THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

ETV Joint Verification Statement

TECHNOLOGY TYPE:	Natural-Gas-Fired Microturbine Combined With Heat Recovery System
APPLICATION:	Distributed Electrical Power and Heat Generation
TECHNOLOGY NAME:	Capstone 60 Microturbine CHP System
COMPANY:	Capstone Microturbine Corporation
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The U.S. Environmental Protection Agency (EPA) has created the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative or improved environmental technologies through performance verification and dissemination of information. The goal of the ETV program is to further environmental protection by accelerating the acceptance and use of improved and cost-effective technologies. ETV seeks to achieve this goal by providing high-quality, peer-reviewed data on technology performance to those involved in the purchase, design, distribution, financing, permitting, and use of environmental technologies.

ETV works in partnership with recognized standards and testing organizations, stakeholder groups that consist of buyers, vendor organizations, and permitters, and with the full participation of individual technology developers. The program evaluates the performance of technologies by developing test plans that are responsive to the needs of stakeholders, conducting field or laboratory tests, collecting and analyzing data, and preparing peer-reviewed reports. All evaluations are conducted in accordance with rigorous quality assurance protocols to ensure that data of known and adequate quality are generated and that the results are defensible.

The Greenhouse Gas Technology Center (GHG Center), one of six verification organizations under the ETV program, is operated by Southern Research Institute in cooperation with EPA's National Risk Management Research Laboratory. The GHG Center has collaborated with the New York State Energy and Development Authority (NYSERDA) to evaluate the performance of a combined heat and power system (CHP system) designed and installed by CDH Energy Corporation. The primary components of

the CHP system tested are a Capstone 60 MicroTurbine™ and a Unifin International heat exchanger. This verification statement provides a summary of the test results for the CHP system.

TECHNOLOGY DESCRIPTION

Large- and medium-scale gas-fired turbines have been used to generate electricity since the 1950s. Technical and manufacturing developments during the last decade have enabled the introduction of microturbines with generation capacities ranging from 30 to 200 kW. The CHP system tested here is a cogeneration installation that integrates microturbine technology with a heat-recovery system. The following description of the CHP system tested is based on information provided by CDH Energy and the equipment vendors and does not represent verified information.

Electric power is generated by a Capstone 60 microturbine with a nominal power output of 60 kW (59 °F, sea level). The system operates on natural gas and consists of an air compressor, recuperator, combustor, turbine, and a permanent magnet generator. Preheated air is mixed with fuel and this compressed fuel/air mixture is burned in the combustor under constant pressure conditions. The resulting hot gas is allowed to expand through the turbine section to perform work, rotating the turbine blades to turn a generator which produces electricity. The need for a gearbox and associated moving parts is eliminated because of the inverter-based electronics that enable the generator to operate at high speeds and frequencies. The rotating components are mounted on a single shaft supported by patented air bearings that rotate at over 96,000 revolutions per minute (rpm) at full load. The exhaust gas exits the turbine and enters the recuperator that pre-heats the air entering the combustor to improve the efficiency of the system. The exhaust gas is then directed to the Unifin heat-recovery unit.

The Unifin is a fin-and-tube heat exchanger (Model MG2) suitable for up to 700 °F exhaust gas. A nominal 25-percent mixture of propylene glycol (PG) in water is used as the heat-transfer media to recover energy from the microturbine exhaust gas stream. The PG fluid is circulated at a rate of up to 50 gallons per minute (gpm). A digital controller monitors the PG fluid outlet temperature and, when the temperature exceeds the user set point, a damper automatically opens and allows the hot exhaust gas to bypass the heat exchanger and release the heat through the stack. The damper allows hot gas to circulate through the heat exchanger when heat recovery is required (i.e., the PG fluid outlet temperature is less than user setpoint). This design allows the system to protect the heat recovery components from the full heat of the turbine exhaust while still maintaining full electrical generation from the microturbine.

The generator produces high-frequency alternating current which is rectified, inverted, and filtered by the line power unit into conditioned 480-volts alternating current (VAC). The unit supplies an electrical frequency of 60 hertz (Hz) and is supplied with a control system which allows for automatic and unattended operation. An active filter in the generator is reported by the turbine manufacturer to provide power that is free of spikes and unwanted harmonics. All operations, including startup, setting of programmable interlocks, grid synchronization, operational setting, dispatch, and shutdown, can be performed either manually or remotely using an internal power controller system. This CHP system also incorporates a Copeland-Scroll Model SZN22C1A gas booster compressor with a nominal volume capacity of 29 standard cubic feet per minute (scfm) and the capability of compressing natural gas from inlet pressures of 0.25 to 15 pounds per square inch gauge (psig) to outlet pressures of 60 to 100 psig.

The verification of the Capstone 60 microturbine system was conducted at a 57,000-sq ft Waldbaums Supermarket constructed in 2002. The store uses energy-efficient T4 light fixtures so the load in the sales

area is about 1.2 watts per square foot. The facility electric demand is never expected to drop below 200 kW in this store. The three-phase 480 volt power generated by the microturbine is wired directly into the store's 480-volt main panel. This CHP unit was integrated with a 20,000-cfm Munters Drycool air-handling unit previously installed at the Waldbaums. The Munters is the primary source of space heating, air conditioning, and air-dehumidification at the store. Recovered heat from the Capstone 60 CHP System is used to supplement the Munters' primary functions of heating the main sales areas of the store, and air dehumidification. The CHP system can provide heat to either the PG coil in the supply air stream that provides space heating in the winter or the PG coil that preheats the air entering the direct-fire burner that regenerates the desiccant wheel.

VERIFICATION DESCRIPTION

Testing commenced on June 4, 2003, and was completed on June 20, 2003. The testing included a series of controlled test periods in which the GHG Center intentionally modulated the unit to produce electricity at nominal power output commands of 15, 30, 45, and 60 kW. Demand for space heating and dessicant regeneration was low during the testing period due to the mild weather. The PG was, therefore, manually directed to the Munter's space-heating coil during each of the controlled test periods. This was done to maximize the heat demand on the CHP system and verify CHP performance under periods of high heat demand. The controlled tests at the 30 and 60 kW power command points were also repeated with the Unifin heat exchanger damper open (heat recovery bypass mode) to evaluate the impact of heat exchanger back-pressure on microturbine performance. The controlled test periods were followed by 14 days of extended monitoring to verify electric power production, heat recovery, power quality performance, and efficiency during an extended period of normal site operations. The classes of verification parameters evaluated were:

- **Heat and Power Production Performance**
- **Emissions Performance (NO_x, CO, THC, CO_2, and CH_4)**
- **Power Quality Performance**

Evaluation of heat and power production performance includes verification of power output, heat recovery rate, electrical efficiency, thermal efficiency, and total system efficiency. Electrical efficiency was determined according to the ASME Performance Test Code for Gas Turbines (ASME PTC-22) and tests consisted of direct measurements of fuel flow rate, fuel lower heating value (LHV), and power output. Heat recovery rate and thermal efficiency were determined according to ANSI/ASHRAE test methods and tests consisted of direct measurements of heat-transfer fluid flow rate, differential temperatures, and specific heat of the heat transfer fluid. Ambient temperature, barometric pressure, and relative humidity measurements were also collected to characterize the condition of the combustion air used by the turbine.

The evaluation of emissions performance occurred simultaneously with efficiency testing conducted during the controlled test period. Pollutant concentration and emission rate measurements for nitrogen oxides (NO_X), carbon monoxide (CO), total hydrocarbons (THC), carbon dioxide (CO_2), and methane (CH_4) were conducted in the turbine exhaust stack. All test procedures used in the verification were U.S. EPA reference methods recorded in the Code of Federal Register (CFR). Pollutant emissions are reported in two sets of units – as concentrations in parts per million volume, dry (ppmvd) corrected to 15-percent oxygen (O_2), and as mass per unit time (lb/hr). The mass emission rates are also normalized to turbine power output and reported as pounds per kilowatt hour (lb/kWh).

Annual NO_X and CO_2 emissions reductions for the CHP system at the test site are estimated by comparing measured lb/kWh emission rates with corresponding emission rates for the baseline power and heat-production systems (i.e., systems that would be used if the CHP system were not present). The baseline

systems at this site include electricity supplied from the local utility grid and heat from the facility's natural gas-fired burners. Baseline emissions for the electrical power were determined following Ozone Transport Commission (OTC) guidelines. Baseline emissions from heat production are based on EPA emission factors for commercial-scale gas-fired burners.
Electrical power quality parameters, including electrical frequency and voltage output, were also measured during the 14-day extended test. Current and voltage total harmonic distortions (THD) and power factors were also monitored to characterize the quality of electricity supplied to the end user. The guidelines listed in "The Institute of Electrical and Electronics Engineers' (IEEE) Recommended Practices and Requirements for Harmonic Control in Electrical Power Systems" were used to perform power quality testing.

Quality Assurance (QA) oversight of the verification testing was provided following specifications in the ETV Quality Management Plan (QMP). EPA personnel conducted an on-site technical systems audit during the testing program. The GHG Center staff conducted two performance evaluation audits and an audit of data quality on at least 10 percent of the data generated during this verification. The GHG Center field team leader and project manager have reviewed the data from the verification testing and have concluded that the data have attained the data quality objectives that are specified in the Test and Quality Assurance Plan.

VERIFICATION OF PERFORMANCE

Heat and Power Production Performance

- The average gross power output at full load was 59.6 kW at these test conditions (corresponding gross electrical efficiency was about 28.4 percent). The gross power output would be available to potential users not needing sources of significant parasitic load such as the gas compressor and glycol circulation pump.

- Considering parasitic loads from the gas compressor and glycol circulation pump, the net power delivered at full load averaged 54.9 kW. Net electrical efficiency during the controlled test periods ranged from 26.2 percent at full load to 13.1 percent at the lowest load tested (25 percent of capacity). Electrical efficiency was not impacted by changes in operation of the heat recovery system.

HEAT AND POWER PRODUCTION							
Test Condition	Electrical Power Generation				Heat Recovery Performance		Total CHP System Efficiency (%)
	Gross Power Output (kW_e)	Gross Efficiency (%)	Net Power Delivered (kW_e)	Net Efficiency (%)	Heat Recovery (10^3Btu/hr)	Thermal Efficiency (%)	
Full load, heat recovery maximized	59.6	28.4	54.9	26.2	373.0	52.2	78.4

HEAT AND POWER PRODUCTION							
Test Condition	Electrical Power Generation				Heat Recovery Performance		Total CHP System Efficiency (%)
	Gross Power Output (kW_e)	Gross Efficiency (%)	Net Power Delivered (kW_e)	Net Efficiency (%)	Heat Recovery (10^3Btu/hr)	Thermal Efficiency (%)	
75-percent load, heat recovery maximized	44.5	27.0	39.9	24.2	317.0	56.4	80.7
50-percent load, heat recovery maximized	29.5	23.8	24.8	20.0	239.6	56.7	76.7
25-percent load, heat recovery maximized	14.4	19.3	9.8	13.1	148.5	58.0	71.1
Full load, normal operation	59.6	28.4	54.9	26.2	51.4	7.2	33.3
50-percent load, normal operation	29.5	23.7	24.9	20.0	68.6	16.2	36.2

- Total CHP efficiency during the controlled test periods with operation configured to maximize heat recovery ranged from 71.1 percent at 25-percent load to 80.7 percent at 75-percent load. CHP efficiency was 33.3 percent at full load during normal heat recovery controlled tests because of low space heating and dehumidification demand during testing.

- Electrical, thermal, and CHP efficiencies during the 14-day extended monitoring period averaged 25.7, 8.0, and 33.7 percent, respectively. Low space heating and dehumidification demand was evident throughout the period.

Emissions Performance

- NO_X emissions at full load were 0.00015 lb/kWh and increased as power output decreased. Changes in operation of the heat exchanger did not produce a significant impact on NO_X emissions.

- Emissions of CO, THC, and CH_4 were also lower at full load and increased slightly as power output was reduced. Changes in operation of the heat exchanger did not produce a significant impact on emissions of these pollutants.

- NO_X emissions per unit electrical power output at full load were 0.00015 lb/kWh, well below the average levels reported for the regional grid (0.0024 lb/kWh). The average CO_2 emissions for the regional grid are estimated at 1.53 lb/kWh which is nearly identical to the emission rate for the Capstone 60 (which had 1.54 lb/kWh_e). These values, along with emission reductions attributed to the CHP system heat recovery performance, yield an average annual emission reduction of 1,064 lbs (17 percent) for NO_X and 328,478 lbs (8 percent) for CO_2.

CRITERIA POLLUTANT AND GREENHOUSE GAS EMISSIONS									
Test Condition	**(ppmvd at 15% O_2)**				**(lb/kWh$_e$)**				
	NO_X	CO	THC	CH_4	NO_X	CO	THC	CH_4	CO_2
Full load, heat recovery maximized	3.13	3.53	1.06	< 0.9	1.49×10^{-4}	1.03×10^{-4}	1.77×10^{-5}	$< 1.58 \times 10^{-5}$	1.54
75-percent load, heat recovery maximized	3.30	154	70.3	43.5	1.71×10^{-4}	4.86×10^{-3}	1.27×10^{-3}	7.84×10^{-4}	1.61
50-percent load, heat recovery maximized	4.26	582	1194	721	2.67×10^{-4}	2.26×10^{-2}	2.61×10^{-2}	1.57×10^{-2}	1.87
25-percent load, heat recovery maximized	6.56	338	327	198	6.31×10^{-4}	1.98×10^{-2}	1.09×10^{-2}	6.65×10^{-3}	2.89
Full load, normal operation	3.05	3.90	0.69	Not tested	1.47×10^{-4}	1.14×10^{-4}	1.14×10^{-5}	Not tested	1.49
50-percent load, normal operation	4.50	586	1154	678	2.83×10^{-4}	2.25×10^{-2}	2.53×10^{-2}	1.48×10^{-2}	1.87

Power Quality Performance

- The CHP system maintained continuous synchronization with the utility grid throughout the 14-day test period. Average electrical frequency was 60.000 Hz and average voltage output was 494.48 volts.
- The power factor remained relatively constant for all monitoring days with an average of 99.98 percent.
- The average current THD was 5.66 percent and the average voltage THD was 1.98 percent. The THD threshold specified in IEEE 519 is ± 5 percent.

Details on the verification test design, measurement test procedures, and Quality Assurance/Quality Control (QA/QC) procedures can be found in the Test Plan titled *Test and Quality Assurance Plan for Combined Heat and Power at a Commercial Supermarket, Capstone 60 kW Microturbine* (SRI 2002). Detailed results of the verification are presented in the Final Report titled *Environmental Technology Verification Report for Combined Heat and Power at a Commercial Supermarket, Capstone 60 kW Microturbine* (SRI 2003). Both can be downloaded from the GHG Center's web-site (www.sri-rtp.com) or the ETV Program web-site (www.epa.gov/etv).

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