ECONOMIC ANALYSIS OF AUTOMOTIVE-DERIVED ENGINE-GENERATOR SETS AS ENERGY CONVERSION SYSTEMS AT SMALL LANDFILLS

A Thesis
by
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ABSTRACT

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(August 2011)

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This study is an economic analysis of the cost and longevity of modified automotive engine-generator sets as an economical method for small landfills to produce electricity. Internal combustion engines are common in landfill gas to electricity projects, but automotive engines have not been carefully studied yet represent a less expensive alternative to industrial internal combustion engines. The energy conversion system at the Watauga County Landfill in Boone, North Carolina, is composed of two 93 kW KSD Enterprises-General Motors Vortec (8.1 liters) engines attached to a Taylor Power Systems generator. Interviews with the managers of landfill projects using automotive-derived engine generator sets were conducted by phone and via email. The questions included the landfills' cost of energy conversion systems, revenue, payback period, funding sources, operations, and engine oil and landfill gas testing methods. The findings indicate that small landfills benefit from the economics of this appropriate technology.

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INTRODUCTION

The energy conversion system at the Watauga County Landfill in Boone, North Carolina, is composed of two 93 kW KSD Enterprises-General Motors Vortec (8.1 liters) engines attached to a Taylor Power Systems generator (480 volts) at a rotation speed of 1800 revolutions per minute (rpm). Reciprocating internal combustion engines are common in landfill gas to electricity projects, but spark ignition automotive engines, which have not yet been carefully studied, represent a less expensive alternative. Out of 2,392 landfills in the U.S., 549 have produced electricity and 428 currently produce electricity using reciprocating engines (U.S. Environmental Protection Agency Landfill Methane Outreach Program, 2010a). At least two other landfills in the United States are currently employing auto-derived engine-gen sets to produce electricity: Mid-County Landfill in Christiansburg, Virginia and Chittenden Solid Waste District Landfill in Williston, Vermont. Interviews with the managers of landfill projects using automotive-derived engine-gen sets were conducted by phone and via email in March of 2011. The questions included the landfills' cost of energy conversion systems, revenue, payback period, funding sources, operations, and engine oil and landfill gas testing methods. The findings herein may inform decisions made at the Watauga County Landfill and other smaller landfills that may benefit from the use of an automotive engine-generator set to leverage the capital costs associated with the generation of electricity when using the methane in landfill gas as a fuel.

REVIEW OF RELATED LITERATURE

Landfill Gas Resources

Landfill gas (LFG) is composed of approximately 50% methane (CH_4), a greenhouse gas 23 times more potent than carbon dioxide (CO_2) on a mole basis for a 100-year lifetime (U.S. EPA, 2008). U.S. methane emissions in 2010 are projected at 125.4 million metric tons of carbon equivalent (MtCO2eq) out of the 760.6 MtCO2eq global total (U.S. EPA, 2006). In 2008, the United States generated "approximately 250 million tons of solid waste with 54 percent deposited in municipal solid waste (MSW) landfills" (U.S. EPA Landfill Methane Outreach Program [U.S. EPA LMOP], 2010a, p.3). MSW landfills are the second-largest source of human-related methane emissions in the United States (after livestock), accounting for approximately 22 percent of these emissions and releasing an estimated 30 $MtCO_2eq$ to the atmosphere in 2008 alone (U.S. EPA LMOP, 2010a). Flaring CH_4 or combusting it to produce CO_2 is the simplest form of methane mitigation, but the methane-rich gas can also be used for energy. In the United States, there are 558 operational landfill gas projects in 44 states annually supplying 1,727 MW of thermal energy and electrical power; when the 510 candidate landfills (meaning these are currently open or have been closed for less than five years and have one million metric tons or more of waste in place) are counted (1,170 MW) the potential to reduce greenhouse gases is 13 $MtCO_4eq$/yr (see Figure 1).

Generation of electricity from LFG makes up about two-thirds of the currently operational landfill projects in the United States (U.S. EPA LMOP, 2011a). The 13 billion kWh along with the 100 billion cubic feet of LFG for direct use produced by these projects per year has estimated annual energy benefits equal to the electricity of more than 940,000 homes or the heating of more than 722,000 homes (U.S. EPA LMOP, 2010a).

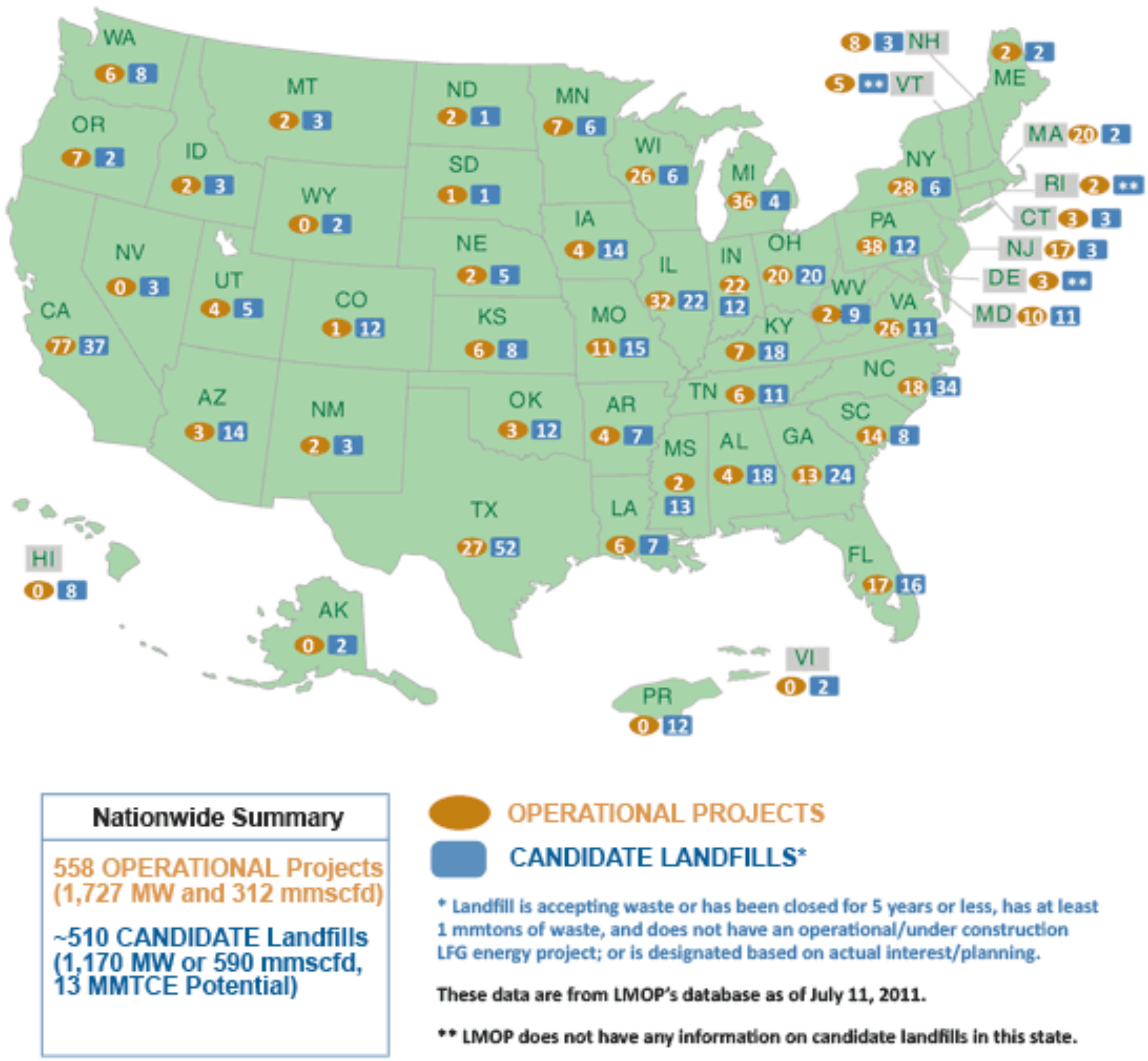

Figure 1. Nationwide Summary, Landfill Methane Outreach Program (U.S. EPA LMOP, 2011b)

Though globally waste accounts for “less than 5% of greenhouse gas (GHG) emissions,” it is the most feasible source to abate (Intergovernmental Panel on Climate Change [IPCC], 2007). Agencies like the U.S. EPA and the Clean Development Mechanism of the Kyoto Protocol provide education and incentives for methane recovery at landfills. “The total global economic mitigation potential for reducing landfill methane emissions in

2030 is estimated to be >1000 $MtCO_2eq$ (or 70% of estimated emissions) at costs below 100 US$/$MtCO_2eq$/yr. Most of this potential is achievable at negative to low costs: 20–30% of projected emissions for 2030 can be reduced at negative cost and 30–50% at costs <20 US$/$MtCO_2eq$/yr" (IPCC, 2007). Flaring methane, or combusting it to produce CO_2 is the simplest form of methane mitigation. The breakeven cost of flaring per one MtCO2eq is $24.69, $73.02 to generate electricity, and $243.45 to compost the municipal solid waste (U.S. EPA, 2006).

In North Carolina, there are 20 operating landfill gas to energy projects, eight of which generate electricity (21 MW capacity) and 12 operate for direct thermal use (11 MW capacity) (U.S. EPA LMOP, 2010b). These projects reduce annual methane emissions by 1.7 MtCO2eq. There are 33 candidate landfills in North Carolina (U.S. EPA LMOP, 2010b).

Watauga County Landfill in Boone, North Carolina, does not meet the criteria for a candidate site because at 546,000 tons of waste in place it is well below the one million metric tons criterion and it has been closed for over five years. Its 186 kW gas to electricity system will produce approximately 1,290,355 kWh/yr in 2011 down to 737,033 kWh/yr in 2025 (according to predicted flow using LandGEM software, an electrical efficiency of 20%, and availability of 92.5% annually). The reduction of annual avoided carbon dioxide and methane using a 200 kW system is .0118 MtCO2eq or 1,374 tons of carbon dioxide and 556 tons of methane. This is equivalent to any one of the following: taking 2,263 vehicles off the road, the carbon sequestered from planting 2,524 acres of pine forest, CO_2 emissions from 27,526 barrels of oil consumed, or the consumption of 1,331,385 gallons of gasoline. This is enough energy to heat 340 homes per year (U.S. EPA LMOP, 2010c).

Economics of Developing Landfill Gas to Electricity Projects

Given the upfront costs associated with landfill gas to electricity projects, incentives are often needed. LMOP provides an online funding guide that describes the federal and state incentives for landfill gas to energy systems. It suggests beginning with each State's Energy Office, as $3.1 billion is allocated under the American Recovery and Reinvestment Act to the U.S. Department of Energy (DOE) to distribute to states under the auspices of State Energy Programs (U.S. EPA LMOP, 2010b). The Database of State Incentives for Renewables and Efficiency (DSIRE), managed by the NC Solar Center, maintains updated information on all federal and state incentives.

Selling "Greenness" on the Market. The carbon market is in a formative stage with pricing, standards of valuation, and the definition of what constitutes additionality in flux. Renewable Energy Certificates (RECs) and carbon credits are environmental commodities intended to provide economic incentives for electricity generation from renewable energy sources. A REC is created when one (net) MWh of electricity is generated from an eligible renewable energy resource. RECs may be sold separately from the electricity being generated and are defined by their "green attributes." Emissions offsets are measured by the amount of carbon being offset and therefore require monitoring, which can be expensive. In order to qualify for carbon credits, the concept of additionality must be proved. The project must go beyond required environmental guidelines; the credits represent the incentive to do so.

The sale of RECs to utility companies helps them to meet the required percentage of electricity sales from renewable energy and energy efficiency as mandated by the Renewable Energy and Energy Efficiency Portfolio Standard (12.5% in North Carolina by 2021) (NC Solar Center, 2010a). Duke Energy buys non-solar RECs for $6.21 per MWh with contracts from 5—15 years and a range of 50—5,000 RECs per year (NC Solar Center, 2010a). The TVA's Generation Partners Program offers $1,000 as an incentive to help offset start-up costs plus $0.03/kWh above the retail rate and any fuel cost adjustments for eligible non-solar renewable energy with a minimum size of 0.5 kW. The TVA's Mid-Sized Renewable Standard Offer Program applies to projects sized from 200 kW—20 MW, pays an average of $0.0561/kWh but can pay up to $0.1596 during specified peak times, and up to a 20 year contract with a 3% increase in base rates per year (NC Solar Center, 2010a).

NC GreenPower is the first statewide green energy program in the nation administered independently by a nonprofit organization and supported by all of the state's utilities (NC Solar Center, 2010a). The NC GreenPower Production Incentive gives production payments for renewable grid-tied electricity, including methane from landfills. The Program, formed in 2003, offers production payments for grid-tied electricity and depends on voluntary contributions from NC electricity consumers. Owners of the renewable energy system apply in an open bid to receive program incentives at any time as long as the system is not net metered. System owners are required to enter into power-purchase agreements with their North Carolina electric utility and with NC GreenPower.

Federal and Global Funding. Incentives to produce renewable energy are growing, and can realize direct investment in the economy. The Energy Improvement and Extension Act (EIEA) of 2008 (The Bailout Bill) and The American Recovery and Reinvestment Act (ARRA) of 2009 (The Stimulus Bill) each extended benefits for clean energy production (California Center for Sustainable Energy, 2009). EIEA (H.R. 1424) passed the month after the Emergency Economic Stabilization Act was defeated in the House (September 2008) and approximately $18 billion of the $700 billion total was allocated for renewable energy

(Soraghan, 2008). ARRA extended the "in-service deadline for most eligible technologies by three years, adding credits for combined heat and power production, and allowing facilities that qualify for the Production Tax Credit (PTC) to opt instead to take the federal business energy investment credit (Investment Tax Credit) or an equivalent cash grant from the U.S. Department of Treasury" (NC Solar Center, 2010a). In addition to federal and state tax incentives, federal bonds and production incentives are also available.

Clean renewable energy bonds (CREBs) is a federal loan program for certain types of public entities to finance renewable energy projects, paying back only the principal of the bond (no interest), and in exchange the bondholder receives federal tax credits ($2.2 billion for 805 projects in 2009) (NC Solar Center, 2010b). The Section 45 PTC currently provides 1.1 ¢/kWh for systems in place as of December 31, 2013 with a 10-year contract but public entities cannot benefit from this credit since they do not pay taxes, therefore a private partner would be necessary. This option allows for up-front incentives such as a one-time 30% investment tax credit (Section 48) or conversion into a 30% cash grant. The Federal Renewable Energy Production Incentive (REPI) is for systems installed until October 1, 2016 and applies to local and state government or non-profit electricity co-op facilities and gives payment for the first 10 years of operation (U.S. EPA LMOP, 2010d).

REPI was created by the U.S. Energy Policy Act of 1992 and allows state governments to disburse a 2.1¢/kWh incentive to power facilities owned by state and local government entities. The REPI program is managed by the Department of Energy. The amount awarded varies each year. "Qualifying systems are eligible for annual incentive payments of 1.5¢ per kilowatt-hour in 1993 dollars (indexed for inflation) for the first 10-

year period of their operation, subject to the availability of annual appropriations in each federal fiscal year of operation" (NC Solar Center, 2010b).

A major international initiative is the U.S. EPA Global Methane Initiative (formerly the Methane to Markets Partnership), which includes 36 partner countries in a targeted approach to funding proposals for capacity building in the countries that have the highest methane emissions. To abate these emissions, in 2011, the Global Methane Initiative will award a total of $5,000,000 to approximately 35 cooperative agreements, each ranging between $100,000 to $750,000 per contract. "Landfills" is one of four international categories including agriculture (anaerobic digester applications), underground coalmines, and oil and gas (U.S. EPA, 2010). The Appalachian State University Energy Center is a recipient of this funding for its work at landfills in Brazil since 2009.

How Landfill Gas is Produced

Landfill gas (LFG) is composed of approximately 50% methane (CH_4), a greenhouse gas 23 times more potent than carbon dioxide (CO_2) on a mole basis for a 100 year lifetime (U.S. EPA, 2010a). Known as a "marsh gas," it is produced by methanogenic bacteria that decompose organic matter in the absence of oxygen (Ewall, 2010). These anoxic conditions allow methane to form either through the direct cleavage of acetate into CH_4 and CO_2 or the reduction of CO_2 with hydrogen (Spokas, Bogner, Chanton, Morcet, Aran, Graff, Moreau-Le Golvan, & Hebe, 2006). This process is influenced by several factors, such as temperature, moisture content, waste composition and diversity of substrates for microbial degradation (Bove & Lunghi, 2006).

The first phase in the production of landfill gas is aerobic decomposition in which bacteria in the presence of air digest organic matter. This produces heat while oxygen (O_2) is consumed, generating CO_2. The time frame, depending on specific conditions, ranges from months to one year. The acidogenic phase occurs under anaerobic conditions, resulting in quantities of H_2, CO_2, H_2O and organic acids (see Table 1).

Table 1.

Typical Landfill Gas Chemical Composition (Bove & Lunghi, 2006)

Component	***Typical U.S. landfill level***
Methane	40–55%
Carbon dioxide	35–50%
Water	1–10%
Nitrogen	0–20%
Oxygen	{0–5%}
Condensable hydrocarbons	250–3000 ppm as hexane
Chlorine compounds	30–300 mg/m3
Hydrogen Sulfide	Up to 200 ppm

The oxidation of acids and alcohols to acetic acids plus CO_2 and H_2 takes place in the acetogenesis phase. The chemical oxygen demand noticeably increases due to the dissolution of acids and leachate. Finally, methanogenesis occurs during which the products of acetogensis are converted to methane and CO_2, and H_2 is consumed. The methane content depends on the available organic compounds. Maturation is due to substrate depletion when gas production drops (Bove & Lunghi, 2006). The entire lifespan of a landfill is estimated to be between 20-30 years with “gas recovery efficiencies typically estimated to be in the range of 50–75% {using a first order kinetic equation based on waste inputs, climate variables, and other factors} ” (Spokas et al., 2006).

Contents of landfill gas. LFG is a water saturated biogas that consists of 50-60% CH_4, 40–50% CO_2, and numerous trace components (Spokas et al., 2006). More than 140 trace compounds have been identified so far in landfill gas, reaching a total concentration of up to 2000 mg/m3 (.15% volume) (Schweigkofler & Reinhard, 2001, p. 184). Contaminants may include hydrogen sulphide, and a broad spectrum of volatile organic compounds (VOCs): organic-sulphur compounds (e.g. carbonyl sulphide, mercaptans), silicon-containing compounds (e.g. siloxanes), halogenated compounds, aromatics and aliphatic hydrocarbons (Urban, Lohmann, & Salazar Gómez, 2009). During engine combustion, the sulphur-containing compounds and halogenated compounds yields acid gases (H_2SO_4, HCI, and HF), which corrode downstream power generating units (Urban et al., 2009).

Landfill gas as a fuel. Landfill gas (LFG) is composed of around 50% CH_4. On a mass basis, CH_4 has a fuel energy content of 55.54 MJ/kg when fully combusted (see Table 2 for comparison with other fuels). The United States consumes approximately 3.7 trillion kWh per year (U.S. Energy Information Administration, 2007). If all the waste that Americans dispose of in landfills could be efficiently tapped to run a (typical 30% efficient) steam boiler turbine, it could provide only 0.1% of America’s total electrical needs” (Duffy, 2010). Landfills are only the tip of the iceberg of biogas applications from which wastewater plants and farms could benefit.

Table 2.

Fuel Energy Content Mass Basis (Hydrogen Properties, 2010)

Fuel	***Higher Heating Value (HHV)***	***Lower Heating Value (LHV)***
Hydrogen	142.35 MJ / kg	120.24 MJ / kg
Methane	55.54 MJ / kg	50 MJ / kg
Propane	49.44 MJ / kg	45.48 MJ /kg
Gasoline	45.7 MJ / kg	42.9 MJ / kg
Diesel	44.3 MJ / kg	41.8 MJ / kg
Methanol	22.69 MJ / kg	19.94 MJ / kg

The interchangeability of biogas with natural gas ensures a future for marketability. As more methods for methane recovery emerge, landfill gas can readily be promoted to replace natural gas, which, is composed of 70%-90% methane. LFG has between 450-550 Btu/ft3 and natural gas has typically 950 Btu/ft3 (Bade & Narayanan, 2008). Given that 24% of total U.S. energy consumed in 2008 was natural gas (U.S. EPA, 2010a), landfill gas presents a renewable alternative to fossil fuels and is typically 10% less the price of natural gas (see Figure 2 for recent natural gas price). Natural gas accounts for 28% of all electric power generation and industrial consumption; residential use, 21%; and commercial use, 13%" (U.S. EPA, 2010a).

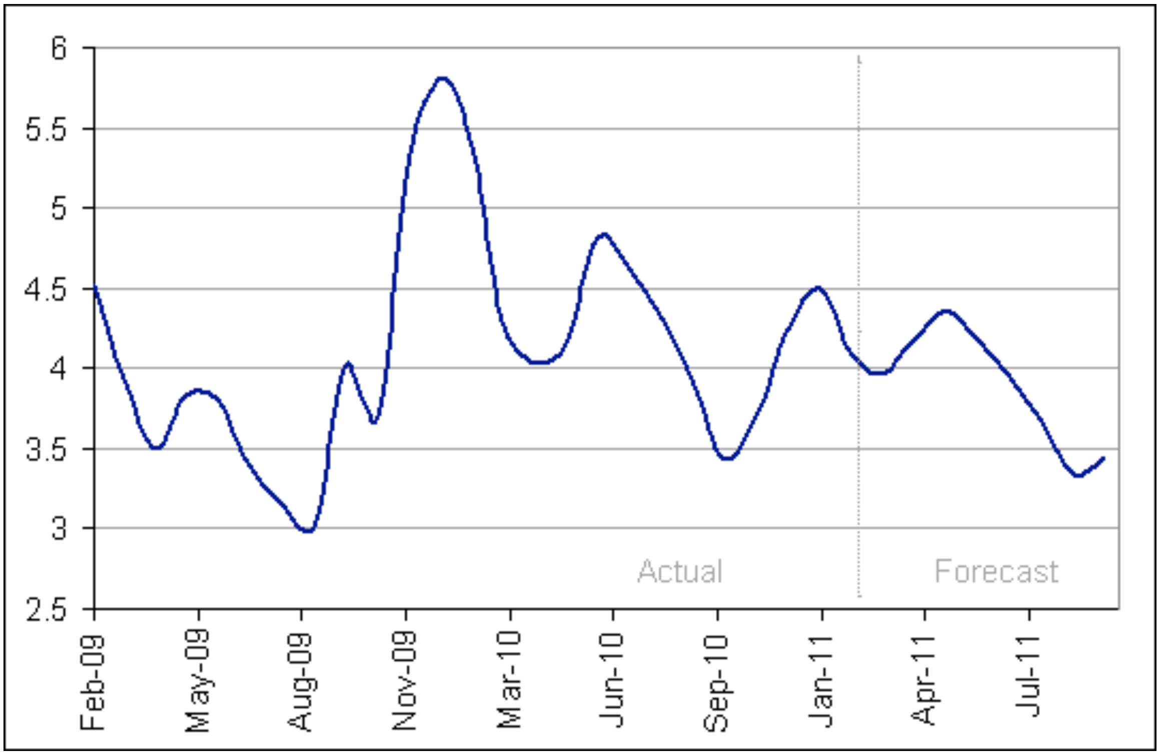

Figure 2. NYMEX Henry-Hub Natural Gas Prices Past Trend Value & Future Projection in U.S. Dollars per Million BTU

LFG to Energy Components and Systems

The components of a LFG to Energy system are a collection system and an energy conversion system. LFG is first extracted from landfills using a series of wells and a blower/flare (or vacuum) system. Collected gas is directed to a central point where it can be processed and treated depending upon the ultimate use for the gas. From this point, the gas can be flared, used to generate electricity, provide process heat, or upgrade to pipeline–quality gas where the gas may be used directly or processed into an alternative vehicle fuel (U.S. EPA LMOP, 2010a).

Electricity generation. Approximately two-thirds of the operational LFG projects in the United States are for electricity generation (U.S. EPA LMOP, 2010a). The common technologies used include: internal combustion engines, gas turbines, microturbines, stirling engines, and fuel cells. Most projects use internal combustion (reciprocating) engines or turbines, with microturbine technology being used at smaller landfills and in niche applications (U.S. EPA LMOP, 2010a). Technologies such as Stirling and organic Rankine cycle engines and fuel cells are still in development.

Types of LFG to electricity conversion systems. The primary types of LFG to Electricity conversion systems are reciprocating internal combustion engines (most common), gas turbines, microturbines, fuel cells, and Stirling engine systems (see Table 3 for comparison). Internal combustion engines have historically provided the best economics for small to medium sized landfills, whereas gas turbines are typically used in larger LFG to Electricity projects (3 MW minimum) in which economies of scale can be achieved. Microturbines can run on low levels of methane and require less maintenance than an internal combustion engine. Fuel cells and Sterling engines are still under development by industry standards.

Table 3.

Technologies for LFG Electricity Projects (U.S. EPA LMOP, 2010a)

Projects listed as operational in the Landfill Methane Outreach Program (LMOP) database as of January 2010.

Project Technology	***Number of Projects***
Internal combustion engine	279
Cogeneration	26
Steam Turbine	14
Micro Turbine	13
Combined Cycle	6
Stirling cycle	2
Gas turbine	28

Direct use. Nearly one-third of the currently operational U.S. LFG to Energy projects are for direct thermal use and often offset the use of another fuel (see Table 4). LFG can be in a boiler, dryer, kiln, greenhouse, or other thermal application. Innovative direct uses include: leachate evaporation, firing pottery and glass–blowing kilns, hydroponics, powering and heating greenhouses and an ice rink, and heating water for an aquaculture operation (e.g. EnergyXchange in Burnsville, NC). “Current industries using LFG include auto manufacturing, chemical production, food processing, pharmaceuticals, cement and brick manufacturing, wastewater treatment, consumer electronics and products, paper and steel production, and prisons and hospitals, just to name a few” (U.S. EPA LMOP, 2011b). Direct use is a notable option for long-term community-based projects due to its simplicity, versatility, and low cost.

Table 4.

Technologies for Direct-Use Projects (U.S. EPA LMOP, 2010a)

Project Technology	***Number of Projects***
Boiler	54
Direct thermal	42
High-Btu	22
Leachate evaporation	16
Greenhouse	6
Alternative fuel (compressed natural gas or liquefied natural gas)	3
Medium-Btu gas injected into natural gas pipeline	1

Cogeneration. Cogeneration is often referred to as combined heat and power, and is by far the most efficient application, as this entails both the generation of electricity and the use of thermal energy. The latter is in the form of steam or hot water. Historically used for industrial operations, the efficiency gains of capturing the thermal energy in addition to electricity generation can make these projects very attractive (see Table 5). At the Watauga County Landfill, the waste heat from the engine cooling will be used in the maintenance building for space heating and hot water.

Table 5.

Estimated Capital Costs ($/kW) for Reciprocating Engine Cogeneration Systems (Onovwiona & Ugursal, 2006)

Cost Component	***Senertec***[a]	***North American cogeneration systems***			***MAN* (Pierce, 2004*)***
Electrical capacity (kW)	5.5	7.1–10.7	20.1–23.3	30.3–35.0	100.0
Electrical efficiency (%)	27.5	28.1	37.4	33.1	30.6
Thermal efficiency (%)	62.5	56.5	50.0	51.2	50.4
Installed cost ($/kW)	2,720	2,800	1,600	1,300	1,080

[a]The Senertec installed cost was based on an investment cost of $15,030 provided in the manufacturer's catalog.

Alternate fuels. LFG has been converted to vehicle fuel in the form of compressed natural gas and liquefied natural gas (LNG). For pipeline quality gas and conversion to LNG, the gas must first be processed to increase its energy content and to meet strict standards for oxygen, hydrogen sulfide, moisture, carbon dioxide, and non-methane organic compounds (U.S. Climate Change Technology Program, 2005). Bowerman Landfill in Orange County, California, a joint venture between Prometheus and Montauk Energy Capital was the world's first commercial LFG-to-LNG facility. It came online in January 2007 and is using the liquefied natural gas in county waste trucks (U.S. EPA, 2010a). The largest LFG-LNG plant is operated by Waste Management at Altamont Landfill near Livermore, California and is designed to produce up to 13,000 gallons of LNG a day, power 300 Waste Management waste and recycling collection vehicles, and is expected to reduce 30,000 tons of greenhouse gas emissions per year (Austin, 2009).

Using internal combustion engines in LFG to electricity applications. Internal combustion engines are used in more than 70% of LFG to Electricity projects. Benefits include the relatively low cost, high efficiency, and good size match with the gas output of many landfills. The typical size of internal combustion engines is 800 kW to 3 MW, which can accommodate LFG flow rates of approximately 0.4 to 1.6 million cubic feet per day at 50 percent methane. Multiple engines can be combined together for projects larger than 3 MW (U.S. EPA LMOP 2010a, p. 6).

Cost-benefit analysis of using internal combustion engines. Though internal combustion engines require more periodic maintenance (e.g. monthly oil changes) than other technologies, the overall efficiency and economic advantages still hold. IC engine-generator sets are relatively efficient at converting LFG into electricity, achieving efficiencies in the range of 25 to 35 percent (U.S. EPA LMOP, 2010a). Because IC engines are universally deployed there is no need for specialized technicians. When used for cogeneration, the diffusion of heat sources (exhaust gases and jacket water) has a deleterious effect on heat recovery when compared with technologies such as microturbines that only have one thermal source (Onovwiona & Ugursal, 2006). Though gas turbines achieve the better economies of scale, for smaller projects the internal combustion engine is more cost-effective (see Table 6). IC engines have better efficiency but more emissions overall (see Table 7).

Table 6.

LFG Electricity Project Technologies Cost Summary (U.S. EPA LMOP, 2010d)

Technology	***Optimal Project Size Range***	***Typical Capital Costs ($/kW)***	***Typical Annual O&M Costs ($/kW)***
Microturbine	1 MW or less	$5,500	$380
Small internal combustion engine	1 MW or less	$2,300	$210
Large internal combustion engine	800 kW or greater	$1,700	$180
Gas turbine	3 MW or greater	$1,400	$130

Table 7.

Characteristics of a Caterpillar 3516 SITA Reciprocating Internal Combustion Engine and a Gas Turbine Operating on LFG (Bove and Lunghi, 2006)

Energy Conversion System	IC Engine	Gas Turbine
Electrical efficiency	33%	28%
Fuel consumption (kJ/kWh)	10,972	12,872
Emissions NOx (lg/kJ)	56.6	15
Emissions CO (lg/kJ)	56.6	19

IC automotive engines. The use of modified automotive engines is not standard practice. Small-scale residential cogeneration data suggests that on natural gas, automotive-derived engines may “operate for 15,000-20,000 hours before an overhaul is needed, whereas industrial engines operate for 30,000-40,000 hours” (Onovwiona & Ugursal, 2006). This is a 50% difference. Furthermore, “automotive engines have a life expectancy of about 20,000 hours" (around 2.5 years of operation assuming 8,000 hours per year) (Onovwiona & Ugursal, 2006). They are cheaper but less reliable than industrial engines that normally last up to 20 years" (Onovwiona & Ugursal, 2006).

Derating engines for landfill gas instead of natural gas. According to a 1994 report from SCS Engineers entitled, "Implementation Guide for Landfill Gas Recovery Projects in the Northeast," the natural-gas based engine ratings standard of the industry are not always applicable to landfill gas-fed engines. "When operated on LFG, engine power ratings are commonly reduced by 5 to 15 percent compared to operation on natural gas. The overall heat rate (after reduction for parasitic loads) ranges from 11,000 to 14,000 BTUs of LFG per kilowatt hour (kWh)" (SCS Engineers, 1994, p. 2-xiv).

Contaminants

The greatest challenge facing manufacturers and users of energy conversion systems at landfills is the deleterious effects of corrosive and lacquering compounds in landfill gas, which can reduce energy conversion and destroy machinery. Chlorine, fluorine, siloxanes, sulfur, and water vapor are the most damaging contaminants (Caterpillar, Inc., 2009). The main components of the biogas, methane and carbon dioxide, are mired in quantities of trace gases such as "nitrogen, oxygen, hydrogen sulphide, mercaptans, halogenated hydrocarbons and siloxanes" (Ajhar, Travesset, Yuce, & Melin, 2010). The "volatile methyl siloxanes (VMS) are typically found in concentrations of 3-24 mg/m3" (Ajhar et al., 2010). "During combustion, siloxanes are converted into silicon dioxide deposits, leading to abrasion of engine parts or the build-up of layers that inhibit essential heat conduction or lubrication" (Ajhar et al., 2010).

Siloxanes. Siloxanes appear in landfills as a result of such commercial and consumer products as detergents, shampoos, deodorants, and cosmetics (see Table 8). When siloxanes enter the engine as insoluble matter in the gas fuel, this forms a white deposit in the combustion chamber, forming a golden lacquer on components outside the combustion chamber (KSD Enterprises, LLC, 2005). “This lacquer can be especially evident on the piston-ring wiped surface of the cylinder liner {and} has a tendency to ‘fill’ the oil retaining honing pattern but rarely builds to the extent of requiring attention prior to routine overhaul” (KSD Enterprises, LLC, 2005).

Table 8.

Commonly Identified Organic Silicon Compounds in Digester and Landfill Gas (Nordic Council of Ministers, 2005; EPRI, 2006b; www.chemfinder.com).

Siloxane	***Abbreviation***	***MP g/mol***	***Boiling point, °C***	***Water solubility 25 °C, mg/l***
Hexamethyldisiloxane	L2	162	107	0.93
Hexamethylcyclotrisiloxane	D3	223	135	1.56
Octamethyltrisiloxane	L3	237	153	0.034
Octamethylcyclotetrasiloxane	D4	297	176	0.056
Decamethyltetrasiloxane	L4	311	194	0.00674
Decamethylcyclopentasiloxane	D5	371	211	0.017
Dodecamethylpentasiloxane	L5	385	232	0.000309
Dodecamethylcyclohexasiloxane	D6	444	245	0.005
Trimethylsilanol	TMS	90	99	4.26E+4

The deposits may cause changes in geometry to the combustion chamber, inducing higher emissions of carbon monoxide and formaldehyde, possibly violating air emissions regulations (Ajhar et al., 2010). Other weakening effects include: “parts of the deposited layers can break off and clog lines, catalysts can be poisoned in steam reforming or fuel cells, and the deactivation of catalysts for both pre-combustion and post-combustion gas purification, e.g., to reduce formaldehyde concentrations in exhaust gas” (Ajhar et al., 2010).

Options for prevention and maintenance against siloxanes. Two general options are available to project managers: installing gas purification equipment or controlling the problem with more maintenance. In cases of insignificant siloxane concentrations, the contaminant is not necessary to remove, as it might not be economically effective. “The investment and operating costs of the installed gas purification system may exceed the costs the siloxanes induce, e.g., due to more frequent oil changes, engine inspections, down-time and associated loss of financial reimbursement” (Ajhar et al., 2010). Though each landfill is different, adsorption on activated carbon (more common) and the use of silica are noted as the most “state of the art” approaches to siloxane removal (Ajhar et al., 2010). Detection of siloxanes in the gas stream comes in a variety of options (see Table 9).

Table 9.

Sampling Techniques of Gaseous Siloxane (Arnold, 2009, p. 21)

Method	***Advantages***	***Representative sample***	***Material/media***	***Recovery***
Gaseous sample taken into canister or gas bag	Simple, fast	Poor representation if consistency varies Less suitable for heavy siloxanes	Metal canister Tedlar bag Aluminium coated bag	Quite good Good Adsorption effects
Collection onto adsorbent	Relatively simple sampling	Possibility of longer sampling time when a representative sample is obtained	XAD Activated carbon Tenax	Imperfect adsorption; Depends on quality of activated carbon
Impinger	Requires ice bath More complex setting	Poor representation if consistency varies; Longer sampling	Methanol, n-hexane, dodecane etc.	Usually good, D3 more difficult

Statement of the Problem

Small landfills such as the Watauga County Landfill in Boone, North Carolina, may not meet the U.S. EPA criteria for a "candidate site" for landfill gas generation, yet they represent viable sources of revenue and electricity to their communities. Whereas the capital costs required to generate electricity at small landfills have been prohibitive in the past, with its universal components and lower cost, an automotive-derived engine-generator set offers a promising alternative to traditional methods.

Purpose of the Study

The purpose of this study is to provide information on leveraging the capital costs of producing electricity at small landfills by using an automotive engine-generator set. An industry survey of the project developers of two existing systems may inform future users of this alternative and appropriate energy conversion system. As the Watauga County Landfill adopts an automotive engine-generator set to produce power in May of 2011, the findings from this study will help it on its course. LFGcost-Web, a spreadsheet tool developed for LMOP, estimated nearly $500,000 for the first year of installation and maintenance with a -10% IRR, but Watauga County has budgeted for a $251,132 system with net profits averaging $32,513 per year, a 26% IRR, and a payback period of 3.29 years. Over its lifetime, the operation will prevent the escape of 235 million cubic feet of methane emissions. U.S. methane emissions in 2010 are projected at 125.4 MtCO2eq out of the 760.6 MtCO2eq global total (U.S. EPA, 2006). This thesis has the potential to advise the future of this technology so that other small landfills with similar budgetary constraints will be able to replicate the project.

Limitations of the Study

Limitations of this study include the level of willingness of operations managers to report accurately the costs, revenues, and maintenance practices at their respective landfills and the amount of information accessible by the Watauga County Landfill since the engine-generator sets are not currently producing electricity.

Significance of the Study

The significance of this study is its potential to present a body of knowledge that could verify the economics of small to medium sized landfills worldwide. To better understand the future, one must understand the past. The experiences informing the project developers at small landfills who have used modified transportation engines to produce electricity when landfill gas separation techniques often cost more than the collection system itself will be instrumental in developing cost-effective solutions for future projects. Automotive engines are fairly inexpensive and are a universal technology. They could help to leverage the cost of energy conversion systems at landfills and possibly for residences and in agricultural applications. In time, the U.S. Environmental Protection Agency may be able to change the definition of a "candidate landfill" to include all landfills. In the U.S. alone, over 1,000 landfills and even more farms could begin to produce electricity from biogas.

Research Hypothesis

The automotive-derived engine-generator sets provide an economical means for small to medium sized landfills and even farms to recover methane gas for energy but regular maintenance is needed and inexpensive gas separation technologies would benefit this industry segment. Critical success factors for other project developers were determined using an industry survey.

Research Methods

Calculating the Project's Potential Energy Supply

The quantity of methane extracted (LFG flow x percent methane) or the quantity of BTUs recovered per hour (LFG flow x percent methane x BTUs per cubic foot of methane x 60 minutes per hour) can be measured (Landtec, 2010). There are approximately 1012 BTUs of heat per cubic foot of pure methane (like natural gas), although this figure varies a little among reference texts (Landtec, 2010) but 960 BTUs is a more appropriate figure when calculating the efficiency of thermal energy conversion in an internal combustion engine. The LHV of methane under standard conditions (0 degrees C, 1 atm) is 960 BTU per ft^3 (Cornell University Biological and Environmental Engineering Department, 2006). LHV is defined as the higher heating value of the fuel less the energy required to vaporize the water produced during combustion (Cornell, 2006). Given there are 3,412 BTUs per kWh, an average gas flow in scfm, and a known methane percentage, the following equations can be used to predict electricity generation at landfills.

f = flow (scfm)

p = percentage of methane

t = time (minutes)

e = efficiency percent as a decimal

E_{in} = fuel energy input (kWh)

E_{out} = energy output (kWh)

P_{in}= power input

P_{out} = power output

In general, efficiency is defined as useful energy output per unit energy input, and can also be expressed in terms of rates (powers):

$$e = \frac{E_{out}}{E_{in}} = \frac{P_{out}}{P_{in}}.$$

In a landfill gas to energy project the energy input is produced by combusting methane, and the rate at which energy is delivered is given by

$$P_{in} = f\,p\,LHV.$$

Where f is the volumetric landfill gas flow, p is the volume fraction of methane, and LHV is the lower heating value of methane (960 BTU/cf).

As an example, the output of Watauga County's landfill gas to electricity project will be estimated. The gas flow has been measured at be on average 100 scfm with a methane concentration of 50%. Assuming a gen set efficiency of 20%, the estimated power output is

$$P_{out} = eP_{in} = (.2)(100 scfm)(0.5)(960 Btu/scfm) = 9{,}600 Btu/\min \approx 169 kW$$.

The selection of two 93 kW gen sets should provide a high capacity factor over time but they should be derated by 10% when using landfill gas, making them 20% efficient since IC engines are 30% efficient when running-on natural gas. Once cogeneration is in place the thermal conversion efficiency will likely be 70%.

Results

There are few advantages to operating smaller landfill gas to electricity projects since they are often improved by economies of scale. Larger operations can purchase gas separation systems to prevent wear from contaminants that can cost more than the collection system itself, whereas smaller landfills are often not required to collect their gas in the first place, making even the upfront cost of the project more daunting. However, at least three manufacturers of auto-derived engine-generator sets, Ed Devarney of Gas-Watt Energy, LLC Steve Cox of Green kW Energy, and Gary Disbennet and Jake Rockwell of KSD Enterprises, LLC, along with Stan Steury of the Appalachian Energy Center, have readjusted the high bar without compromising the integrity of their operations (see Table 10).

Table 10.

Landfills Surveyed Using Automotive-Derived Engine-Generator Sets to Produce Electricity (Cox, Devarney, & Steury, personal communication, April, 2011)

Landfill	***Landfill Owner Organization***	***Project Start Date***	***Project Developer Organization***
Mid-County	Montgomery Regional Solid Waste Authority, VA	10/10	Green kW Energy, Inc.
Chittenden County	Chittenden Solid Waste District, VT	10/09	Gas-Watt Energy, LLC
Watauga County	Watauga County, NC	9/11	Watauga County (Gen sets from KSD Enterprises, LLC)

One advantage to operating at a small landfill, which is likely to have been closed after 1993 when the U.S. EPA amended the 1976 Resource Conservation and Recovery Act by requiring the use of "liners, leachate collection, groundwater monitoring, and other corrective action at municipal landfills," is that "old" landfill gas is much less contaminated by commercial by-products (U.S. EPA, 2011). The presence of siloxanes in today's consumer goods is increasing at annually by 5—8% (Tower & Wetzel, 2006). At the Watauga County Landfill, for example, the total siloxane level is just 1.43 ppm (Jet-Care Si-Test, October 16, 2010) and the threshold for hazardous effects begins at ten ppm (Caterpillar Inc., 2009). Therefore, Steve Cox of GkW Energy and Ed Devarney of Gas-Watt see no need in major gas separation investments for this type of operation. "Engines have run-off low quality gas since before the industrial revolution" (S. Cox, personal communication, March 30, 2011). See Table 11 for a list of project demographics and Table 12 for landfill gas and engine oil monitoring methods used at the three sites.

Table 11.

Landfill Project Demographics (Cox, DeVarney, & Steury, personal communication, April, 2011)

Landfill	***Tons of waste in place***	***Landfill life span (open)***	***Engine-Generator Type***	***Quantity***	***Power Rating in kW***
Mid-County	1,000,000	1982-1997 (15 years)	Waukesha engine (non-auto); Ford 460 V-8 engine	Two (one of each)	265 kW; 75 kW
Chittenden County	262,000	1992-1995 (3 years)	Ford 300 engines; Onan generator	One (two more coming online)	30 KW per gen set
Watauga County	546,000	1972-1993 (21 years)	KSD-General Motors Vortec engine; Taylor Power Systems generator	Two	93 kW per gen set

Table 12.

Landfill Gas and Engine Oil Monitoring (Cox, DeVarney, & Steury, personal communication, April, 2011)

Landfill	***Monitoring***	***Gas Separation***	***Frequency of Oil Change***	***Engine Oil Lubricant***	***Cost of Oil Change***
Mid-County	Methane content, flow rate, and GHG reduction credits every five minutes using hot flow meter and data logger	Particulate matter using filtration	Every 700 hours	Proprietary	$100
Chittenden County	Differential pressure	Water vapor using passive technique	Every 500 hours	Shell Rotella 40 (six quarts and a filter)	$35
Watauga County	LandGEM 2000 and in the future a hot flow meter and data logger	A filter in the engine	Every 500 hours at first	5W30	$30

The economics of a project using an automotive-derived engine-generator set is improved from the start with total system installed costs per kW averaging between $1,029 and $1,350 and system costs not including interconnection to the grid ranging between $780 and $1,147/kW (see Tables 13 and 14). This is one third to half of the cost of smaller industrial internal combustion engines ($2,300/kWh for projects of one MW or less) (U.S. EPA LMOP, 2010a, p.3). The interconnection to the grid and the transmission pipeline are variable costs.

Table 13.

Landfill Gas to Electricity Project Cost (Cox, DeVarney, & Steury, personal communication, April, 2011)

Landfill	***Total equipment and installation cost***	***kW Installed***	***Cost to interconnect to the electrical grid***	***Turnkey cost per kW installed***
Mid-County	$300,000-$400,000	340	$85,000 for both engine-gen sets	$882-$1,176 ($1,029 average)
Chittenden County	$105,000 ($11,500 per 30 kW engine-gen set)	90	$1,700	$1,166
Watauga County	$251,132 ($83,940 for two 93 kW engine-gen sets)	186	$67,000	$1,350

Table 14.

Landfill Gas to Electricity Project Cost without Grid Interconnection (Cox, DeVarney, & Steury, personal communication, April, 2011)

Landfill	***Equipment and installation cost without grid interconnect***	***kW Installed***	***Turnkey cost per kW installed without grid interconnection***
Mid-County	$215,000-$315,000	340	$632-$926 ($780 average)
Chittenden County	$103,300	90	$1,147
Watauga County	$184,132	186	$990

Many landfills are public and can benefit from a private partnership in order to reap the tax credits. The uncertainty of the RECs market affects investor confidence. Therefore, a public-private blend of funding may be optimal (see Table 15). A disadvantage to ARRA is its susceptibility to political will since funds are sometimes dispersed at the state-level by local agencies. In the Southeast and the Northwest, there are neither Regional Transmission Organizations (RTO) nor Independent System Operators (ISO) to help independent power producers by providing net metering tariffs and common standards of trade in accordance with the Federal Energy Regulatory Commission (FERC). These RTOs/ISOs are voluntary by region and are intended by FERC to provide non-discriminatory access to transmission. Chittenden County "saw a 5 ¢ year in 2010 since it goes by the New England ISO rates of transmission" (E. DeVarney, personal communication, March 20, 2011). See Table 16 for a comparison of actual system costs and the U.S. EPA LFGcost-Web predicted costs.

Table 15.

Landfill Gas to Electricity Project Funding and Public Support (Cox, DeVarney, & Steury, personal communication, April, 2011)

Landfill	***Sources of Funding***	***Public Perception***	***Payback Period***
Mid-County	Carbon credits retained by landfill owner; 4 ¢/kWh electricity sale to APCO does not include RECs	Very positive feedback; planning for more projects	5 years
Chittenden County	ARRA 1603 grant, state grant of $15,000, 5 ¢/kWh electricity sale to Green Mountain Power Corporation, private investors, sale of RECs	Very positive feedback also in Randolph, VT; planning another project in Saratoga, NY	2 years
Watauga County	ARRA grant ($40,000), sale of 5.7 ¢/kWh avoided cost of electricity and RECs to Duke Energy (averaging $7.17/MWh), 1.1 ¢/kWh to NC GreenPower, County funding over $200,000	Very positive feedback; other local landfills are interested	3.29 years

Table 16.

Actual System Cost and U.S. EPA LFGcost-Web Prediction Comparison (Cox, DeVarney, & Steury, personal communication, April, 2011)

Landfill	***Engine-Gen Set Manufacturer***	***LFGcost-Web Estimate***	***Actual System Cost***
Mid-County	GkW Energy	$852,630 cost, 2,813,675 kWh, 7% ROI	$350,000[a]
Chittenden County	Gas-Watt Energy	$394,181 cost 682,744 kWh/yr, -5% ROI	$105,000
Watauga County	KSD Enterprises	$479,034, 490,716 kWh, -10% ROI	$251,132

[a]The cost of the GkW Energy System is between $300,000-$400,000.

Analysis

Montgomery County Mid-County Landfill Project

This 340 kW project was presented by Steve Cox at the 14th Annual LMOP Conference in January of 2011 and is located at the Montgomery Regional Solid Waste Authority (MRSWA) in Christiansburg, Virginia. It was developed by Green kW Energy, Inc. (GkW) at the Mid-County Landfill, which opened in1982 and closed in 1997 with one million tons of waste in place. A LFG collection system has been in operation since 1998 although not required by rule. LFG has been flared from 1998 until October of 2010. Current LFG flow rate is 230 scfm at 47% methane. The auto-derived engine-generator set is a 75 kW 460 cubic inch (c.i.) V-8 7.5 liter (L) Ford Engine-Gen Set designed by GkW; there is also a 265 kW generator set equipped with a Waukesha F18GLD prime mover. The MRSWA landfill has been closed since 1998 and siloxane and sulfur concentrations are relatively modest. The process is housed in a 900 ft^2 building equipped with several noise reduction systems. Steve Cox recommends shopping for items such as gas valves, pressure regulators, and high amperage circuit breakers online to achieve lower starting costs. He says the project's genius is its simplicity (see Figures 3 and 4) (S. Cox, personal communication, March 30, 2011).

Figure 3. GkW Energy's Waukesha Engine-Gen Set (Cox, 2011)

Figure 4. GkW Energy's 460 c.i. V-8 7.5 L Ford Engine-Gen Set (Cox, 2011)

Chittenden County Landfill Project

The Chittenden County Landfill, owned by the Chittenden Solid Waste District in Williston, VT, has been producing electricity using the design of Ed DeVarney of Gas-Watt, LLC, since October of 2009. With 262,000 tons of waste in place over a three-year life, the landfill had 130 scfm on closure day in 1995; Ed estimates the flow decreases and maintains 95% of the value of the previous years (60 scfm today) and 50% methane. The synchronous generators in the 300 c.i. inline 6 cylinder 4.9 L Ford-Onan engine-gen sets use three-phase or single-phase electricity. Gas-Watt systems parallel to the grid at an interconnect cost of only $1,700. The collection system is parallel passive, relying on naturally occurring pressure and using evacuation only to properly supply the gen sets. See Figure 5 for a picture of Ed with students from Vermont Tech and Figure 6 of the engine-gen set (E. DeVarney, personal communication, March 20, 2011).

Figure 5. Ed DeVarney and students with Gas-Watt Energy’s Ford-Onan Engine-Gen Set (DeVarney, 2011)

Figure 6. Gas-Watt Energy's 300 c.i. Inline 6 Cylinder 4.9 L Ford-Onan Engine-Gen Set (DeVarney, 2011)

The transparency of the grid is enhanced in locations with ISOs/RTOs (everywhere but the Northwest and Southeast). To find-out what a facility gets paid, one simply visits the ISO-NE website for selectable hourly data by zone and also market node pricing in real-time (E. DeVarney, personal communication, March 27, 2011). Class 1 MA RECs "were about 3.4¢/kWh two years ago, down to about 1.24¢/kWh now" (E. DeVarney, personal communication, March 27, 2011). The current market volatility would benefit from common standards and qualifiers for "greenness". "Because PURPA (1978) mandates that utilities pay the producer 'full avoided costs' for the power, the 'ancillary products' were included into a 10% adder on the market value. So, for every hour, I receive the posted rate for my network node plus 10% for ancillary products (including transmission loss abatement) and then I sell the RECS to a utility of my choice" (E. DeVarney, personal communication, March 27, 2011).

Watauga County Landfill Project

The Watauga County Landfill in Boone, NC, opened in 1972 and closed in 1993. The landfill was capped at 546,000 short tons of waste in place, yielding a methane generation rate of .04 k (LandGEM Version 302, 2010). The non-methane organic compound (NMOC) concentration (in parts per million by volume as hexane) was found to be 595 in 2005. The methane content (% by volume) is typically between 48-52%. In 2005, a collection system consisting of 22 vertical wells (one well per acre) and passive solar flares was installed on the 22-acre landfill. In 2010, two 93 kW KSD Enterprises, LLC auto-derived engine-gen sets were installed to produce electricity. With the initial operations beginning in September of 2011, the project is estimated to endure (in decline) between ten to twenty years, producing 1,290,355 kWh/yr in 2011 down to 737,033 kWh/yr in 2025 according to a predicted flow decrease from 94 scfm to 53 scfm using LandGEM, an electrical efficiency of 20%, and availability of 92.5% annually. See Figure 7 for a map of the Watauga County Energy Park.

Since the installation of the collection system and active flare in 2005, planning for the energy conversion system has involved the following entities: Watauga County, Blue Ridge Electric Membership Corporation (BREMCO), Duke Energy, and the Appalachian Energy Center. In late 2009, the Watauga County Board of Commissioners unanimously approved $200,000 towards the project from the Watauga County Sanitation Department's Retained Earnings Account (Calhoun, 2009). Lisa Doty, the Watauga County Recycling Coordinator, said she "hopes to pay back the County by applying for the American Recovery and Reinvestment Act (ARRA), or stimulus grants through the NC Energy Office with help from the High Country Council of Governments" (Calhoun, 2009).

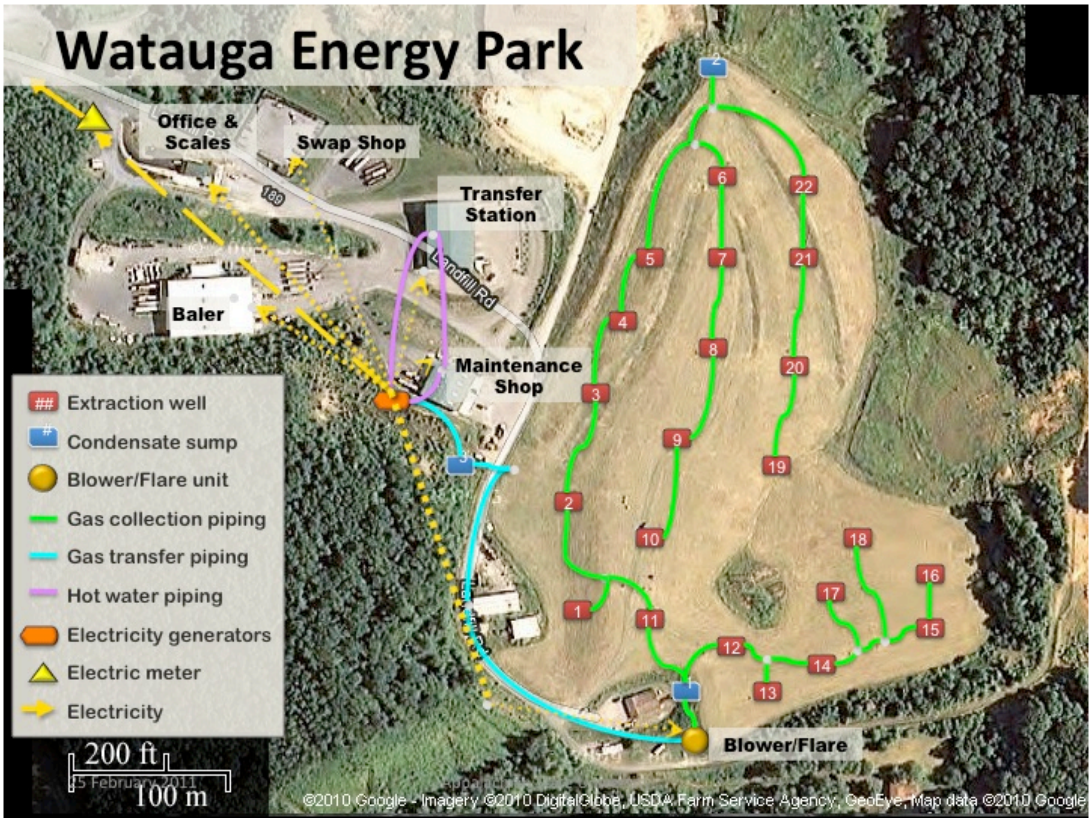

Figure 7. Watauga Energy Park (Hoyle, 2011)

In 2011, the Watauga County Landfill received an additional $40,000 from ARRA through the State Energy Office and is transitioning into an energy park. Watauga Solar has proposed a 1-2 MW solar photovoltaic power plant on site. Watauga Energy Park will harness the methane fuel currently being flared into the atmosphere as CO_2. While at this time, the municipal solid waste is being transported to Hickory for a tipping fee of $49 a ton, its future is open to composting, and there are plans for the maintenance building and maybe a greenhouse to use the residual heat from the landfill gas to electricity operation (see Tables 17 and 18 for the financial projection and cash flow analysis).

Table 17.

Financial Outlook for Watauga County-KSD Enterprises Landfill Gas Cogeneration Project over 14 Years

Project cost	($251,132)
Net Present Value, May 2011	$301,563
Internal Rate of Return	26%
Payback Period	3.29 years
Average Annual Cash Flow (2011-2025)	$32,513

The initial investment planning stage involved the consideration of two Capstone Models 330 Microturbines (60 kW total) for $460,000, two Ingersol-Rand Microturbines (140 kW total) for $460,000, a KSD/Comvest Methane Buster engine-generator set (70 kW) for $60,000, or two Power Secure Caterpillar generator-sets (250 kW total) for $270,000. Watauga County ultimately determined to use two 93 kW KSD-GM automotive-derived engine gen sets at a total installed cost of $83,940.

The Landfill Gas Utilization Program of the Appalachian State University Energy Center is dedicated to a community-based approach acting to foster "business incubators" by providing energy to promulgate the trade specialization of a specific area (e.g. EnergyXchange, Burnsville, NC). Since the Methane Buster had tremendous success in leveraging businesses while mitigating methane, it was a natural avenue for exploration. "The Methane Buster typically sells for $60,000 or $70,000, said H. David Cutlip of KSD investor Comvest Capital, with installation and collection pipes adding $250,000 to $500,000. Most applications pay for themselves in three to four years" (Kasey, 2006). The Watauga County project has a payback of 3.29 years. See Table 19 for specific line items.

Table 18.

Cash Flows for 2011-2012 at the Watauga Cogeneration Landfill Project

Revenues and Expenses	***2011 Projected Cash Flow***	***2012 Projected Cash Flow***
Capital cost, $251,132		
NC Greenpower (grid only at 1.1¢ /kWh)[a]	$11,307	$10,751
Sale to Duke Energy 5.7¢ /kWh	$58,169	$55,305
RECs annual income (262,365 kWh electricity used on site)[b]	$1,574	$1,619
Avoided Cost of electricity[c]	$20,860	$20,860
Avoided cost of propane, 2% increase/yr[d]		$7,000
Grant (ARRA)	$40,000	
Operations and Maintenance (labor, consumables, contingency)[e]	-$21,148	-$31,148
Pipeline for cogeneration[f]		-$2,000
Net Cash Flow[g]	$110,763	$62,387

[a] Values for kWh generated are derived from the efficiency equation using 20% and the LandGEM predictions for scfm over 14 years.

[b] Duke's RECs Price MWh/year ($6—$8.41 from 2011—2025).

[c] The avoided cost of electricity is 262,365 kWh used in prior years at an average of 11¢/kWh with a 2% annual increase minus an $8,000 fixed utility cost.

[d] Propane becomes an avoided cost with a $2,000 investment in a heat recovery pipeline, raising thermal energy conversion efficiency to 70% from 20% (estimated).

[e] A $10,000 annual maintenance cost except for year one plus $2.61/operating hour accounting for the overhaul cost of $17,400 occurring every 10,000 and 30,000 hours.

[f] Additional piping to heat the maintenance building costs an estimated $2,000.

[g] 5% discount rate to account for inflation and time.

Table 19.

Budget for the Watauga County Landfill Gas to Electricity Project (May, 2011)

Cost	***Item***
$3,300.00	Gas line hook-up by Eric McGee
$350.00	Flow meter by McGee
$5,800.00	Building ventilation
$762.00	Raised pads
$71,420.00	Two engine-generator sets from KSD
$10,520.00	One year O&M (KSD)
$2,000.00	Startup assistance (KSD)
$1,850.00	Wiring between generator building and maintenance building
$1,279.00	Heat recovery conduits (paid by ASU)
$979.00	Control panel specs stay same (paid by ASU)
$4,500.00	Itron Data Collection System
$3,000.00	Donated meters from BREMCO
$450.00	To support gathering data through meters
$31,450.00	Transmission line (variable cost)
$710.69	Pressure control valves
$242.00	Gravel
$16.16	Plans for conduits/drawings
$786.52	Meter bases (13 terminal meter sockets)
$740.53	Exhaust pipes and support frame for muffler and catalytic converter
$7,382.88	Two upgraded controllers
$67,000.00	Replacement switch gear by T3 Automation
$114.00	Roof penetration of exhaust (donated by Stan Steury)
$1,200.00	Exhaust and roof penetration (donated by Steury)
$279.00	Heat recovery conduits
$35,000.00	Upgrades to BREMCO (transformer, light pole, etc) donated to County
$251,131.78	**Preliminary Total**[a]

[a] Final budget may include hot flow meter, actuator and $2,000 for CHP pipeline.

KSD Enterprises, LLC has unique experience with automotive engine-powered methane recovery. It has invested 15 years into developing the Methane Buster as one of the most cost advantageous resource for mitigation of methane at coalmines. The exhaust system consists primarily of a Ford engine attached to a blower that can run solely on methane levels as low as 30% (KSD Enterprises, LLC, 2010). See Figures 8 and 9 for pictures of the GM-Vortec-KSD engine-gen set.

Figure 8. KSD Enterprises, LLC's 8.1 L (496 c.i.) GM-Vortec Engine-Gen Set (Mosteller, 2011)

Figure 9. Stan Steury with KSD Enterprises, LLC's GM-Vortec Engine-Gen Set (Moore, 2011)

Gary Disbennett, Manager of The Methane Exhauster, noted that auto-engine lives have improved with the times. "With the older Fords, it would be 10,000 to 12,000 hours when we would overhaul the head. The major overhaul was somewhere around 30,000 hours. The current engines are going past the 12,000 hours with good compression. You loose compression when you have wear in the cylinder head" (G. Disbennett, personal communication, August 3, 2010). The latest engines have so far stood the test. Mr. Disbennet commented, "We have not overhauled one of the new GM engines to this date. We have some with 15,000 to 16,000 hours running great. Not even a cylinder head repair." Mr. Disbennet continued, stating, "Running approximately 8,000 hours a year, we should get 5 years (or longer) before a major overhaul. We may need some headwork before the overhaul, but the reports from the factory are pretty encouraging. No guarantees, but we are very optimistic about the life expected with proper maintenance. They will live longer in a clean, controlled environment, with the engine running at a constant rpm" (G. Disbennet, personal communication, August, 3 2010). If the engine-generator sets do indeed run for 40,000 hours before major overhaul on biogas, the financials of the small to medium sized landfill gas industry will be transformed entirely.

DISCUSSION

The electrical efficiency of the auto-derived engine-gen set was predicted to be 20% (10% less than the expected 30 % for an IC engine-gen set) since the engines were rated on natural gas and not landfill gas. The time before a major overhaul for an automotive engine is likely at around 20,000 hours as compared to 40,000 hours using a typical industrial IC engine (Onovwiona and Ugursal, 2006). If an auto-derived engine-gen set produced electricity for 8,100 hours per year (92.5% online), 20,000 operational hours would occur 2.5 years after installation**.** At this point an engine core replacement, costing between $2,000-$4,000 may be in order. Ed DeVarney, the certified master auto-technician behind Gas-Watt Energy, says the key to engine longevity is to keep the engines running to avoid condensation and subsequent deterioration (E. DeVarney, personal communication, March 30, 2011). Those interviewed agree that preventive maintenance is required due to the contaminants and corrosives in landfill gas. However, with payback periods between 2 to 5 years, the automotive engine makes the additional investment in maintenance worth the cost. Students at Appalachian State University will likely conduct future studies on the efficiency and the longevity of auto-derived engine-gen sets.

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APPENDIX

Survey of Managers of Small Landfill Gas to Electricity Projects Using Automotive-Derived Engine-Generator Sets

1. What is the name and location of the landfill?
2. How many tons of waste in place at the landfill?
3. Is the landfill still open?
   a) If so, how many tons of waste are introduced annually?
4. What company manufactured the engine-generator set?
   a) What is the size in peak kW per engine-generator set?
   b) What company manufactured the engine?
   c) What model is the engine?
   d) How many engines are operating?
   e) Do they provide combined heat and power?
5. Do you regularly, or have you ever, conducted an engine oil analysis for contaminants and wear metals?
   a) If so, what type of test was used?
   b) Which company did you use?
   c) How often are the tests conducted?
   d) How long have you used the company?
6. Do you now, or have you ever, conducted landfill gas analysis using a specialized laboratory?

a) If so, what type of test was used?

b) Which company did you use?

c) How often are the tests conducted?

d) How long have you used the company?

7. Do you monitor the concentration of landfill gas using a portable gas analyzer or an automatic system such as a gas chromatograph?

a) If so, how is concentration monitoring conducted?

b) How often?

c) Is monitoring automatic/built into the system?

8. Do you mind sending information on average methane concentration (as a percentage), flow in scfm, and kWh produced? This information will allow me to estimate the efficiency of your system.

9. Do you use separation techniques against contaminants such as hydrogen sulfide, siloxanes, and water vapor to preserve the longevity of the energy conversion system?

a) If so, what contaminants are controlled?

b) What separation techniques are used (e.g. adsorption, membranes)?

10. How often do you perform an oil change?

a) What type of engine oil lubricant is used (e.g. synthetic, petroleum, low ash)?

b) How much does the oil change cost?

11. At what time interval do you schedule preventive maintenance in each of the following categories?

a) Minor tune-ups?

b) Cylinder head replacement?

c) Major overhaul?

d) How much annual downtime is needed for the maintenance?

e) What is the average annual cost of the maintenance?

12. What was the total equipment and installation or "turnkey" cost of the energy conversion system (not including interconnection to the grid and gas collection)?

    a) What was the cost of the grid-tie interconnect equipment and installation?

13. What were the sources of funding for the capital cost of the project? (e.g. private investors, tax credits, special programs, municipality/county/state sources)

14. What type of arrangement with the utility company is there for the sale of electricity? (e.g. RECs and carbon credits)

    a) What is the annual revenue from the sale of electricity?

15. What was the initial projected payback in years of the cost of the project?

    a) Is the revenue generated meeting expectations?

    b) How long have the engines been used for landfill gas to energy?

16. How would you characterize the attitudes of local citizens and policy makers to the landfill gas to electricity project before electricity was generated at the landfill?

    a) How would you characterize the attitudes to the project after operations began?

17. Are there any questions that should be added to this survey?

    a) If another question is suggested may I contact you again?

18. Would you like to stay informed on the outcome of this research?

    a) What contact information and medium do you prefer?

VITA

Miriam Makhyoun was born in Ashville, North Carolina in 1982 and attended Appalachian State University (ASU) for a Bachelor of Arts in French and a Bachelor of Science in International and Comparative Politics (2005) and for graduate school, obtaining a Master of Business Administration in Sustainable Business and a Master of Science in Technology with a Concentration in Appropriate Technology (2011). Her five cumulative years of experience supporting energy efficiency and renewable energy goes back to 2004 when she co-authored the Renewable Energy Initiative as a senator in the Student Government Association, a student referendum for a $5 per semester fee towards renewable energy installations at ASU, which she further developed in the following year as the Student Body President. In 2006, she supported Senator Harry Reid's Environmental Staff as an intern. During 2008, she assisted with the Appalachian Experimental Economics Laboratory, which worked with many institutions on environmental studies; in 2010 she assisted with a project with the World Resources Institute. In 2009 as a graduate student in business, she formed the ASU Graduate Chapter of the Net Impact Club and created the Sustainability Symposium. In 2010 leading-up to the Symposium, she organized Define Our Decade, a campaign for sensible wind energy policy in Western North Carolina, garnering over 2,000 petition signatures, including one from a world-renowned climate economist. As a graduate student, she wrote this thesis on the automotive-derived technology being used at the local landfill to leverage the capital cost of producing electricity from methane, which, she presented at Wastecon 2011, hosted by the Solid Waste Association of North America.