbial biomass production is neglected. The theoretical thermal efficiency exceeds 90%. In practice the efficiency of production, the CH_4:CO_2 ratios, and rates of biogas production depend on feedstock composition, nutrient availability, and physical-chemical factors (temperature, mixing, pH, etc.). Energy recoveries can vary from less than 50% (for many plant materials) to almost 90% (food processing wastes). Time-scales range from days for food processing wastes and other soluble materials, to decades for landfills. Besides CH_4 and CO_2 biogas can contain other components, depending on the feedstock being digested. Biogas properties and compositions are summarized in Table 1.

Table 1
Compositions of Gases from Anaerobic Digestion

Component	Gas Origin(a)	Concentration Range
methane (all sources)	all sources	45-70 percent
carbon dioxide	"	30-50+ percent
water vapor	"	1-10 percent
NMOC's(b)	"	0.01-1 percent
Hydrogen sulfide	SD, MD, LFG	0-1 percent
Ammonia	MD	0-10 ppm
Nitrogen	LFG	up to 20% (c)
NMOC's (see text)	LFG	up to 1 % gas carbon (d)
halocarbons	LFG	see note (e)
particulates	LFG	traces

Notes to Table 1: (a) SD: Sewage Digester MD Manure Digestion; LFG: Landfill Gas. (b) NMOC's: Non-methane organic compounds. (c) Entrained as a consequence of extraction process (d) Up to 1 percent of total carbon in landfill gas may be contained in higher molecular weight compounds (NMOC's) that come from material discarded with the waste (see text). (e) The halogens in halocarbons may comprise 30 to 300 micrograms per liter. Sources include : Augenstein and Pacey, 1992; Jewell, ed. 1975; Authors' estimates.

In most cases where biogas is produced, the primary interest is not the biogas itself, but in other purposes such as stabilizing organic materials to produce a residue that can be safely disposed of (e. g. by land application).

For biogas recovery the digesting material must be contained, and reaction conditions may be managed to varying degrees. There are scores of different processes and designs for biogas reactors, ranging from highly engineered mixed tanks to simple covered anaerobic lagoons. Heated, mixed and closely managed reactors (digesters) are used to treat sludge at most municipal sewage treatment plants. For food processing wastes, which are both highly digestible and often dilute, short retention time anaerobic filters or sludge blanket reactors are available. High solids mixed reactors may be used for solid substrates such as municipal wastes (Kayhanian, 1994). For animal wastes, low cost covered anaerobic lagoons have been used for almost two decades, but such technology still has not been widely exploited for electricity as less than 10 MWe may now be generated by animal wastes (Roos 1994). For agricultural residues, high solids unmixed digesters have been demonstrated, but are not in commercial use. Complex multi-stage processes have been developed (e. g. two phase digesters; Ghosh, 1984). Choosing between alternative designs for reactors is made difficult by conflicting claims, undocumented performances, and uncertain economics.

Biogas is also recovered as the by-product of landfill operations, normally with vertical extraction wells adjusted to maximize gas recovery. Landfills support the greatest energy use with about 300 MWe being generated at over 80 sites (Augenstein and Pacey, 1992, Pacey et. al. 1994). The total electric potential from landfills large enough for economic power recovery has been variously estimated as shown in Table 2. Overall, only about 5 to 10 percent of the potential landfill biogas resource is currently utilized. The current energy use of biogas from U. S. sewage is uncertain, but from fragmentary data (such as Wander Associates, 1993) may be one to two hundred MWe. U. S. sewage digester gas might support the order of 1000 MWe if all produced fueled electric power generation (Benemann and Augenstein, 1994). The potential with animal manures from confined animal operations, where manure collection is practical, may be of the same order of magnitude.

Table 2
Estimates of Electricity Potentials from U. S. Landfill Gas

Source	Estimated Potential, MW
EPRI TR-101068, 1992	5000-6000 (fuel cells, 6820 Btu/kWh)
EPA, 1993a	4000-5000 (11,000 Btu/kWh)
Derived from Augenstein, 1992[1]	2500-6000 (see note)

1. Note: Assuming 70% of methane generation estimate in Augenstein, 1992 convertible to methane at 11,000 Btu/kWh. .

2. ELECTRICAL GENERATION FUELING WITH BIOGAS

Biogas is produced continuously, requiring continuous use, or storage (or disposal by flaring). Storage is generally not practical. Electric generation is normally the most attractive energy use, favored by proximity of most biogas production facilities to an electric grid, capable of accepting electricity (at market prices, discussed later) 24 hours a day, and availability of commercial generating equipment that is capable of using biogas. Other than electricity generation, possible uses are site-specific and limited. Appropriate direct firing users are only occasionally close to landfills and other biogas sources. Gas cleanup/compression for pipeline use competes poorly because of high energy and economic costs for small-scale purification and pipeline compression, as well as market conditions. (This situation is likely to continue regardless of energy prices because of intrinsic energy and cost factors.)

Current electric generation from biogas is primarily with commercial package engine-generator or gas turbine-generator sets. These are variants of "stand-alone" units developed for remote applications, such as in the oil and gas industry. Piston engine manufacturers originally adapted their engine-generator sets for sewage digester gas use, then to landfill gas use. Turbines, though lower-efficiency, are used in cases (larger gas sources as at landfills) where restrictions on reciprocating engine NO_x emissions might limit generation. Steam turbines are used at a very few large sites (all large landfills). Other occasionally used approaches include biogas supplementation of utility boiler fuel. Existing equipment as well as a number of case studies documenting LFG use within and outside the U. S. are discussed in detail elsewhere (Augenstein and Pacey, 1992). Other energy equipment information may be found in Walsh, et. al. 1988 and Benemann and Augenstein, 1994. Table 3 summarizes equipment used at U. S. landfills, where gas exploitation is most advanced. Potential future generation technologies, for example fuel cells, are discussed later.

Biogas has several features unique in comparison with "conventional" fuels and these must be allowed for in its use:

- Water and condensables are always present in gas as produced; condensate must be removed for use in most energy equipment .
- Carburetion adjustments are needed to compensate for the lower energy value.
- In contrast to the situation with most fuels, energy content of the gas can vary, making combustion stoichiometry control (i. e. engine carburetion, gas turbine burner, etc.) demanding.
- Biogas must be compressed for its use in both high manifold pressure "lean-burn" piston engines and for gas turbines. This is in contrast to pipeline gas which is at the required high pressures. With piston engines the air compressor (turbocharger) can sometimes be conveniently used to

Table 3
Typical Landfill Gas Electric Plant Characteristics
(Source: Benemann and Augenstein, 1994)

Gas systems: normally vertical wells adjusted to maximize Btu recovery; gas delivered to plant by low pressure blowers, < 5psi pressure differential

Typical plant size range: 700 kW to 5 MW[1]

Reciprocating engine gensets (Caterpillar, Waukesha and Cooper Superior)

Sizes of gensets: 700kW to 1.5 MW
Heat rate on gas HHV, net Btu/kWh: 10,000 (newer) to 15,000 (older)
Capital costs per net kW capacity (not including landfill gas system) $1000-2000[2]
Operating costs (excluding gas system) ca. 0.012-0.02/kWh

Gas turbine powered gensets (Solar Turbine Division of Caterpillar)

Sizes of sets 700kW (Solar Saturn) to 2700kW (Solar Centaur)[3]
Heat rate on gas HHV, net Btu/kWh: 19,000 (700 kW) to 16,000 (2700)[3]
Capital costs of gensets per net kW capacity (not including landfill gas system): $2000 to 5000[4]

Steam-electric plants (few)

Size range 15-47MW; Efficiencies and capital costs similar to natural gas firing.

Cost ranges reported for power generated: 0.025-0.08/kWh[5]

Notes to Table 3
1. A few plants may range in size up to 15 MW. One, Puente Hills, CA is 47MW.
2. See economics, figure 16, in Jansen, Appendix L in Augenstein and Pacey, 1992
3. Both output and heat rates can vary with ambient temperature.
4. Reported by Solar. See Augenstein and Pacey, 1992
5. See discussion of economics in Augenstein and Pacey, 1992. Also see Markham, M in Augenstein and Pacey, 1992.

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compress the mixed gas after carburetion (Chadwick, 1990)

- Biogas available for use can vary, making part load performance critical.
- Landfill biogas, the largest current resource, contains traces of halogenated organics (solvents, chlorofluorocarbons, etc.) that burn to form HCl and HF which can be corrosive to steel. Thus one critical IC engine operating adaptation is to use high total base number (TBN) oils (Gonzalez, 1987)
- Intricacies of operations normally dictate (at present) operators at sites, a very significant cost at small scales of the order of one to a few megawatts.

Many of these issues, such as compensating for low energy content, condensables, and corrosion effects on equipment can generally be addressed straightforwardly (Augenstein and Pacey, 1992). Others, such as variations in fuel energy content and fluctuating biogas availability are at present less well resolved. Difficulties tend to be greatest in exactly those situations of highest interest, where the objectives are to maximize the electricity yield on both the available gas and equipment. (Improvements in prospect are discussed later).

Despite the potential pitfalls, operations of commercially available natural-gas-fired equipment on landfill and other biogas (e. g. that from sewage) have been largely successful. For example with appropriate attention to landfill gas pretreatment, the intervals between engine overhauls are found the same as with natural gas (Jansen, 1992). The landfill gas-to-electricity industry by and large does well, as might be inferred from number of sites. Many sites, including some operated by municipal and other entities who had no previous experience, have on-line service factors considered very satisfactory for the equipment of 80-95% (Augenstein and Pacey, 1992). In fact, about half of down time is normally because of landfill gas recovery system problems rather than with electric generating plant. The largest operator of landfill gas energy systems in the U. S. is Waste Management of North America, which has reported in detail on their equipment's operation (Markham, 1992).

Economics of electricity from biogas vary considerably more than with most electric technologies. This is because of widely varying scales, site-specific factors, tax treatments, and other factors. Reported costs of electricity now generated at landfill sites vary typically within the $0.025-0.08/kWh range in Table 3. It should be noted that the lower limit of $0.025/kWh is stated by Waste Management to be the lowest electric sale price that they will consider, presumably at the most favorable landfill sites (Markham, 1992). While many utilities may now offer only $0.02-0.04/kWh for electric power continuously supplied to grids, U. S. tax credits have the effect of subsidizing much landfill gas electric generation by about $ 0.01/kWh more. This significant benefit has made a number of otherwise marginal projects economically feasible. Newer regulations (discussed below) will also help. Much more discussion of economic factors is presented in Augenstein and Pacey, 1992. Economic analyses of manure to electricity are presented in U. S. EPA 1993a.

Cost of power as it enters grids is but one index of economic feasibility. In many cases transmission costs may be high from the grid entry point to users, or transmission capacity itself limiting. It is worth noting that landfills and sewage plants tend to be near population centers--which both generate the wastes and consume the electricity. Thus electricity from landfill gas and digester gas tends to be almost ideally distributed as an electric power resource. On the other hand, manure biogas sources are not so advantageously distributed and captive uses of generated electricity may be more desirable with manure in many cases (U. S. EPA 1993a).

It must be noted that most of the biogas currently generated within landfills is not now collected, and some of what is collected is flared. The reason is that for most landfills the costs cannot be justified by the revenues generated from power sold. However the U. S. EPA has announced regulations that will mandate gas collection from many landfills now without recovery systems (Federal Register, May 1991). These regulations will make available, in effect, much lower-cost or "free" gas at many sites producing sufficient gas to support electric generating systems. Continuing improvements in equipment and operating strategies, discussed later, will also help.

3. BIOGAS AND CLIMATE CHANGE

Climate change and the "greenhouse effect" are increasing concerns. Renewable energy sources, such as biogas-fueled electricity production, displace fossil carbon dioxide emission that would otherwise occur, thus mitigating the greenhouse effect. Biogas-fueled electricity shares the CO_2 "offset" advantage with other renewably based electricity. However methane, molecule for molecule emitted into the atmosphere, is approximately 20 fold more potent as a greenhouse gas than CO_2. Thus, when methane capture and energy use prevents emission into the atmosphere that would otherwise occur, the "instant" effect is equivalent to mitigating emission of about 20 times as much volume of fossil CO_2 emission. Various evaluations, depending on factors such as time span considered, show methane abatement benefit with biogas use to be an order of magnitude, or more, the normal benefit from "offset" of fossil CO_2 emission alone (Augenstein, 1992, Rodhe, 1990). To give perspective on this potential, it can be noted that biogas fueling of 1% of U. S. electric power generation (which appears possible) would have major climate change benefit from associated methane abatement--

equivalent in effect to a reduction of 10-20% of total U. S. fossil CO_2 emissions from electric generation. To give further perspective, the greenhouse gas abatement cost from methane mitigation has been shown equivalent to about $1 to $3 per ton of CO_2 carbon abated, among the least cost of greenhouse gas mitigation strategies by this index (Augenstein, 1992, Rubin et al 1992, Hachey, 1994). Other environmental pluses to biogas emission reduction include mitigation of both methane's stratospheric ozone destruction, and also effects of higher molecular weight organic pollutants in biogas (Blake and Augenstein, 1994). Therefore, biogas methane capture and use in electric generation can play an important role in addressing climate change and other environmental concerns.

4. PROSPECTS

Improvements with biogas-fueled electric generation should occur in several areas. Solid waste landfills are the largest current biogas source (above). As presently designed and operated, landfills have the problems of incomplete degradation of the organics, and very slow generation of methane. Additionally, inefficient "standard" gas recovery techniques allow losses to the atmosphere estimated between 10-50% of that gas which is generated. (Augenstein and Pacey, 1991). Pilot projects are underway to manage landfills' biological reaction conditions so that methane is generated more rapidly and to its full potential. This can be combined with established membrane coverage technology to allow nearly complete gas capture. Such strategy should at least double gas recovery compared to conventional landfilling (and prevent nearly all methane emissions). It should also improve economics of scale downstream because of the consequent greater electricity generation (or other use). The status of such "controlled landfill" projects has been recently reviewed (Augenstein et. al., 1993; Reinhart and Carson, 1993).

Advances continue toward efficient, small-scale generating technology better suited to biogas. Fuel cells, though not yet commercial for landfill gas use, are of high interest to U. S. utilities for such application (Meade et. al., 1991, Gauntlett, 1992). Fuel cells would enable a roughly 50% increase in electricity obtained per unit of gas over that now typical (see Augenstein and Pacey, 1992). Fuel cells in combination with controlled landfilling could more than double electric yield at given landfills. With newer IC engines, turbocharger compression of the air-fuel mix now eliminates need for auxiliary landfill gas compressors (Chadwick, 1990). In addition, with former IC engine control methods, variation in gas energy content (a common biogas problem) could result in shutdown or severe engine damage by detonation. Now, automatic carburetion control is reported available to compensate for gas energy content variation to any value between 400 and 900 Btu/ cubic foot to maintain proper air-fuel mixtures. (Lloyd, 1994). This also facilitates pipeline gas supplementation of biogas when needed. Additional IC engine efficiency improvement as well as safeguard is provided by detonation-sensitive ignition timing. With developing monitoring and control methods fuel cells and IC engines should be able to operate on biogas unattended, reducing operator costs that have been to now very significant. Space precludes discussion here of other technologies such as organic Rankine cycle which are promising and also continue to develop.

Changing waste disposal patterns will undoubtedly impact landfill gas based electrical generation. Recycling would level off or somewhat reduce disposal of the organics that are sources of the methane. Waste-to-energy incineration facilities, as they are implemented in particular locations, will also reduce landfilling in those locations. Offsetting this is the strong current trend toward fewer larger landfills where efficiencies and economies of scale favor landfill gas collection and energy use.

Non-technical barriers have also impeded biogas energy applications. These are now being addressed. One barrier has been stringent and narrowly focused local point-source emission restrictions. These often constrain biogas fueling--while not crediting demonstrable wider environmental benefits--also air-quality related--to its use. Other impediments regard permitting issues, concern over potential liabilities, low avoided cost credits, and failure to credit the extra environmental benefits or "externalities" to power generation from biogas. Because of environmental benefits the U. S. EPA is taking a role in helping reduce barriers to biogas use (Jacobs, 1994). Information transfer is key and the U. S. EPA has also been active in this area (Augenstein and Pacey, 1992, Thorneloe, 1993)

The many factors affecting electrical generation from biogas make prediction difficult. A many-fold increase in electricity from biogas should be possible over the next decade through a combination of technology improvements and regulatory changes that recognize the important advantages of biogas recovery and use on the local, regional and global environment.

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