other state digesters. ✓

PERFORMANCE EVALUATION OF A CAPSTONE MICROTURBINE AND RECIPROCATING ENGINE RUNNING ON BIOGAS AT A COLORADO HOG FARM

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Abstract

Since August, 1999, Colorado Pork, a 5,000 head swine facility located near Lamar Colorado, has used a modified natural gas reciprocating engine and generator set to produce power using biogas from its anaerobic digestion system, while simultaneously reducing the air and water pollution associated with the facility's waste streams.

In 2001, the Colorado Governor's Office of Energy Management and Conservation (OEMC) formed a partnership to make a direct, side-by-side comparison of the performance of a 30 kilowatt (kW) Capstone MicroTurbine™ and a 75 kW reciprocating engine, both using biogas from a hog farm's anaerobic digestion system as fuel.

In December, 2001, OEMC purchased and installed a 30 kW microturbine at the facility. This is the first known application of a microturbine using biogas from an anaerobic digester at a working hog farm in the United States. The microturbine is operating alongside the reciprocating engine and using biogas from the facility's anaerobic digester. As of June, 2002, the microturbine has operated for about 1,300 hours. The microturbine study will collect performance data covering the period from July, 2002 through July, 2003. Data will be collected for both the microturbine and the reciprocating engine to provide the basis for an analysis of the following: capital, engineering and set-up costs; power and thermal efficiency; levelized electricity generation cost and overall economic performance; exhaust stack emissions; engine noise and vibration; footprint and facility requirements; reliability, maintenance and general operational considerations; ability of the microturbine to supply waste heat to the digester to optimize biogas production; and opportunities for other value-added uses of microturbine waste heat. The facility will also be interconnected to the grid, and the requirements and costs of that process will be documented.

This paper provides a status update on the technical and economic performance of the existing anaerobic digester and reciprocating engine. It also describes the current status of the microturbine installation and documents the data that will be collected during the year-long project period.

Background

Recent Colorado legislation (Amendment 14) created more stringent air and water quality requirements for confined swine facilities. The new rules require large Colorado facility owners to cover their waste storage and treatment lagoons or implement other approved means to reduce odors from their sites. For swine facilities that opted to use high-density polyethylene covers at their lagoons, the new regulations have created an opportunity to recover methane from and produce heat and power for their facility. This topic was the subject of a recent study completed by the Colorado Governor's Office of

Energy Management and Conservation (OEMC) and the Western Regional Biomass Energy Program (WRBEP).[1]

The objective of the first project was to evaluate the impact of Amendment 14 on industry, assess the manure resource and current waste management systems, and determine the economic and technical feasibility of coupling anaerobic digestion (AD) with biogas heat and power equipment as one option for regulatory compliance in Colorado. The project coincided with the independent installation and operation of an AD/energy generation system at Colorado Pork LLC (CP) near Lamar, Colorado.

In late 2000, OEMC decided to monitor the long-term performance of the AD and energy generation system at CP and make it a "model facility" for the Colorado hog industry. One goal of that on-going effort is to document the utility savings and payback associated with the system through utility billing analysis, and recording and analyzing the generator log data.[2] OEMC and WRBEP also provided funding through a separate contract to monitor the environmental performance of the AD system.[3] In late 2001, OEMC conducted an energy audit of the facility to determine whether opportunities exist to reduce energy use at the farm, and assess potential opportunities for other farms in the state.[4]

In 2001, OEMC formed a partnership to install, test, evaluate and monitor the performance of a Capstone 30 kW Microturbine at the site, and compare it to the existing system. The OEMC, U.S. Department of Energy's Office of Power Technologies, and the U.S. Environmental Protection Agency's Environmental Technology Verification (ETV) Program provided funding for this effort. Other partners include Capstone Microturbine Corporation, Williams Distributed Power Systems, Colorado Department of Health and Environment, Colorado Pork, M2M Matrix, Martin Machinery, and Southeastern Land and Environment. McNeil Technologies Inc., (McNeil) is managing the project on behalf of OEMC and performing long-term data collection and analysis. The Southern Research Institute will be performing a formal ETV assessment of the facility in late 2002.

Colorado Industry Overview and Amendment 14

Commercial swine farming is a significant component of rural Colorado's economy. During 2000, there were over 500 Colorado operations with hogs. These operations generated $290 million in gross income, and maintained an inventory of 840,000 pigs and hogs.[5] Like most of the industry in other states, animal populations are being concentrated at fewer utilities.

In November, 1998 Colorado voters passed Amendment 14 to the Colorado state constitution, requiring the Colorado Department of Public Health and Environment (CDPHE) to develop new regulations aimed at controlling odors and preventing water quality impairment from commercial hog facilities. The new regulations apply to facilities that have over 800,000 pounds of animal capacity, either at a single site or aggregated over multiple sites if they are affiliated through common ownership. Affected producers are required to implement effective odor control technologies at their waste storage

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[1] McNeil Technologies, Inc., 2000

[2] McNeil Technologies, Inc., 2002

[3] Mattocks, 2002

[4] Econergy International Corporation, 2002

[5] U.S. Department of Agriculture National Agricultural Statistics Service. (July 2001). Colorado Agricultural Statistics, available on-line at http://www.nass.usda.gov/co/pub/buletn01/01-bultn.pdf

sites. Approved control technologies include covering anaerobic lagoons, construction of anaerobic digesters, and maintaining aerobic lagoon conditions. Most facilities in Colorado are now in compliance with the regulations through adopting various control technologies. Only Colorado Pork has implemented anaerobic digestion with energy recovery.

In 1999, the affected facilities had a total animal capacity of over 1 million head of swine, weighing over 152 million pounds. It is estimated that total manure generation from these facilities is over 1.4 million tons per year. Compliance is expected to cost the industry over $800,000 in initial capital costs, with additional annual costs of at least $900,000, including a fee of $0.20 per animal unit per year to cover the state's costs of administering permits and conducting facility inspections. The fee alone equates to an average cost to each company of over $27,000 per year.

The majority of the waste storage and treatment sites are located in counties on the Eastern plains of Colorado, with the exception of one facility in Weld county. Yuma county has the largest number of sites (35) followed by Kit Carson with 29 and Kiowa with 12. These data are depicted in Figure 1. The shading shows estimated levels of manure production per year. For companies that are already using anaerobic lagoons as an odor control technology, the study estimated that up to 4 megawatts (MW) of power could be produced, and if all facilities were converted, 6.5 MW could be produced.[6]

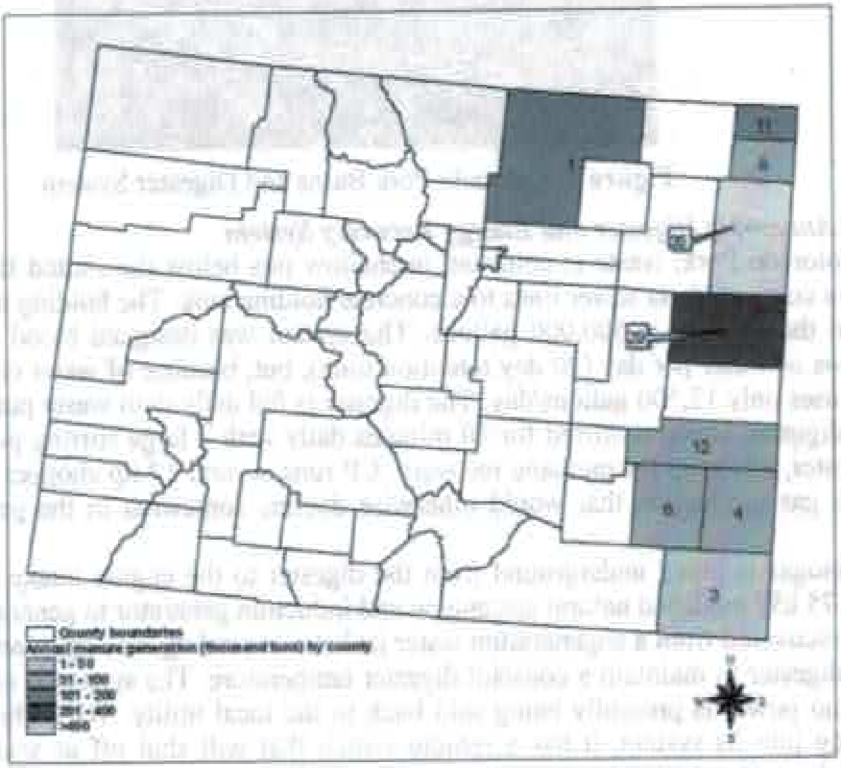

Figure 1. Location of Colorado Hog Facilities and Manure Production

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[6] McNeil Technologies, Inc., 2000

Colorado Pork, LLC - Facility Profile

Colorado Pork is a 5,000 head breed-to-wean facility located in Lamar, Colorado. The facility has pull plug manure removal to a complete mix digester and a storage lagoon. The facility is new and began operation in 1999. The digester has been operating since 1999, processing all of the manure produced by the 5,000 sows and 16,000 piglets housed at the facility over the course of the year. Resource Conservation Management Inc., based in Berkeley, California, designed and installed the AD system. The EPA AgStar Program provided technical assistance and engineering design support to the system.

Figure 2. Colorado Pork Barns and Digester System

Overview of Anaerobic Digester and Energy Recovery System

At Colorado Pork, waste is collected in shallow pits below the slatted floors of the hog barns. These pits are connected via sewer lines to a concrete holding tank. The holding tank has 50,000 gallons capacity, and the digester is 500,000 gallons. The system was designed based on estimated flows of 25,000 gallons of water per day (20 day retention time), but, because of water conservation efforts, the facility now uses only 12,500 gallons/day. The digester is fed daily with waste pumped from the holding tank. In the digester, waste is stirred for 30 minutes daily with 2 large stirring pumps. An HDPE cover tops the digester, allowing for methane recovery. CP runs several 17 hp chopper motors in the evening to rejuvenate gas production that would otherwise decline somewhat in the period between digester feedings.

The biogas is piped underground from the digester to the engine intake manifold, and is used directly by a 75 kW modified natural gas engine and induction generator to generate heat and electricity. Hot water is recovered from a cogeneration water jacket surrounding the engine and recirculated through tubes in the digester to maintain a constant digester temperature. The system is connected in parallel to the grid but no power is presently being sold back to the local utility. When the utility detects excess power flowing into its system, it has a remote switch that will shut off or scale back the generator. Colorado Pork staff monitor biogas production and electricity generation along with several other performance variables including pH, digester temperature and gas production. The digester and engine/generator system requires, on average, 30-45 minutes semi-skilled labor per day, including recording and monitoring. The system has undergone several minor repairs that include valve replacements and one major repair that included replacing the engine head gasket. Figure 3 and Figure 4 show the system.

Figure 3. Digester System

Figure 4. Reciprocating Engine

Facility Energy Use

As a newer facility, CP employs many energy efficiency measures that may not be present at older facilities. Colorado Pork can serve as an example of some of the measures that may help save money at other swine facilities in Colorado.

The largest energy using functions at Colorado Pork include lighting for facilities, heat lamps and heat mats for farrowing rooms, electric fans for cooling, natural gas heaters for swine living areas, motors for feed delivery systems, water pumping for swine living areas and the AD system, and several fans and mid-sized (15-17 horsepower) pumps for the digester.

Examples of energy efficiency measures that CP currently employs include using natural ventilation, avoiding electricity demand spikes by staggering motor start-ups over time and using compact fluorescent bulbs in most of their fixtures to reduce electricity usage. Colorado Pork limits fan usage in farrowing and breeding and gestation areas to periods when the outside temperature exceeds 82 degrees Fahrenheit. Colorado Pork uses natural gas heaters in finishing rooms only when the outside temperature is less than 30 degrees Fahrenheit and in hallways when the temperature is less than 40 degrees Fahrenheit to reduce natural gas consumption. Colorado Pork uses a network of 16 central processing units to monitor and manage environmental controls.

CP buys electricity from the Southeast Colorado Power Association (SECPA), a rural electric cooperative, and natural gas from a nearby natural gas wellhead operated by Lamar Oil and Natural Gas Exploration Company. SECPA electricity purchase rates for industrial customers are $0.04 per kilowatt-hour (kWh). The demand charges are $12.25 per kilowatt (kW). For CP, the measured demand is the maximum kilowatt demand for any 15-minute period in the billing month. Demand charges for CP are adjusted to correct for average power factors less than 95 percent by increasing the measured power demand 1 percent for each 1 percent by which the average power factor is less than 95 percent lagging.[7] Colorado Pork's natural gas rate is $4.50 per thousand cubic feet.

Facility Energy Use Data

Colorado Pork's utility bills have been tabulated in an Excel spreadsheet since December 1999. Table 1 shows a summary of nearly two years worth of data for Colorado Pork. On average, the facility

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[7] Southeast Colorado Power Association. Large Power Rate Schedule LP. Colorado PUC No. 2, 12th revised version, Sheet 14. Effective date January 1, 1997.

purchases 43,000 KWh per month from the utility, and has an average monthly demand of 125 kW. Over the period, demand has ranged between 80 and 160 kW. Actual facility energy use is somewhat higher, since the utility bills reflect the impact of on-site production by the biogas generator.

Monthly utility bills average about $3,260. Based on conversations with another facility owner of a similar sized operation, it was determined that the other facility is paying about $10,000 per month in utility bills. From the numbers presented, it is clear that Colorado Pork is a well-run, efficient operation enjoying significant savings from their efforts to implement energy efficiency measures and on site energy generation.

Table 1. CP Utility Billing Data - Summary

Dec 2000- - Sep 2001	Monthly Consumption (kWh)	Monthly Demand (kW)	Monthly Electricity purchase cost ($)	Monthly Demand cost ($)	Total electricity cost ($)
Maximum	62,840	160.68	$ 2,513	$ 1,968	$ 4,481
Minimum	19,320	80.96	$ 772	$ 991	$ 1,894
Average	43,223	125.14	$ 1,728	$ 1,532	$ 3,261

Economic and Technical Performance of the Existing System

Digester Performance

Under a separate contract, the OEMC and WRBEP monitored the digester to assess its performance in terms of odor and water quality management. The report also documented engine performance.[8] The results show the following for digester effluent compared to influent:

1) Fecal coliform indicator organisms are being reduced by >99%,
2) Volatile acids are being reduced by 89%,
3) Volatile solids are being reduced by nearly 65%,
4) COD and BOD reductions are 70% and 80%, respectively,
5) Virtually all manure is being processed by the digester,
6) The digestion system is stable,
7) Nitrogen mineralization in the digester is increasing ammonia nitrogen by >9%,
8) Biogas is being flared on about 49% of the recorded days,
9) Metered biogas is not representative of total gas production because of the flare,
10) Facility water use declined steadily, from 17,000 gallons/day to 12,500 gallons/day.

Total daily biogas production from the digester could not be calculated because there is a flare by-pass system that does not have a flow meter. When excess gas builds up, gas will by-pass the engine to the flare. Since 1999, an average of 25,000 cubic feet of gas per day is being burned in the engine, which does have a flow meter. Digester production was stable as indicated by consistent gas quality: 31% CO_2

[8] Mattox, 2002.

(± 2.5%), 66.3% methane (± 1%), and the remainder primarily H_2S, O and N. The Btu content of the gas averaged 661 @ 60 °F wet, with an average deviation of ±13.7. Hydrogen sulfides were estimated at 5912 ppm, with an average deviation of ±1063 (18%). For pH, the average was 8.1 with an average deviation of ±4%.

On-going Engine/Generator Performance and Utility Savings

Table 2 shows a summary of the generator energy production data. In total, the system has produced 814,260 kWh of electricity and saved the facility $32,570 in energy costs since installation. Average monthly production is 30,158 kWh, with monthly savings averaging $1,200. The average capacity of the system is 44 kW for the periods when the engine is running. The average capacity factor is 55 percent. Average generator uptime (not shown in Table) is 92 percent. On average, the system produces about 35 percent of the total facility energy used, and saves about 25 percent on each month's utility bill.

Savings are calculated by multiplying total kWh production by the cost of electricity, or $0.04/kWh. It is likely that the facility is realizing some capacity savings as well, though there are insufficient data to calculate this value. Without knowing the coincident values of the facility demand and the generator output, it is not possible to calculate savings from demand reduction due to the ratchet clause in the utility rate. If the generator is down during a peak period, the facility is charged the peak value for the entire month, even if the generator runs every other hour of the month and reduces the demand. Notice that the overall performance of the system has been improving steadily each year.

Table 2. Summary of CP's Generator Production (1999-2001)

Year	Months of Data	Generation (kWh)	Estimated electricity purchase savings ($)	Average monthly capacity (kW)	Average monthly capacity factor (%)
1999 – Total	4	112,105	$4,484		
1999 – Monthly Avg		28,026	$1,121	40	51%
2000 – Total	12	351,784	$14,071		
2000 – Monthly Avg		29,315	$1,173	44	54%
2001 – Total	11	350,371	$14,015		
2001 – Monthly Avg		31,852	$1,274	47	58%
Overall Total	27	814,260	$32,570		
Overall Average		30,158	$1,206	44	55%

Economic Analysis

Table 3 shows the comparative costs of several options that a typical 5,000 head hog farm in Colorado could use to comply with Amendment 14. The AD/engine generator system at Colorado Pork cost approximately $375,000 to design and install. The alternative system they were considering was the single cell lagoon for about $300,000.

As shown in Table 2, Colorado Pork is saving about $14,000/year in electricity costs by offsetting utility power purchases at a rate of $0.04/kWh. Using the incremental cost that it took to construct the AD/generator system compared to the next alternative, the simple payback on the existing system is expected to be less than 6 years. This, however, does not include O&M costs, as these data are still being collected. The real payback to the facility owner is almost immediate, since the EPA AgStar program provided nearly $75,000 in design and construction assistance to Colorado Pork. There are insufficient data to estimate any potential payback on the microturbine at this time.

Table 3. Comparative Costs of Control Technologies for a 5,000 Head Hog Farm

SYSTEM TYPE	CONSTRUCTION COSTS TO NEAREST $500	ELECTRICITY COSTS SAVED PER YEAR
Single Cell Lagoon	$301,500	None
Two Cell Lagoon	$357,500	None
Covered Single Cell Lagoon	$476,500	None
Covered Two Cell Lagoon	$473,500	None
Anaerobic Digester (w/ small scale single cell lagoon and 75kW genset)	$375,000	$14,000
Retrofit To Add AD and genset for any of first four above	Approx $250,000 additional	$14,000
Incremental cost and payback of AD/genset vs. single cell lagoon	$75,000	5.5 year simple payback

Microturbine Project

Installation and Start-up

Williams Distributed Power Systems (Williams) completed the installation of the microturbine, compressor and heat exchanger in early December, 2001. On December 15, 2001, with the command power set at 30 kW, the actual power output was 24.5 kW, indicating losses due to parasitic loads and/or altitude of 5.5 kW. After approximately 200 hours of run time, the system stopped working. CP and Williams determined that a board on the microturbine had shorted out because the system had not been grounded properly at the transformer during installation. Capstone's instructions for installing the unit did not properly indicate that this part should be grounded. Also during this time, the Copeland compressor was damaged – most likely resulting from corrosion and lack of gas dryers being in place. Williams replaced the compressor in February, 2002. Williams also installed two desiccant water absorption systems to help remove the moisture form the gas stream prior to its entering the compressor.

After these repairs, the microturbine ran for about 200 more hours before it stopped working once more. Colorado Pork determined that the compressor was failing, caused by either the high content of hydrogen sulfides or moisture in the biogas. In the interim, Copeland Corporation, the manufacturer of the compressor, decided that they would no longer support their compressors for use with microturbines running on farm biogas. Williams has also decided to get out of the microturbine business altogether. CP made slight repairs to the compressor and the system began operating again in May, 2002. In June, 2002 the compressor broke once more. The Microturbine has a total of 1,300 hours of run time. OEMC and CP believe that the hydrogen sulfides are causing the problems with the compressor. OEMC is working with Capstone to locate a new compressor that will work with the high hydrogen sulfides present in the biogas. OEMC is also investigating other potential solutions to reduce hydrogen sulfides.

The cost of the microturbine was $41,000, including the compressor, heat exchanger, transformer and all ancillary equipment. This price included a 10 percent discount offered by Williams.

Future Monitoring Efforts

OEMC initiated discussions with the Southern Research Institute (SRI), which manages the Greenhouse Gas Technology Center (GHG Center) as part of EPA's Environmental Technology Verification (ETV) program. Through discussions with SRI, OEMC agreed to provide additional funding to have SRI perform a formal (two week long) environmental technology verification test on the microturbine and reciprocating engine. The ETV Program is paying for about 60 percent of the costs and OEMC is paying the rest.

The EPA operates the ETV program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The GHG Center is an independent verification organization operating under the ETV program. The GHG Center's verification process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other data, obtaining independent peer-review input, reporting findings, and distributing and showcasing the results. Performance evaluations are conducted according to externally reviewed verification Test Plans and established protocols for quality assurance. Since 1997, the GHG Center has evaluated technologies in the following areas: electrical utility, oil and gas, distributed electrical power, combined heat and power, solid waste disposal, refrigeration, and large internal combustion (IC) engines.

In addition to the SRI ETV test, McNeil will collect data for one year to analyze long-term technical and economic performance of the system. McNeil is working with M2M Matrix to set up a monitoring protocol, satellite uplink and Internet website that will allow remote data collection and real-time display of certain select variables on-line. Data collected via the system will be archived for analysis. A draft plan for collecting data has been developed and is in the process of being implemented. In general, the team will collect data to analyze the following parameters:

- Power and heat production performance:
    - Electrical power output at selected loads
    - Thermal energy recovered due to waste heat recovery at selected loads
    - Total electrical energy generated throughout the test period
    - Electricity offset from the grid
    - Electrical, thermal, and total energy efficiency at selected loads
- Electrical power quality performance:
    - Electrical frequency, voltage transients, voltage and current total harmonic distortion, power factor
- Emissions performance for greenhouse gases and other pollutants:
    - NO_X, CO, VOC, PM-10 and 2.5, NH_3, H_2S, SO_2, CO_2, CH_4
- Digester gas production, composition and quality (performed during ETV test only)
- Ambient air temperature at gas inlet valve
- Operational performance, maintenance requirements
- Overall economics, utility billing analysis, analysis of electricity sent back to grid (after interconnect)
- Financial analysis (paybacks, internal rate of return, net present value, levelized costs of production)

Interconnection

Colorado Pork is in the process of applying for the permits to interconnect the facility to the grid. Under the draft agreement worked out between OEMC, CP and SECPA, a separate meter system will be used to measure the amount of energy going back to the grid. Initially, SECPA will not pay CP for any electricity sent back to its system. After an initial trial period, a power purchase rate will be negotiated. Current buyback rates in the state are about 1.5 cents/kWh. The estimated cost of interconnection is $10,000, which will be funded by OEMC. The potential to sell green power will be explored.

Summary

In 1999, Colorado Pork installed an anaerobic digester and engine/generator to produce electricity. The system has performed exceptionally well since installation. The system produces about 35 percent of the facility load, and saves about $1,200/month in energy bills.

The on-going project at Colorado Pork will provide data and information on the performance of a 30 kW microturbine in a real-world setting. Real-time performance data on both the microturbine and the reciprocating engine will be available through a link from OEMC's website (http://www.state.co.us/oemc/). Combined with the on-going evaluation of digester performance, energy use analysis, and energy production at the site, a great deal of information will be available for other hog producers who may be interested in implementing an AD/energy recovery system. Electric utilities and technology developers will also benefit from the results.

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