CHP Systems for Landfills and Wastewater Treatment Plants

August 11, 2005

Salt Lake City, Utah

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Reciprocating Engines for ADG and LFG

- Reciprocating engines are either Otto (spark ignition) or Diesel (compression ignition) cycle systems
- Natural gas engines, as well as those powered by ADG or LFG, are typically spark ignition systems
- Most reciprocating engines used for ADG or LFG are under 2 MW

- Some dual fuel engines have been developed using ADG/LFG with a portion of diesel as the pilot fuel (compression ignition), but this presentation is focused on spark-ignition engines using 100% ADG/LFG

Reciprocating Engine Performance

- When running on natural gas, reciprocating engines have an electric efficiency of 30-40%, with overall efficiencies of up to 80% when using CHP
- ADG and LFG engines are about 10% less efficient than NG engines, with net power output decreasing by about 10% - this results in a slightly higher $/kW cost

Fuel	Electrical Efficiency	Power Output
Natural Gas	30-40%	100%
ADG/LFG	27-36%	90%

- Some necessary equipment modifications for NG engines to run on ADG and LFG (modified fuel injectors, larger manifolds) cause the $/kW to rise an additional 5%

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Reciprocating Engines: Increased Costs for ADG and LFG

- In addition to engine modifications, the purchase of fuel treatment equipment is required to remove moisture, particulates, and other contaminants - this adds to both capital and maintenance costs
- A coalescing dryer for moisture, a carbon filter for siloxane, an iron filter for H_2S, and various particulate filters are typically installed
- Overall, reciprocating engines using ADG or LFG cost about 20% more than their natural gas counterparts
- Maintenance usually costs about 80% more than NG engines

Reciprocating Engines	**Natural Gas**	**ADG/LFG**
Installed Cost (CHP, $/kW)	800-1,400	1,000-1,700
Maintenance Cost (cents/kWh)	1-3	1.5-4.5

Emissions and Emission Controls for Reciprocating Engines

- Reciprocating engines generate relatively high NOx emissions
- Post-combustion control technologies are complicated and expensive to implement, and certain impurities found in ADG/LFG (H_2S, siloxanes) create by-products that can negate their effects
- Three-way catalyst and selective catalytic reduction can not be used with ADG/LFG unless the gas is highly cleaned (otherwise the by-products will "poison" the catalyst)
- Lean-burn technologies are almost always used, but burning too lean with low-Btu gases has a negative effect on performance and raises CO and VOC emissions - effective turbocharging can help remedy this problem
- Lean-burn technologies are difficult to employ with smaller (<150 kW) engines, so post-combustion controls may be necessary

Applications for Reciprocating Engines

- While reciprocating engines designed for low-Btu fuels have a relatively low capital cost, maintenance costs are high and emissions can become a major challenge
- The best near-term markets for reciprocating engines with opportunity fuels are ADG and LFG operations in areas where emissions regulations are not very strict and capacity needs are less than 5 MW
- In these applications, reciprocating engines have the lowest capital cost of all the DER/CHP technologies
- In severe or extreme non-attainment areas, required selective catalytic reduction can kill project economics - microturbines or combustion turbines are usually better options in these locations

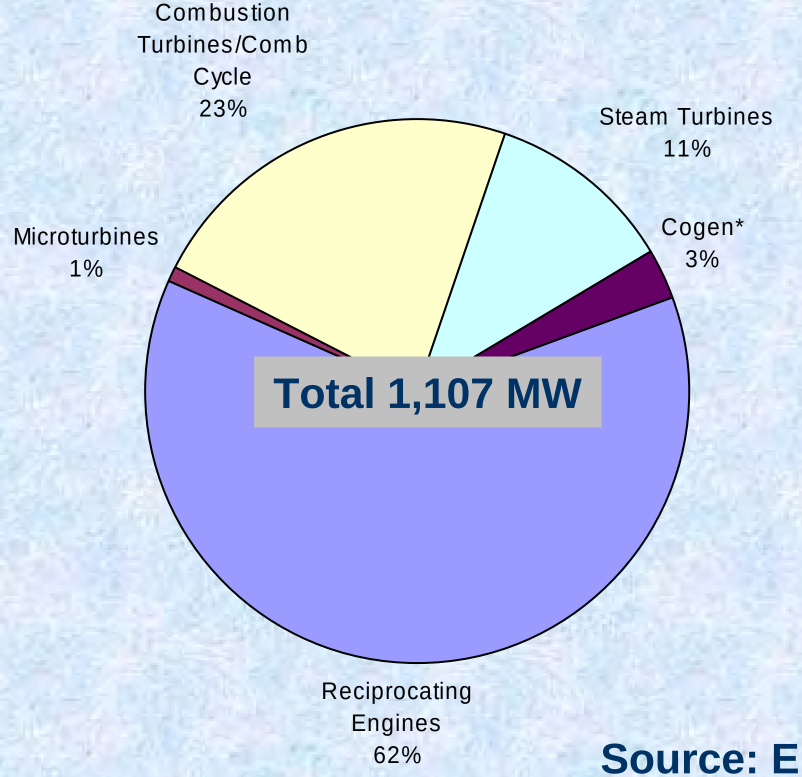
Example ADG Reciprocating Engine Installations

- Central Weber Wastewater Treatment Plant in Ogden, Utah
  - A 1.2 MW reciprocating engine at this Utah plant has been producing power from ADG for over 5 years
- Papillion Creek Wastewater Treatment Plant in Bellevue, Nebraska
  - 6 small IC engines have been installed throughout the past 30 years to power this plant - typically only 4 run at a time, so there is no downtime for maintenance and repairs
- Colorado Pork pig farm in Lamar, Colorado
  - This farm utilizes a 80 kW CHP engine generator (about half of the peak load) - it has been running on ADG since 1999

Example LFG Reciprocating Engine Installations

- Davis County Landfill in Layton, Utah (under construction)
  - Ameresco, Inc. is currently installing a 1 MW reciprocating engine at this landfill - this is Utah's first landfill gas to energy project
- Roosevelt Regional Landfill in south central Washington
  - Allied Waste Systems installed (4) 2.1 MW Waukesha engines at this landfill in 1999 to provide power for utilities and industrial customers
- Coffin Butte Landfill in Corvallis, Oregon
  - In a project developed by the Pacific Northwest Generating Cooperative and Allied Waste Industries in 1995, this landfill produces LFG power with a 2.4 MW reciprocating engine
- Bradley Avenue Landfill in Sun Valley, California
  - Waste Management Inc. has installed (2) 5 MW reciprocating engines running on LFG at this plant - electricity is sold to the local utility

Most of LFG Installed Base is Reciprocating Engines



Source: EPA LMOP 2005

Microturbines for ADG and LFG

- Microturbine combustor design allows them to easily accommodate low-Btu fuels (down to about 35% methane content)
- Most units have recuperators that utilize waste heat to improve efficiency
- A fuel compressor and fuel treatment equipment are usually necessary, which can add significantly to the capital and maintenance costs

Microturbine Performance

- Microturbines have relatively low electric efficiencies - even with a recuperator and running on natural gas, electric efficiencies are typically 20-30%, with overall CHP efficiencies of 60-80%
- When using low-Btu fuels, the electric efficiency will fall on the lower side of these ranges
- Power output is reduced 5-10% compared to NG
- Fuel cleaning, drying, and particulate removal (including filters for siloxanes and hydrogen sulfide) are usually required, adding to both capital and maintenance costs
- A special fuel compressor is necessary for both fuels, requiring up to 10% of the power produced by the microturbine, and adding $100-$200 per kW to capital costs

Microturbines: Increased Costs for ADG/LFG

- Combining the factors discussed on the previous slide, the installed cost for microturbines running on ADG or LFG are typically 25-30% more than NG
- For O&M, gas treatment, extra compressor maintenance and increased cleaning cause maintenance costs to rise about 60%

Microturbines	**Natural Gas**	**ADG/LFG**
Installed Cost (CHP, $/kW)	1,400-2,300	1,800-3,000
Maintenance Cost (cents/kWh)	1-2	1.5-3

Emissions and Emission Controls for Microturbines

- In general, only fuel cells (and potentially Stirling engines) produce lower emissions than microturbines
- NOx levels are less than 9 ppm for 30 kW Capstone microturbines running on NG - it is harder to achieve this with ADG and LFG, but NOx emissions are generally kept under 25 ppm for all fuels
- Microturbines' small size usually exempts them from emissions regulations, so controls are typically not required

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Applications for Microturbines

- Microturbines have been used extensively in ADG and LFG projects because they are well-suited for small DER/CHP applications, they can handle these fuels with “off-the-shelf” units and they generate very low emissions
- Microturbines are ideal for small projects in non-attainment areas where reciprocating engines would require SCR
- They are most ideal when the electric load is less than 300 kW - microturbines are usually <100 kW, and multiple units can be employed for flexibility
- However, with ADG and LFG applications, many projects fell short of expectations because costs required for fuel preparation and turbine maintenance became too high (especially when siloxane issues were encountered)

Example Microturbine Installations

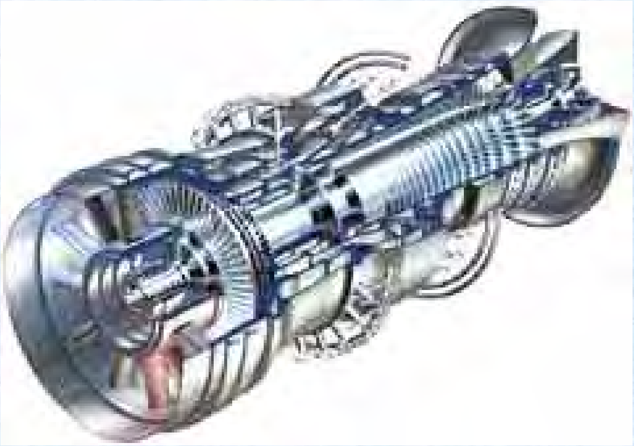
- Columbia Blvd Wastewater Treatment Plant in Portland, Oregon
  - A fuel cell and several microturbines have been installed at this Oregon plant
- Lewiston Wastewater Treatment Plant in Lewiston, New York
  - Two 30 kW Capstone microturbines produce power from ADG at this plant - one of the first to adopt microturbine technology
- Antioch Community High School in Antioch, Illinois
  - First school to utilize LFG for both heat and power in 2003 with twelve 30-kW microturbines (360 kW total)
- Jamacha Landfill in Jamacha, California
  - Working with SCS and San Diego County, (4) 70 kW Ingersoll Rand microturbines were installed at the Jamacha Landfill in 2001

Example Microturbine Installations

- Operating Industries, Inc. (OII) Landfill in Monterey Park, California
  - (6) 70 kW Ingersoll-Rand microturbines (420 kW total) were installed in 2002 with the help of project developer SCS
- Lopez Canyon Landfill in Lake View Terrace, California
  - At this demonstration project, (50) 30 kW microturbines work together to produce 1.3 MW of total power
  - Largest microturbine power plant to run strictly on landfill gas

Combustion Turbines for ADG and LFG

- Combustion turbines can range from small 1 MW units to 100+ MW power plants, although most ADG/LFG applications are 3-15 MW
- Most NG turbines require significant modifications to accommodate low-Btu fuels



- Most ADG/LFG turbine installations are dual fuel, using a natural gas blend, so that fewer modifications are required
- This presentation focuses on units burning 100% ADG or LFG

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Combustion Turbine Performance

- Natural gas combustion turbines have electric efficiencies of 25-40%, and overall CHP efficiencies of up to 80%
- Like microturbines, efficiency can be improved with the use of recuperators
- Efficiency is reduced by about 10% for turbines utilizing ADG or LFG
- Power output is also reduced by about 10%

Fuel	Electric Efficiency	Power Output
Natural Gas	25-40%	100%
ADG/LFG	23-36%	90%

Combustion Turbines: Increased Costs for Opportunity Fuels

- With ADG and LFG, many equipment modifications (larger manifolds, more filters, diffusion combustors, etc.) are required, as well as fuel treatment equipment
- Overall, equipment costs are increased by about 50% for ADG and LFG units
- The turbine systems require more inspections, cleaning and general maintenance with ADG and LFG - costs are typically 75% more than natural gas

Combustion Turbines	**Natural Gas**	**ADG/LFG**
Installed Cost (CHP, $/kW)	600-1,400	900-2,100
Maintenance Cost (cents/kWh)	0.5-1	1-2

Emissions and Emission Controls for Combustion Turbines

- In order to reduce NOx emissions, most natural gas combustion turbines pre-mix the fuel with a large volume of air, but low-Btu fuels can not sustain combustion with with these burners
- Most turbines designed for ADG/LFG use a diffusion combustor to burn low-Btu fuels, which produces about 25-35 ppm of NOx emissions
- Low NOx, lean burn technology can not be deployed with ADG/LFG
- To bring emissions below 25 ppm, selective catalytic reduction could be used - but in order to use SCR with ADG/LFG, extensive fuel cleaning prior to combustion would be necessary (even trace amounts of hydrogen sulfide or siloxanes could poison the catalyst) and capital costs would be much higher

Applications for Combustion Turbines

- Combustion turbines are common for DER/CHP applications greater than 3 MW in size
- Combustion turbines have been used for large ADG/LFG operations with relatively few problems, but most of these are dual fuel units using a NG blend
- For ADG and LFG, potential is generally limited to: 1) large wastewater treatment plants, and 2) landfills with a third party company/utility nearby to take on the project
- For small (<3 MW) ADG/LFG applications, reciprocating engines and microturbines are more common

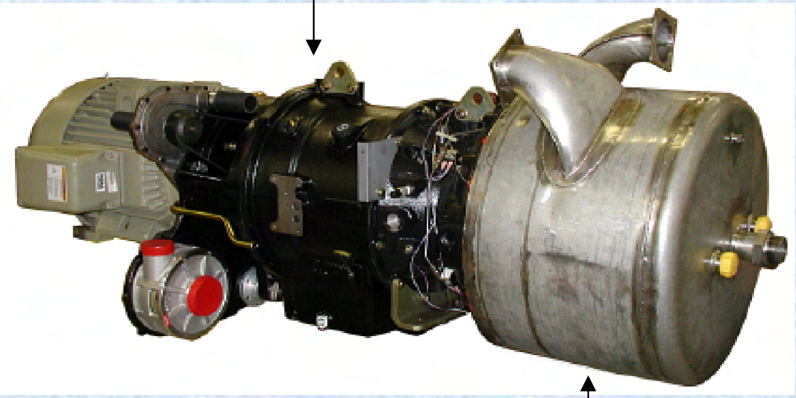
Example Combustion Turbine Installations

- Stickney Water Reclamation Plant in Cicero, IL
  - 3 MW turbine has been operating on the plant's ADG since 1991
- Santa Cruz Landfill and San Marcos Landfill in California
  - In 1989, Gas Recovery Systems installed a small 740 kW turbine at the Santa Cruz facility to produce power for PG&E, and two of the 740 kW turbines at San Marcos to produce power for SDG&E
- Altamont Landfill in Livermore, CA
  - Bio Energy Partners and Waste Management, Inc. teamed up to install two 3 MW Solar turbines at this landfill in 1989 - the facility also installed two 1.3 MW recips in 2002 to produce additional power
- SC Johnson's Waxdale Manufacturing Facility in Racine, WI
  - 3.5 MW turbine provides power and steam for the manufacturing facility, and is powered by LFG from a nearby landfill

Stirling Engines for ADG and LFG

- Although Stiring engine technology has been around for many years, it is only now entering commercialization for DER/CHP applications
- Stirling engines rely on external combustion - inside the engine, trapped hydrogen gas pushes the pistons towards the heat source created by the fuel

Engine (hydrogen gas)



External Combustor (ADG/LFG)

Stirling Engines: Advantages and Drawbacks

- Stirling engines are very fuel flexible, and better control of emissions is possible due to the external combustion design
- Stirling engines can handle fluctuating Btu levels (which can be a problem with ADG/LFG streams) and they do not require compressors - a simple blower will suffice
- The burners can be modified to handle fuels with different Btu contents without any modification to the engine itself
- Stirling engine burners also have a relatively high tolerance for siloxane and other particulates
- The primary drawbacks to Stirling engines are limited CHP capability (hot water only) and a capital cost higher than most DER/CHP technologies (i.e. recips and combustion turbines)

Stirling Engines: The Future Market

- STM Power has developed a 28% efficient, 55 kW Stirling Engine expected to be commercially available this fall, with burners specially designed for ADG and LFG fuels
- An Oregon WWTP has installed one of these units for testing purposes - it has been running for 2000 hours
- Projected costs for these engines will be $1300-$1400 per kW (installation not included), while maintenance is expected to be around 1 cent per kWh

Fuel Cells for ADG and LFG

- Fuel cells are a developing technology, but 200 kW phosphoric acid units have been produced by UTC and installed at wastewater treatment plants utilizing ADG
- Several installations in California, Oregon, Washington, New York, and other locations have proven the technology's reliability

- Fuel cells produce very few emissions (no combustion) and have high electric efficiencies (30-40%), but require more maintenance (2-4 cents/kWh)

Fuel Cells: Still Challenged by Costs

- Although many different types of fuel cells are in development (PEM, SOFC, etc.), phosphoric acid fuel cells (PAFCs) are the only type currently available, and they cost several times more than traditional DER/CHP technologies ($4,000-$5,000/kW vs. ~$1,000/kW)
- Hydrogen sulfide poisoning is an important issue with fuel cells - serious damage could occur with stack exposure to H_2S
- ADG/LFG fuel reformers require more filters, a larger fuel injector, larger piping, and more maintenance than natural gas fuel reformers, so they are more expensive
- Until the price of fuel cell technologies drops significantly, they will not have a significant impact on the opportunity fuel market

Summary Table for ADG/LFG Technologies

Technology	Size Range (Current)	Electric Efficiency	Installed Cost ($/kW)	Maintenance (cents/kWh)	Emission Controls
Reciprocating Engine	75 kW - 5 MW	27-36%	1,000-1,700	1.5-4.5	Lean Burn, Possibly 3WC/SCR
Microturbine	30-300 kW	20-27%	1,800-3,000	1.5-3	None Required
Combustion Turbine	> 1 MW	23-36%	900-2,100	1-2	Possibly SCR (<25 ppm)
Stirling Engine	55 kW	25-30%	1,500-2,000*	0.8-1	None Anticipated
Fuel Cell	200 kW	30-40%	4,000-5,000	2-4	None Required

*Assuming a $300-$500/kW installation cost for Stirling engines