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Environmental Technology Verification Report

Building Energy Solutions, LLC Tecogen CM-100 Combined Heat and Power System

Prepared by:

Greenhouse Gas Technology Center

Operated by
Southern Research Institute

Under a Cooperative Agreement With
U.S. Environmental Protection Agency

and

Under Agreement With
New York State Energy Research and Development Authority

EPA REVIEW NOTICE

This report has been peer and administratively reviewed by the U.S. Environmental Protection Agency, and approved for publication. Mention of trade names or commercial products does not constitute endorsement or recommendation for use.

THE ENVIRONMENTAL TECHNOLOGY VERIFICATION PROGRAM

ETV Joint Verification Statement

TECHNOLOGY TYPE:	Electric Power and Heat Production using Natural Gas
APPLICATION:	Combined Heat and Power System
TECHNOLOGY NAME:	Tecogen Model CM-100
COMPANY:	Tecogen
ADDRESS:	45 First Avenue Waltham, MA 02451
WEB ADDRESS:	http://www.tecogen.com/

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of ETV is to further environmental protection by accelerating the acceptance and use of improved and innovative environmental 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), operated by Southern Research Institute (Southern), is one of six verification organizations operating under the ETV program. A technology area of interest to some GHG Center stakeholders is distributed electrical power generation (DG), particularly with combined heat and power (CHP) capabilities.

The GHG Center collaborated with the New York State Energy Research and Development Authority (NYSERDA) to evaluate the performance of an array of six Tecogen Model CM-100 units - combined heat and power (CHP) system manufactured by Tecogen and fueled with natural gas. The system is owned and operated by BOCES in Verona, New York.

TECHNOLOGY DESCRIPTION

The following information has been supplied by the vendor and has not been verified. Building Energy Solutions (BES) has installed six natural gas-fired Tecogen Model CM-100 Premium Power CHP modules as part of a DG / CHP upgrade at the Madison-Oneida Board of Cooperative Educational Services (BOCES) campus located in Verona, NY. The technical basis for the technology is as follows.

The Tecogen system utilizes natural gas fuel, combusted in an internal combustion engine, which is used to drive an electric generator. Thermal energy in the engine's exhaust heat and other heat sources is recovered and used for various purposes. The CHP array operates in response to the site's electrical demand; power is not exported to the grid. Management of the host facility's peak electrical demand is a fundamental economic driver for the system.

The installation recovers thermal energy from the IC engine jacket coolant, oil cooler, and exhaust. The recovered energy is designed to supply up to 4.4 million British thermal units per hour (MMBtu/h) from the array of six units to the following district heating and cooling applications:

- year-round domestic hot water (DHW)
- heat supply to two 100-ton absorption chillers for air-conditioning during warm weather
- hydronic space heating during cold weather

The facility also incorporates two 7500-gallon insulated thermal storage tanks. Their function is to provide approximately 2.5 MMBtu carry-through capacity for space heating and DHW needs during cold weather periods when electrical demand is low.

The CHP heating and cooling applications displace fuel consumption by five existing natural gas-fired boilers rated at1.94 MMBtu/h each. Two of the boilers are located adjacent to the CHP installation while the remaining three are located elsewhere on the campus. Hydronic heating, DHW, and chilled water piping is generally located in the ceiling spaces and corridors which connect the various building sections. The electrical generators, panel boards, circulation pumps, and most other parasitic loads are connected to the main service bus located in the building "Section H" mechanical room.

VERIFICATION DESCRIPTION

Rationale for the experimental design, determination of verification parameters, detailed testing procedures, test log forms, and QA/QC procedures can be found in the draft ETV Generic Verification Protocol (GVP) [3] for DG/CHP verifications developed by the GHG Center. Site specific information and details regarding instrumentation, procedures, and measurements specific to this verification were detailed in the Test and Quality Assurance Plan titled *Test and Quality Assurance Plan – Building Energy Soulutions, LLC Tecogen DG / CHP Installation.* Both can be downloaded from the ETV Program web-site (www.epa.gov/etv).

Controlled Testing

Controlled testing for the field testing was conducted on September 9, 2009 through September 11th, 2009. The defined system under test (SUT) was tested to determine performance for the following verification parameters:

- Electrical Performance
- Electrical Efficiency
- CHP Thermal Performance
- CHP Thermal Efficiency
- Atmospheric Emissions (controlled test period only).
- NO_x and CO_2 emissions reductions (offsets) relative to baseline conditions

Electrical and thermal performance and efficiency were quantified following the rationale and approaches detailed in the GVP. Specifically, electrical generation efficiency can also be termed the "fuel-to-electricity conversion efficiency." It is the net amount of energy a system produces as electricity compared to the amount of energy input to the system in the fuel. Heat rate expresses electrical generation efficiency in terms of British thermal units per kW-hour (Btu/kWh). For determination of thermal performance, applicable CHP devices use a circulating liquid heat transfer fluid for heating or chilling. The CHP equipment itself is considered to be within the SUT boundary. The balance of plant (BoP) equipment, which employs the heating or chilling effect, is outside the system boundary. The GVP does not consider how efficiently the BoP uses the heating or chilling effect. Actual thermal performance is the heat transferred out of the SUT boundary to the BoP for both CHP heaters and chillers. Actual thermal efficiency in heating service is the ratio of the thermal performance to total heat input in the fuel. Detailed definitions and equations appear in Appendix C of the GVP.

The verification included a series of controlled test periods on September 10, 2009 in which the GHG Center maintained steady system operations for three test periods at loads of 100%, 75%, and 50% of capacity (100, 75, and 50 kW, respectively) on one of the six Tecogen CM 100 units. Equipment tag name, Cogen 4 was selected from the six units to evaluate electrical and CHP efficiency and emissions performance. Testing took place at night so it would not interfere with normal operations of the facility. Five of the six units were shutdown during the controlled test period and temporary installation of independent electrical power analyzers were placed on the Cogen 4 output bus. The analyzers recorded the electrical performance parameters at 1-minute intervals. Water serves as the CHP heat transfer fluid. Southern installed supply and return temperature sensors and an ultrasonic fluid flow meter to determine heat recovery from the CHP system heat recovery loop.

Emissions data were recorded from the Cogen 4 exhaust stack on the roof of the mechanical room. Southern's Horiba OBS-2200 PEMS (Portable Emissions Monitoring System) was installed on the exhaust stack to measure atmospheric emissions including THC, CO, CO_2, and NO_x. Other parameters including exhaust flow, exhaust temperature, exhaust pressure, moisture, ambient temperature, and ambient pressure were also collected from the OBS-2200 to allow for computing exhaust gas flow at dry, standard conditions. Fuel gas consumption was determined by a data logger connected to a revenue-grade gas meter. Southern installed a Dresser brand Roots meter (model 11M175) in the CHP array gas line. The meter incorporates a high-frequency pulse output for flow rate determinations. Test personnel connected the meter output to the data logger and recorded the gas flow rate at least once per minute during all test periods. Testing personnel also temporarily installed ports for collecting natural gas samples for lower heating value (LHV) analysis.

Long-term Monitoring
The controlled tests were followed by a 1 year period of continuous monitoring to determine heat recovery and power output, electrical and thermal efficiency, and estimated annual emission reductions on the full array of six CHP units under normal operation.

Quality Assurance
Quality assurance (QA) oversight of the verification testing was provided following specifications in the ETV Quality Management Plan (QMP). On September 10th 2009, the EPA conducted a Technical Systems Audit on site. Bob Wright from EPA and David Gratson from Neptune and Company, Inc conducted the audit while controlled testing was underway. The GHG Center's QA manager conducted an audit of data quality on the data generated during this verification and a review of this report. Data review and validation was conducted at three levels including the field team leader, the project manager, and the QA manager.

VERIFICATION OF PERFORMANCE

Electrical and Thermal Performance – Controlled Test Period
Gross and net electrical performance and efficiency as measured during the controlled test period are presented in Table 1. Net electrical performance is exclusive of power consumed by CHP system electrical loads required for system operation (parasitic loads). Parasitic loads are disproportionally high during the controlled test period when only one unit is operating as compared to normal operations when up to six cogeneration units may be operating. Parasitic loads during the controlled test period averaged about 7 percent of gross power output, whereas during the long term monitoring, parasitic loads averaged only 2-4 percent of gross power output (depending on load conditions). Uncertainties given in table 1 were determined by measurement error propagation as detailed in Section 7 of the GVP.

Thermal performance as measured during the controlled test period is not reported. The thermal performance measurements are not considered representative for several reasons. The heat recovery fluid flow measurement is not considered reliable because the flow velocities with only a single unit operating were at or below the velocity at which the instrument accuracy rapidly deteriorates. Heat losses with only a single unit operating are disproportionately high compared to normal operations with up to six units operating. System controls, which seek to maintain the return temperature to the cogeneration array at a constant level, did not appear to be able to operate as intended with only a single unit operating, resulting in cycling of flow rate and return temperature. A detailed assessment of these factors is provided in section 3.2.3 of the full verification report.

Table 1. Controlled Test Electrical and Thermal Performance						
			Electrical Power Generation Performance			
Test ID		**Heat Input (MMBtu/h)**	**Net Power Generated (kW)**	**Net Electrical Efficiency (%)**	**Gross Power Generated (kW)**	**Gross Electrical Efficiency (%)**
100 kW	Run 1	1.18	91.8	26.5	98.0	28.3
	Run 2	1.17	91.2	26.6	97.3	28.4
	Run 3	1.17	91.4	26.6	97.7	28.4
	Avg.	**1.18**	**91.5**	**26.6**	**97.7**	**28.4**
	+/-	**1.8%**	**0.7%**	**3.0%**	**0.7%**	**3.0%**
75 kW	Run 1	0.85	66.2	26.5	72.3	28.9
	Run 2	0.85	66.1	26.4	72.3	28.9
	Run 3	0.86	66.5	26.4	72.6	28.8
	Avg.	**0.86**	**66.3**	**26.4**	**72.4**	**28.9**
	+/-	**1.8%**	**0.7%**	**3.0%**	**0.7%**	**3.0%**
50 kW	Run 1	0.57	41.6	24.7	47.3	28.1
	Run 2	0.57	41.4	24.6	47.2	28.0
	Run 3	0.58	42.8	25.2	47.5	28.0
	Avg.	**0.58**	**41.9**	**24.8**	**47.3**	**28.0**
	+/-	**1.8%**	**0.7%**	**3.0%**	**0.7%**	**3.0%**

Reported uncertainties by measurement error propagation per GVP in percentage of reported value. Net electrical performance is exclusive of electrical loads required for system operation (parasitic loads). Parasitic loads are disproportionately high during the controlled test conditions as described above.

Emissions Performance – Controlled Test Period
Table 2 summarizes emissions performance of the Cogen 4 unit during the controlled test period.

THC and NO_x emissions at the 50kW load condition are elevated. This is due to poor engine performance at partial load – an abnormal operating condition. In normal operations, the units are run at greater than 60 percent load and individual units are taken on and off line in response to facility electrical demand.

Uncertainties given in this table were determined by calculating a 95 percent confidence interval over the mean of all three runs at each load condition. The higher uncertainty for CO emissions at the 75kW load conditions is due to a greater degree of fluctuation in CO concentration at the lower load conditions. CO emissions measurements for the 50kW load condition were invalidated and are not reported. The analyzer failed the span drift check at the conclusion of the test run, and examination of the data showed that negative values were frequently reported.

Power Quality Performance – Controlled Test Period
Power quality was not monitored during the controlled test period due to a malfunction of data logging equipment. This is not considered to have a significant impact on the quality of the performance verification as power quality is proven to be sufficient for grid interconnect.

Electrical and Thermal Performance – Long Term Monitoring Period
Measurements necessary to determine electrical and thermal performance and efficiency were collected over a period from September 2009 through September 2010. Table 3 provides a summary of the results. During normal operations at the BOCES facility, the cogeneration array operates in response to electrical demand. As such, the array typically operates at nearly full load during weekdays, with partial load at nights and on weekends. Full load conditions are characterized by power generation rates over 300kW, and night/weekend conditions are characterized by generation rates less than 300 kW. The cogeneration array operated nearly continuously throughout the year of monitoring, with only one brief period of down time (43 hours) in late June 2010.

Gross electrical efficiency during the extended test was 24.1 percent on an annual basis, 26.4 percent at full load conditions, and 22 percent at partial load conditions. Parasitic loads accounted for 2 to 4 percent of power production depending on load conditions.

As can be seen in Table 3, the electrical and thermal efficiency of the system is somewhat lower at partial load than at full load. The lower thermal efficiency at partial load may be due to system heat losses - which amount to a greater proportion of the total heat recovered at partial load than at full load.

The lower electrical efficiency at partial load is not fully explained by the data. However, at the very lowest loads (occurring during weekend daytimes), fuel consumption was consistently observed to increase as power output decreased. This could be due to the cogeneration array running in an inefficient operating range at the lowest load conditions. During the controlled tests with only one of six units operating, electrical efficiency decreased slightly at the 50 percent load condition, but not as much as was observed during extended monitoring of the full cogeneration array.

Table 2. Tecogen Emissions During Controlled Test Periods

Test ID		Gross Power (kW)	CO Emissions			CO2 Emissions		
			ppm	lb/hr	lb/MWh	Volume %	lb/hr	lb/MWh
100kW	Run 1	98	175	0.17	1.8	9.3	91	930
	Run 2	97	162	0.16	1.6	9.2	90	927
	Run 3	98	168	0.16	1.7	9.2	91	928
	Avg.	**98**	**168**	**0.17**	**1.7**	**9.2**	**91**	**928**
	95% CI		**1.7%**			**0.02%**		
75 kW	Run 1	72	44	0.04	0.5	9.1	80	1113
	Run 2	72	81	0.08	1.1	9.1	85	1182
	Run 3	73	96	0.09	1.2	9.1	86	1180
	Avg.	**72**	**74**	**0.07**	**0.9**	**9.1**	**84**	**1158**
	95% CI		**5.3%**			**0.06%**		
50 kW	Run 1	47	not reported*	0.06	1.4	9.2	52	1095
	Run 2	47	not reported*	0.08	1.7	9.2	59	1250
	Run 3	48	not reported*	0.09	1.8	9.2	63	1328
	Avg.	**47**		**0.08**	**1.6**	**9.2**	**58**	**1224**
	95% CI					**0.07%**		
Test ID		**Gross Power (kW)**	**THC Emissions**			**NOx Emissions**		
			ppm	**lb/hr**	**lb/MWh**	**ppm**	**lb/hr**	**lb/MWh**
100kW	Run 1	98	5.7	0.006	0.06	12.8	0.013	0.1
	Run 2	97	4.8	0.005	0.05	12.9	0.013	0.1
	Run 3	98	4.9	0.005	0.05	13.1	0.013	0.1
	Avg.	**98**	**5.1**	**0.005**	**0.05**	**12.9**	**0.013**	**0.1**
	95% CI		**1.2%**			**2.5%**		
75 kW	Run 1	72	8.8	0.008	0.11	8.4	0.007	0.1
	Run 2	72	8.5	0.008	0.11	8.3	0.008	0.1
	Run 3	73	8.7	0.008	0.11	7.8	0.007	0.1
	Avg.	**72**	**5.8**	**0.008**	**0.11**	**5.6**	**0.008**	**0.1**
	95% CI		**2.3%**			**4.0%**		
50 kW	Run 1	47	273	0.154	3.2	843	0.475	10.0
	Run 2	47	288	0.185	3.9	881	0.567	12.0
	Run 3	48	292	0.201	4.2	881	0.608	12.8
	Avg.	**47**	**284**	**0.180**	**3.8**	**869**	**0.550**	**11.6**
	95% CI		**1.5%**			**1.6%**		

*Carbon monoxide results for the 50 percent load condition are not reported because the instrument failed the span drift check at the conclusion of the testing at this condition and the results appeared suspect upon examination (concentrations during the run were frequently recorded as negative values).

Table 3. Extended Test Results Summary

	Average Net Power Output (kW)	+/-	Average Heat Recovery (MMBtu/hr)	+/-	Average Thermal Efficiency (%)	+/-	Average *Net* Electrical Efficiency (%)	+/-	Average Total Efficiency (%)	+/-
Annual Average	293	0.7%	2.26	4.4%	53.7	4.9%	23.5	3.0%	77.2	3.5%
Full Load - (Weekday) (>=300kW)	394	0.7%	2.98	4.4%	60.4	4.9%	25.8	3.0%	86.2	3.5%
Partial Load - (Night) (<300kW)	211	0.7%	1.68	4.4%	48.2	4.9%	21.3	3.0%	69.5	3.5%

Reported uncertainties by measurement error propagation per GVP.

Signed by Cynthia Sonich-Mullin (3/7/2013)

Cynthia Sonich-Mullin
Director
National Risk Management Research Laboratory
Office of Research and Development

Signed by Tim Hansen (1/3/2013)

Tim Hansen
Director
Greenhouse Gas Technology Center
Southern Research Institute

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Greenhouse Gas Technology Center

A U.S. EPA Sponsored Environmental Technology Verification (ETV) Organization

Environmental Technology Verification Report

Building Energy Solutions, LLP Tecogen CM-100 Combined Heat and Power System

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ACKNOWLEDGMENTS

The Greenhouse Gas Technology Center wishes to thank NYSERDA, especially Jim Foster, for supporting this verification and reviewing and providing input on the testing strategy and this Verification Report. Thanks are also extended to Madison-Oneida Board of Cooperative Educational Services (BOCES) campus, and Todd Vandresser for his input supporting the verification and assistance with field testing activities. Thanks also go out to CDH Energy Corp., specifically Adam Walburger, for his assistance with field testing activities. Finally, many thanks are due to Rae Butler of Building Energy Solutions for supplementing the long term monitoring data with data from BOCES system sensors and to Joe Gehret or Tecogen for his assistance in data interpretation.

ACRONYMS AND ABBREVIATIONS

ADQ	Audit of Data Quality
BES	Building Energy Solutions
BOCES	Board of Cooperative Educational Services
Btu/h	British thermal units per hour
Btu/scf	British thermal units per standard cubic feet
CHP	combined heat and power
CO	carbon monoxide
CO_2	carbon dioxide
CT	current transformer
DG	distributed generation
DHW	domestic hot water
DQO	data quality objective
DUT	device under test
EPA	Environmental Protection Agency
ETV	Environmental Technology Verification
FID	flame ionization detector
FS	full scale
GHG Center	Greenhouse Gas Technology Center
GVP	generic verification protocol
gpm	gallons per minute
Hz	hertz
kVA	kilovolt-amperes
kVAR	kilovolt-amperes reactive
kW	kilowatts
kWh	kilowatt hours
lb/h	pounds per hour
lb/kWh	pounds per kilowatt-hour
lb/MWh	pounds per megawatt-hour
LHV	lower heating value
MMBtu/h	million British thermal units per hour
MQO	measurement quality objective
MWh	megawatt-hour
NDIR	non-dispersive infra-red
NIST	National Institute of Standards and Technology
NO_x	nitrogen oxides
NYSERDA	New York State Energy Research and Development Authority
O_2	oxygen
PEMS	portable emissions measurement system
ppm	parts per million volume, dry
psia	pounds per square inch, absolute
QA/QC	Quality Assurance/Quality Control
QMP	Quality Management Plan
RTD	resistance temperature detector
scfh	standard cubic feet per hour
SUT	system under test
TQAP	Test and Quality Assurance Plan
THCs	total hydrocarbons
THD	total harmonic distortion

1.0 INTRODUCTION

1.1. BACKGROUND

The U.S. Environmental Protection Agency's Office of Research and Development (EPA-ORD) operates the Environmental Technology Verification (ETV) program to facilitate the deployment of innovative technologies through performance verification and information dissemination. The goal of ETV is to further environmental protection by accelerating the acceptance and use of improved and innovative environmental technologies. Congress funds ETV in response to the belief that there are many viable environmental technologies that are not being used for the lack of credible third-party performance data. With performance data developed under this program, technology buyers, financiers, and permitters in the United States and abroad will be better equipped to make informed decisions regarding environmental technology purchase and use.

The Greenhouse Gas Technology Center (GHG Center) is one of six verification organizations operating under the ETV program. The GHG Center is managed by EPA's partner verification organization, Southern Research Institute (Southern), which conducts verification testing of promising greenhouse gas mitigation and monitoring technologies. The GHG Center's verification process consists of developing verification protocols, conducting field tests, collecting and interpreting field and other data, obtaining independent stakeholder input, and reporting findings. Performance evaluations are conducted according to externally reviewed verification Test and Quality Assurance Plans (TQAPs) and established protocols for quality assurance.

The GHG Center is guided by volunteer groups of stakeholders. The GHG Center's Executive Stakeholder Group consists of national and international experts in the areas of climate science and environmental policy, technology, and regulation. It also includes industry trade organizations, environmental technology finance groups, governmental organizations, and other interested groups. The GHG Center's activities are also guided by industry specific stakeholders who provide guidance on the verification testing strategy related to their area of expertise and peer-review key documents prepared by the GHG Center.

In recent years, a primary area of interest to GHG Center stakeholders has been distributed electrical power generation systems. Distributed generation (DG) refers to equipment, typically ranging from 1 to 1,000 kilowatts (kW) that provide electric power at a site closer to customers than central station generation. A DG unit can be connected directly to the customer or to a utility's transmission and distribution system. Examples of technologies available for DG include: internal combustion engine generators; photovoltaics; wind turbines; fuel cells; and microturbines. DG technologies provide customers one or more of the following main services: standby generation; peak shaving generation; base load generation; or cogeneration. DG systems that utilize renewable energy sources can provide even greater environmental and economic benefits.

Since 2002, the GHG Center and the New York State Energy Research and Development Authority (NYSERDA) have collaborated and shared the cost of verifying several new DG technologies throughout the state of New York under NYSERDA-sponsored programs. The verification described in this document evaluated the performance of one such DG system: an array of six natural gas-fired Tecogen Model CM-100 Premium Power combined heat and power (CHP) modules. The system is owned and operated by Madison-Oneida Board of Cooperative Educational Services (BOCES) campus located in Verona, NY.

The GHG Center evaluated the performance of the BOCES DG/CHP system by conducting controlled field tests over a 3-day verification period (September 9, 2009 – September 11, 2010) and long term monitoring over a period of one year beginning at the conclusion of the controlled testing and ending September 30, 2010. These tests were planned and executed by the GHG Center to independently verify electricity generation rate, thermal energy recovery rate, electrical power quality, energy efficiency, emissions, and greenhouse gas emission reductions for a six unit array DG/CHP system as operated at BOCES. In order to avoid the cost and complexity of measuring emissions from each of the six separate exhaust stacks, the controlled tests focused on a single selected unit from the array.

Details on the verification test design, measurement test procedures, and quality assurance/quality control (QA/QC) procedures are contained in two related documents. Technology and site specific information can be found in the document titled *Test and Quality Assurance Plan – Building Energy Solutuions, LLP Tecogen DG / CHP Installation*[1]. It can be downloaded from the GHG Center's web-site (www.sri-rtp.com) or the ETV Program web-site (www.epa.gov/etv). This TQAP describes the system under test (SUT), project participants, site specific instrumentation and measurements, and verification specific QA/QC goals. The TQAP was reviewed and revised based on comments received from NYSERDA, and the EPA Quality Assurance Team. The TQAP meets the requirements of the GHG Center's Quality Management Plan (QMP) and satisfies ETV QMP requirements.

Rationale for the experimental design, determination of verification parameters, detailed testing procedures, test log forms, and QA/QC procedures can be found in the Association of State Energy Research and Technology Transfer Institutions (ASERTTI) DG/CHP Distributed Generation and Combined Heat and Power Performance Protocol for Field Testing [2]. This document can be downloaded from the web location www.dgdata.org/pdfs/field_protocol.pdf. The GHG Center has adopted portions of this protocol as a generic verification protocol (GVP) for DG/CHP verifications [3]. This ETV performance verification of the Tecogen system was based on the GVP.

The remainder of Section 1.0 describes the BOCES DG/CHP system technology and test facility, and outlines the performance verification procedures that were followed. Section 2.0 presents test results, and Section 3.0 assesses the quality of the data obtained.

1.2. BOCES TECOGEN DG/CHP TECHNOLOGY DESCRIPTION

The following information has been supplied by the vendor and has not been verified. Building Energy Solutions (BES) has installed six natural gas-fired Tecogen Model CM-100 Premium Power CHP modules as part of a DG / CHP upgrade at the Madison-Oneida Board of Cooperative Educational Services (BOCES) campus located in Verona, NY. The technical basis for the technology is as follows.

The CHP array operates in response to the site's electrical demand; power is not exported to the grid. Management of the host facility's peak electrical demand, is a fundamental economic driver for the system.

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- year-round domestic hot water (DHW)
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The facility also incorporates two 7500-gallon insulated thermal storage tanks. Their function is to provide approximately 2.5 MMBtu carry-through capacity for space heating and DHW needs during cold weather periods when electrical demand is low.

The CHP heating and cooling application displaces fuel consumption at five existing natural gas-fired boilers rated at 1.94 MMBtu/h each. Two of the boilers are located adjacent to the CHP installation while the remaining three are located elsewhere on the campus. Hydronic heating, DHW, and chilled water piping is generally located in the ceiling spaces and corridors which connect the various building sections. The electrical generators, panel boards, circulation pumps, and most other parasitic loads are connected to the main service bus located in the building "Section H" mechanical room.

Figure 1-1. BOCES in Verona, New York

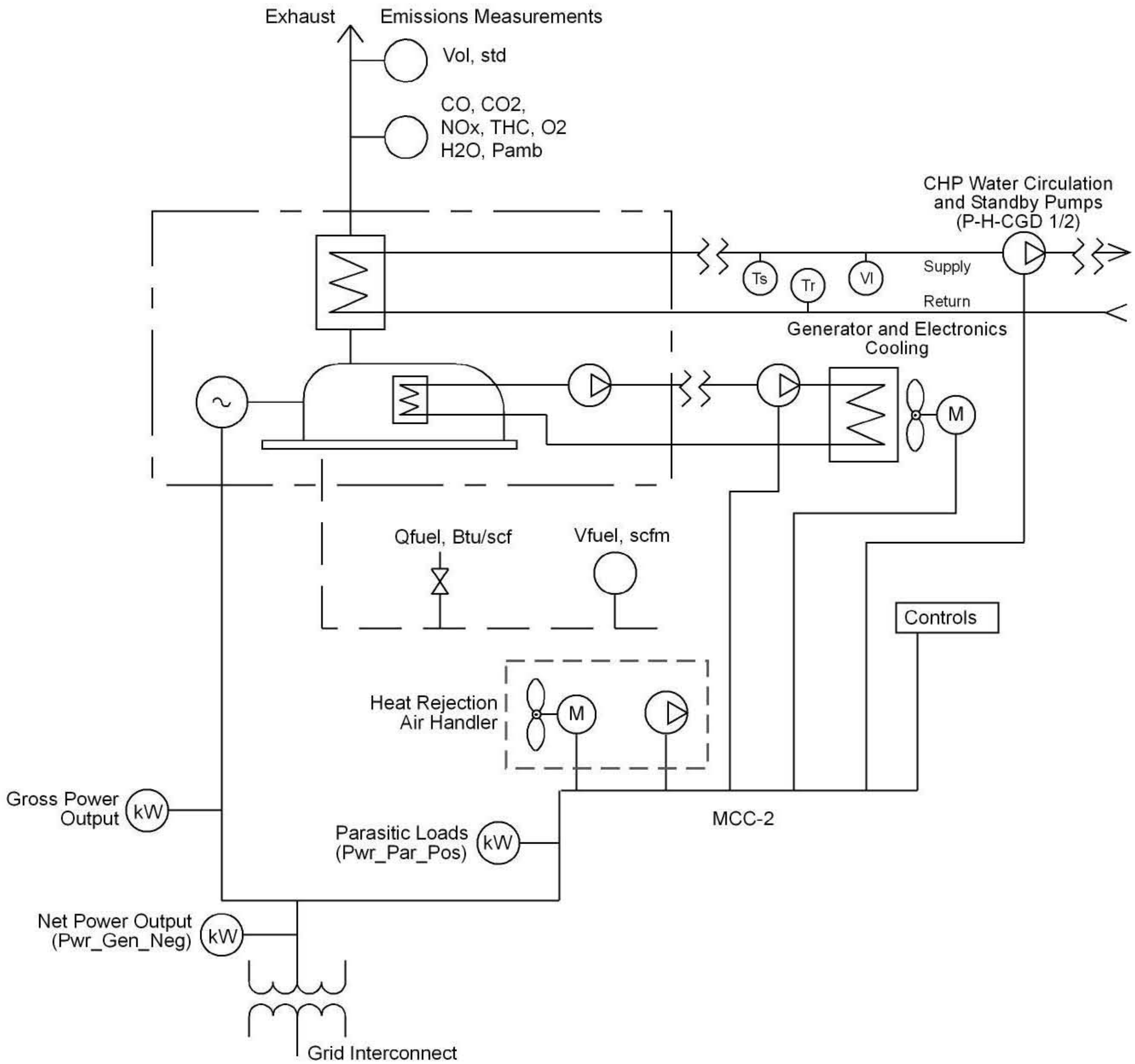
1.3. PERFORMANCE VERIFICATION OVERVIEW

The verification included evaluation of the DG/CHP system performance over a series of controlled test periods on a single unit of the six unit array. The GVP specifies testing at three loads: 100%, 75%, and 50% of capacity (100, 75, and 50 kW, respectively). In addition to the controlled test periods, the test plan specifies that one year of continuous fuel consumption, power generation, and heat recovery data be collected to characterize the system performance of the six unit array over normal facility operations. Southern Research and its subcontractor, CDH Energy Corp., installed instrumentation and provided data acquisition/telemetry equipment during the long term monitoring period. Long term monitoring data was supplemented by data from the BOCES building management system provided by Building Energy Solutions.

BOCES verification was limited to the performance of the system under test (SUT) within a defined system boundary that includes the Tecogen units and supply and return lines from the hot water storage tanks and heat rejection air handling unit. Figure 1-2 illustrates the system boundary and monitoring configuration for the controled test period. Figure 1-3 illustrates the system boundary and monitoring configuration for the long-term test period.

Electrical and thermal performance and efficiency were quantified following the rationale and approaches detailed in the GVP. Specifically, electrical generation efficiency can also be termed the "fuel-to-electricity conversion efficiency." It is the net amount of energy a system produces as electricity compared to the amount of energy input to the system in the fuel. Heat rate expresses electrical generation efficiency in terms of British thermal units per kW-hour (Btu/kWh). For determination of thermal performance, applicable CHP devices use a circulating liquid heat transfer fluid for heating or chilling. The CHP equipment itself is considered to be within the SUT boundary. The balance of plant (BoP) equipment, which employs the heating or chilling effect, is outside the system boundary. The GVP does not consider how efficiently the BoP uses the heating or chilling effect. Actual thermal performance is the heat transferred out of the SUT boundary to the BoP for both CHP heaters and chillers. Actual thermal efficiency in heating service is the ratio of the thermal performance to total heat input in the fuel. Detailed definitions and equations appear in Appendix C of the GVP.

Figure 1-2. System Boundary Diagram – Controlled Test Period



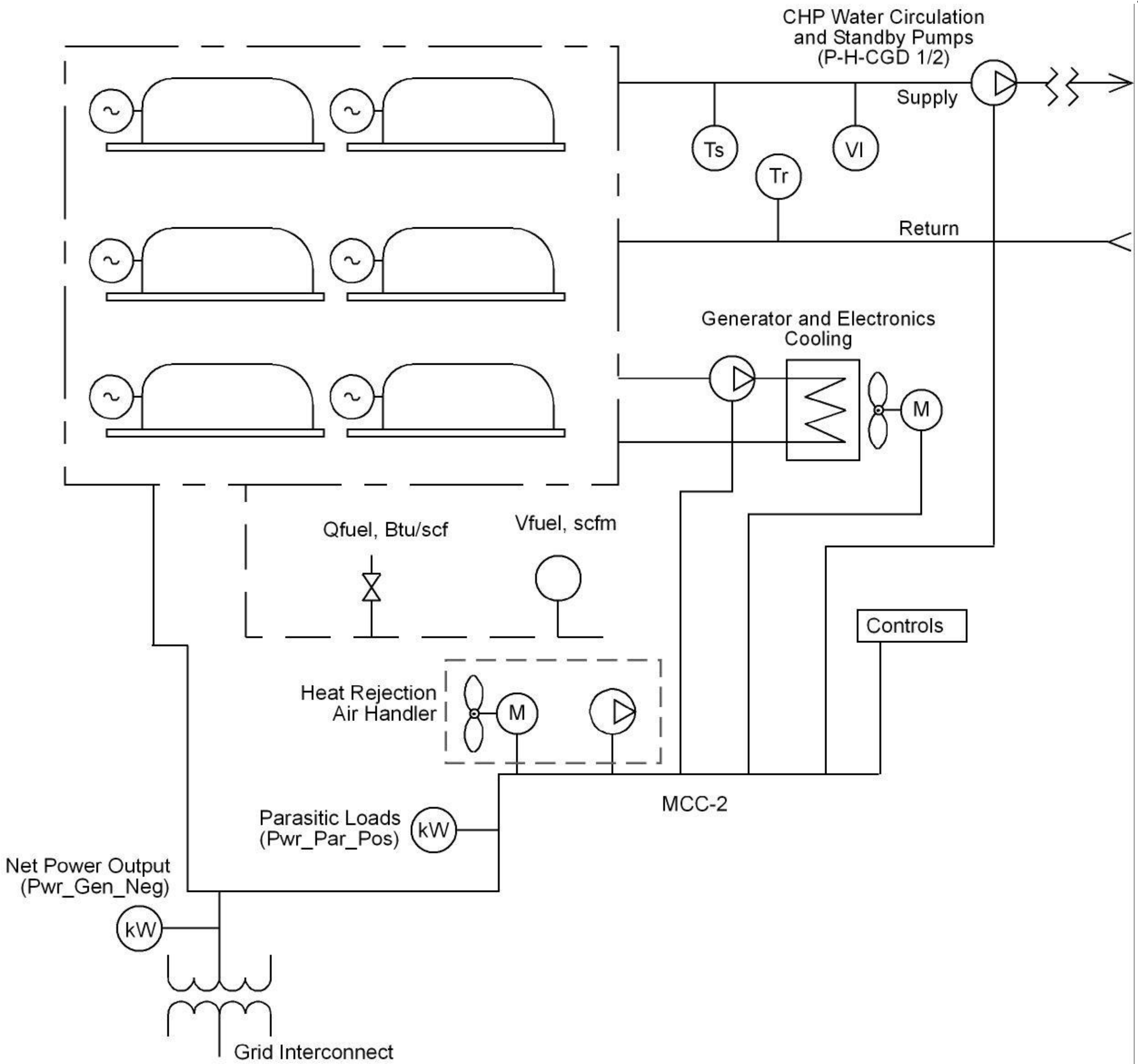


Figure 1-3. System Boundary Diagram – Extended Monitoring Period

The SUT was tested to determine performance for the following verification parameters:

- Electrical Performance
- Electrical Efficiency
- CHP Thermal Performance
- CHP Thermal Efficiency
- Atmospheric Emissions (controlled test period only).
- NO_x and CO_2 emissions reductions (offsets) relative to baseline conditions

Each of the verification parameters listed above was evaluated during the controlled or extended monitoring periods as summarized in Table 1-1. This table also specifies the dates and time periods during which the testing was conducted. Simultaneous monitoring for power output, heat recovery rate, heat input, ambient meteorological conditions, and exhaust emissions was performed during each of the controlled test periods. Fuel gas samples were collected to determine fuel lower heating value and other gas properties. Average electrical power output, heat recovery rate, energy conversion efficiency (electrical, thermal, and total), and exhaust emission rates are reported for each test period.

Table 1-1. Controlled and Extended Test Periods

Controlled Test Periods			
Start Date, Time	**End Date, Time**	**Test Condition**	**Verification Parameters Evaluated**
09/10/2009, 00:25	09/10/2009, 01:55	Power command 100 kW, three 30 minute test runs	NO_X, CO, CO_2, and THC emissions; electrical, thermal, and CHP efficiency.
09/10/2009, 02:05	09/10/2009, 03:35	Power command 75 kW, three 30 minute test runs	NO_X, CO, CO_2, and THC emissions; electrical, thermal, and CHP efficiency.
09/10/2009, 03:45	09/10/2009, 05:15	Power command 50 kW, three 30 minute test runs	NO_X, CO, CO_2, and THC emissions; electrical, thermal, and CHP efficiency.
Extended Test Period			
Start Date	**End Date**	**Test Condition**	**Verification Parameters Evaluated**
0912/2009	09/12/2010	Unit operated at normal power command	Electricity generated; electrical, thermal, and CHP efficiency; emission offsets.

The following sections identify the sections of the GVP that were followed during this verification, identify site specific instrumentation for each, and specify any exceptions or deviations from the TQAP that occurred.

1.3.1. Electrical Performance

Determination of electrical performance was conducted following §2.0 and Appendix D1.0 of the GVP. The following parameters were measured:

- net real power produced (less parasitic loads), kW
- voltage (for each phase and average of all three phases), volts (V) (controlled period only)
- current (for each phase and average of all three phases), amperes (A) (controlled period only)

Measurements of the following parameters were planned for the controlled test period, but were not obtained due to a malfunction in the data logging equipment. This is not considered to have a significant impact on data quality since the power quality is known to be acceptable for grid interconnection.

- total reactive power, KVA reactive
- total power factor, percent
- frequency, Hertz (Hz)

1.3.2. Electrical Efficiency

Determination of electrical efficiency was conducted following §3.0 and Appendix D2.0 of the GVP. The following parameters were calculated:

- net power output, kW
- fuel input, standard cubic feet per hour (scfh)
- heat input (Q_{in}), British thermal units per hour (Btu/h)
- net electrical generation efficiency ($\eta_{e,LHV}$) including external parasitic loads

Net real power production (excluding parasitic loads) was measured by the Power Measurements Ltd. Digital power meter. The power meter installation was such that power was measured after parasitic loads were taken off the circuit.

Fuel gas flow to the CHP units was measured by a Dresser brand Roots meter, model 11M175 with a specified accuracy of ± 1 percent. Three gas samples were collected and shipped to Empact Analytical of Brighton, Colorado for LHV analysis according to ASTM Method 1945.

1.3.3. CHP Thermal Performance

Determination of CHP thermal performance was conducted following §4.0 and Appendix D3.0 of the GVP. The following parameters were quantified:

- heat transfer fluid supply and return temperatures, degrees Fahrenheit (^oF),
- heat recovery fluid flow rate, gallons per minute (gpm)
- thermal performance (Q_{out}), Btu/h
- thermal efficiency ($\eta_{th,LHV}$)

To quantify these parameters, a heat recovery rate from the SUT was measured on the heat transfer loop. This represents recovered heat available for use by the facility. Recovered heat actually used by the facility was not measured as the focus of the test was on the performance of the Tecogen array independent of integration with other building systems.

An Ultrasonic Systems Model 1010 flow meter with a nominal linear range of 0 to 40 gallons per minute (gpm) was used to monitor flows during the controlled test period. The manufacturer states that accuracy of this meter is ± 1.0 % of reading. Class A 4-wire platinum RTDs were used to determine the transfer fluid supply and return temperatures. The specified accuracy of the RTDs is ± 0.6 °F. Pretest calibration checks documented the RTD performance. Following Section 4.2 of the GVP, CHP performance determinations also require heat transfer fluid density (ρ) and specific heat (c_p). These values were obtained from standard tables for water [4].

Due to a problem with the sensor mounting, the RTDs installed by SRI/CDH ceased producing reliable data after December 2009. Data were obtained from BES temperature sensors in similar locations on the supply and return lines and used for the remainder of the long term data analysis. Overlapping valid data for these sensors are available from November 17-24 2009 and compare reasonably well (average percent difference between delta_T from CDH and BES data is on the order of 10%). Long term results based on the BES sensors are considered acceptable.

1.3.4. Emissions Performance

Determination of emissions performance was conducted following §5.0 and Appendix D4.0 of the GVP and included emissions of nitrogen oxides (NO_X), carbon monoxide (CO), carbon dioxide (CO_2), and total hydrocarbons (THC). Emissions testing was performed by GHG Center personnel using a Horiba OBS-2200 PEMS. The PEMS is essentially a miniaturized laboratory analyzer bench which has been optimized for portable use. The instrument meets or exceeds Title 40 CFR 1065 requirements for in-use field testing of engine emissions.

This PEMS is suitable for testing a wide variety of stationary sources as well as the mobile sources for which it is intended. Accuracy for all analytes is better than ± 2.5 % full scale (FS), while linearity is better than ± 1.0 % FS. Exhaust gas concentrations must be integrated with exhaust gas flow rates to yield mass emission rates. The PEMS incorporates a pitot flow tube that measures exhaust flow.

Response times for all OBS-2200 analyzers are approximately two seconds alone and five seconds with the heated umbilical in the sample line. Test personnel established exact analyzer response times prior to testing. Software algorithms then align analyzer data outputs with other sensor signals, such as exhaust gas flow. Resolution depends on the analyzer range setting, but is between four and five significant digits.

The OBS-2200 measures CO and CO_2 with non-dispersive infra-red (NDIR) detectors. The OBS-2200 does not require a separate moisture removal system for the CO and CO_2 NDIR detectors. The NO_X analyzer section consists of a chemilumenescence detector with a NO_2 / NO converter. This is the kind of system specified in Title 40 CFR 60, Appendix A, Method 7E, "Determination of Nitrogen Oxides Emissions from Stationary Sources", which is a reference method for NO_X.

The OBS-2200 measures THC with a flame ionization detector (FID). This method corresponds to the system specified in Title 40 CFR 60 Appendix A, Method 25, "Determination of Total Gaseous Non-methane Organic Emissions as Carbon", which is a reference method for THC.

The PEMS sample pump conveys all samples through a heated umbilical directly to heated analyzer sections, which eliminates the need to remove moisture and eliminates possible errors in readings due to moisture scavenging.

Results for each pollutant are reported in units of parts per million volume, dry (ppm), pounds per hour (lb/h), and pounds per kilowatt-hour (lb/MWh).

1.3.5. Field Test Procedures and Site Specific Instrumentation

Field testing followed the guidelines and procedures detailed in the following sections of the GVP:

- Electrical performance - §7.1
- Electrical efficiency - §7.2
- CHP thermal performance and efficiency - §7.3
- Emissions performance - §7.4 (controlled test only)

Controlled Testing

Controlled testing was conducted from September 9-11, 2009. The verification included a series of controlled test periods on September 10, 2009 in which the GHG Center maintained steady system operations for three test periods at three loads: 100%, 75%, and 50% of capacity (100, 75, and 50 kW, respectively) on one of the six Tecogen CM 100 units. Equipment unit, Cogen 4 was selected from the six units to evaluate electrical and CHP efficiency and emissions performance. Testing took place at night so it would not interfere with normal operations of the facility. Five of the six units were shutdown during the controlled test period and temporary electrical power analyzers were installed on the Cogen 4 output bus. The analyzers recorded the electrical performance parameters at 1-minute intervals. Water serves as the CHP heat transfer fluid. Southern installed supply and return temperature sensors and an ultrasonic fluid flow meter to capture the heat recovery data. The host site has a paddlewheel flow sensor on this heat recovery loop that was not functioning during the controlled test period.

Emissions data were recorded from Cogen 4 exhaust stack on the roof of the mechanical room. The Horiba OBS-2200 PEMS (Portable Emissions Monitoring System) was installed on the exhaust stack to measure atmospheric emissions including, THC, CO, CO_2, and NO_x. Other parameters including exhaust flow, exhaust temperature, exhaust pressure, ambient temperature, and ambient pressure were also collected from the OBS-2200 real time at 1s/ps (sample per second). Gas consumption was determined by a datalogger connected to a revenue-grade gas meter. Southern installed a Dresser brand Roots meter, model 11M175, in the CHP array gas line. The meter incorporates a high-frequency pulse output for flow rate determinations. Test personnel connected the meter output to the datalogger and recorded the gas flow rate at least once per minute during all test periods. Testing personnel also installed ports for collecting natural gas fuel samples for lower heating value (LHV) analysis. Figure 1-1 illustrates the monitoring configuration for the controlled test period.

Long-term Monitoring

The controlled tests were followed by a 1 year period of continuous monitoring to determine heat recovery and power output, electrical and thermal efficiency, and estimated annual emission reductions on the full array of six

CHP units during normal facility operations. Long term measurements consisted of net real power output, fuel consumption, and heat recovery rate. Thermal and electrical efficiency was determined from these measurements.

For the long term monitoring, a paddlewheel type flow meter was used to measure the heat recovery loop flow rate and Wattnode power meters were used to measure gross and net power production. Data from the system's thermistor type temperature sensors was used after the RTDs installed for the controlled test stopped functioning. Specifications for instruments used during the controlled and extended tests is summarized in Table 1-2.

Table 1-2. Site Specific Instrumentation for BOCES DG/CHP System Verification

Verification Parameter	Supporting Measurement	Actual Range of Measurement	Instrument	Instrument Range	Instrument Accuracy
Electrical Performance	Real power (gross)[1]	45 – 100 kW	Power Measurements Ltd. ION power meter (Model 7500)	0 – 260 kW	± 0.1% of reading
	Voltage[1]	275.0 – 282.0 V		0 – 600 V	± 0.1% of reading
	Current[1]	56 – 121 A		0 – 400 A	± 0.1% of reading
	Real Power (net)[3]	41 - 94 kW	WattNode WNB-3Y-480	800A CT	± 1.0% of reading
	Real Power (parasitic)[3]	3.8-8.5 kW	WattNode WNB-3Y-480	50A CT	± 1.0% of reading
Electrical and Thermal Efficiency	Fuel gas flow[1]	630 – 1320 cfh	Model 5M175 Roots Meter	0 – 10000 cfh	± 1% of reading
	Fuel gas flow[2]	0 - 7800 cfh	Model 5M175 Roots Meter	0 – 10000 cfh	± 1% of reading
CHP Thermal Performance	Heat transfer loop flow[1]	8-24 gpm	Ultrasonic Systems Model 1010 flow meter	0 –100 gpm	± 1.0% of reading
	Heat transfer loop flow[2]	0-170 gpm	Onicon F1110 Turbine Flowmeter	8-800 gpm (4 inch pipe)	± 1.0% of reading
	Heat transfer supply temp.[3]	178.0 – 209.0 °F	Class A 4-wire RTD	0 – 250 °F	± 0.3 °F
	Heat transfer return temp.[3]	131.0 – 178.0 °F	Class A 4-wire RTD	0 – 250 °F	± 0.3 °F
	Heat transfer supply temp. (BES)[2]	0 – 240 °F	Alerton Uni-curve Type II Thermistor	0 – 250 °F	± 0.5 °F
	Heat transfer return temp. (BES)[2]	0 – 200 °F	Alerton Uni-curve Type II Thermistor	0 – 250 °F	± 0.5 °F
Emissions Performance (controlled test only)	NO_X concentration	0 – 1650 ppmv	Chemiluminescence, Horiba OBS-2200	0 – 3000 ppmv	± 2% FS
	CO concentration	0 – .05%	NDIR, Horiba OBS-2200	0 – 5%	± 2% FS
	CO_2 concentration	7 - 11%	NDIR, Horiba OBS-2200	0 – 16 %	± 2% FS
	THC concentration	0 – 505 ppmv	FID, Horiba OBS-2200	0 – 10000 ppmv	± 2% FS
	Ambient temperature	55.0 – 59.0 °F	Horiba OBS-2200	-40 – 185 °F	± 0.3 °F
	Barometric pressure	14.6 – 14.6 psia	Horiba OBS-2200	0 – 17 psia	± 1.5% FS

Notes: [1]controlled test only, [2]extended test only, [3]controlled and extended test

1.3.6. Estimated NO_X and CO_2 Offset Emission Reductions

Use of the Tecogen Cogen units changes the NO_x and CO_2 emission rates associated with the operation of the BOCES facility. Annual emission offsets for these pollutants are estimated and reported by subtracting emissions of the on-site DG-CHP unit from emissions associated with baseline electrical power generation technology and baseline space heating equipment (five, natural gas fired boilers rated at 1.94 MMBtu/hr each).

Electricity Offset

The annual electricity production from the Tecogen array of six units was determined from average net power production in the long term data set. NO_x and CO_2 emissions measured from the controlled test period (at 100% load), in which only one of the six units was running, were increased in proportion to the ratio of average power output between the long term and controlled test periods to get a representative estimate of emissions for normal operation. Tecogen emissions were then compared with utility emissions for New York State and Nationwide to obtain the emissions reduction corresponding with offset of grid power that would otherwise be consumed. These emission factors were obtained from the most recent available EPA eGrid database (2007) [5].

Heat Recovery Offset

To obtain NOx emissions reductions associated with heat recovery, emission factors for NO_x and CO_2 were obtained for small natural gas fired boilers (< 100 MMBtu/hr) from EPA's AP42 Table 1.4-1 (7/98). The factor for NOx is 100 lb/MMscf (the BOCES boilers do not have NO_x control). The factor for CO2 is 120,000 lb/MMscf. Using a heating value of 1020 Btu/scf for natural gas results in emission factors of 0.1 lb/MMBtu for NO_x and 117.6 lb/MMBtu for CO_2. These emission factors were then applied to the average heat recovery for the Tecogen Cogen array during the long term monitoring period to obtain annual emissions associated with the proportion of baseline boiler operation offset by heat recovered from the Cogen array. This assumes that all of the heat recovered from the Tecogen CHP array is utilized at BOCES. This is a reasonable assumption since the average heat recovered from the CHP array during normal operations (approx. 3 MMBtu/hr) is only 1.5 times higher than the output rating of one of BOCES's five boilers (approx. 2 MMBtu/hr). The facility is easily capable of using all of the recovered heat.

2.0 VERIFICATION RESULTS

Test results are presented in the following subsections:

Section 2.1 – Electrical and Thermal Performance and Efficiency
Section 2.2 – Power Quality Performance
Section 2.3 – Emissions Performance
Section 2.4 – Emissions Reductions

2.1. ELECTRICAL AND THERMAL PERFORMANCE AND EFFICIENCY

2.1.1. Controlled Test Results

The heat and power production performance evaluation included electrical power output, heat recovery, and CHP efficiency determinations during controlled test periods. Following the test runs, analysts reviewed the data and determined that all test runs were valid by meeting the following criteria:

- 100 percent of the one-minute average power meter data were logged
- data and log forms that show SUT operations conformed to the permissible variations throughout the run (refer to Table 2-1)
- ambient temperature and pressure readings were recorded at the beginning and end of the run
- field data log forms were completed and signed
- records demonstrate that all equipment met the allowable QA/QC criteria

Based on ASME PTC-17, the GVP-specified guidelines state that efficiency determinations were to be performed within 60 minute test periods in which maximum variability in key operational parameters did not exceed specified levels. Though the generic protocol recommends 1-hour test runs for internal combustion engines and 30-minute test runs for microturbines, Southern has found that 30-minute test runs provide stable data with narrow confidence intervals for both types of power plants. Therefore the controlled testing periods were planned to consist of three (3) test runs, each 30 minutes long, at each power level (100kW, 75kW, and 50kW). The actual test runs were somewhat shorter than planned (see section 3.1); however sufficient data were collected to characterize emissions under each load condition.

Table 2-1 summarizes the maximum permissible variations observed in power output, ambient temperature, and ambient pressure for each test run. The table shows that the PTC-17/GVP requirements for these parameters were met for all test runs. Table 2-2 summarizes the ambient conditions during the controlled load tests.

Table 2-1. Variability in Operating Conditions During Controlled Test Periods

		Maximum Observed Variation in Measured Parameters		
		Power Output (% difference)[a]	Ambient Temp. (°F)	Ambient Pressure (% difference)[a]
Maximum Allowable Variation		**± 2 %**	**± 4 °F**	**± 0.5 %**
100kW	Run 1	-1.0	0.3	0.02
	Run 2	-1.7	0.3	0.03
	Run 3	-1.8	0.3	0.04
75 kW	Run 1	-1.0	0.2	0.06
	Run 2	0.4	0.4	0.07
	Run 3	-0.6	0.3	0.08
50 kW	Run 1	-1.4	0.2	0.10
	Run 2	-1.8	0.3	0.10
	Run 3	1.1	0.2	0.12

[a] (Maximum – Minimum Value) / Average Value for Test Run * 100

Table 2-2. BOCES DG/CHP System Ambient Conditions during Controlled Tests

Test ID		Run Average Temp (°F)	Run Average Pbar (psia)
100 kW	Run 1	59.6	14.6
	Run 2	59.0	14.6
	Run 3	58.6	14.6
	Avg.		
75 kW	Run 1	**59.1**	**14.6**
	Run 2	57.6	14.6
	Run 3	57.2	14.6
	Avg.	56.6	14.6
50 kW	Run 1		
	Run 2	**57.1**	**14.6**
	Run 3	56.0	14.6
	Avg.	55.6	14.6

Gross and net electrical performance and efficiency as measured during the controlled test period are presented in Table 2-3. Net electrical performance is exclusive of power consumed by CHP system electrical loads required for system operation (parasitic loads). Parasitic loads are disproportionally high during the controlled test period when only one unit is operating as compared to normal operations when up to six cogeneration units may be operating. Parasitic loads during the controlled test period averaged about 7 percent of gross power output, whereas during the long term monitoring, parasitic loads averaged only 2-4 percent of gross power output (depending on load conditions). Uncertainties given in table 1 were determined by measurement error propagation as detailed in Section 7 of the GVP. The heat input determinations corresponding to the controlled test results are summarized in Table 2-4.

Thermal performance as measured during the controlled test period is not reported. The thermal performance measurements are not considered representative for several reasons. The heat recovery fluid flow measurement is not considered reliable because the flow velocities with only a single unit operating were at or below the velocity at which the instrument accuracy rapidly deteriorates. Heat losses with only a single unit operating are disproportionately high compared to normal operations with up to six units operating. System controls, which seek to maintain the return temperature to the cogeneration array at a constant level, did not appear to be able to operate as intended with only a single unit operating, resulting in cycling of flow rate and return temperature. A detailed assessment of these factors is provided in section 3.2.3 below.

Table 2-3. Controlled Test Electrical and Thermal Performance

Test ID		Heat Input (MMBtu/h)	Electrical Power Generation Performance			
			Net Power Generated (kW)	Net Electrical Efficiency (%)	Gross Power Generated (kW)	Gross Electrical Efficiency (%)
100 kW	Run 1	1.18	91.8	26.5	98.0	28.3
	Run 2	1.17	91.2	26.6	97.3	28.4
	Run 3	1.17	91.4	26.6	97.7	28.4
	Avg.	**1.18**	**91.5**	**26.6**	**97.7**	**28.4**
	+/-	**1.8%**	**0.7%**	**3.0%**	**0.7%**	**3.0%**
75 kW	Run 1	0.85	66.2	26.5	72.3	28.9
	Run 2	0.85	66.1	26.4	72.3	28.9
	Run 3	0.86	66.5	26.4	72.6	28.8
	Avg.	**0.86**	**66.3**	**26.4**	**72.4**	**28.9**
	+/-	**1.8%**	**0.7%**	**3.0%**	**0.7%**	**3.0%**
50 kW	Run 1	0.57	41.6	24.7	47.3	28.1
	Run 2	0.57	41.4	24.6	47.2	28.0
	Run 3	0.58	42.8	25.2	47.5	28.0
	Avg.	**0.58**	**41.9**	**24.8**	**47.3**	**28.0**
	+/-	**1.8%**	**0.7%**	**3.0%**	**0.7%**	**3.0%**

Reported uncertainties by measurement error propagation per GVP in percentage of reported value. Net electrical performance is exclusive of electrical loads required for system operation (parasitic loads). Parasitic loads are disproportionately high during the controlled test conditions as described above.

Table 2-4. Heat Input Determinations

Test ID		Fuel Input		
		Heat Input (Btu/h)	Gas Flow Rate (scfh)	LHV (Btu/scf)
	Run 1	1.2E+06	1303	
	Run 2	1.2E+06	1294	
	Run 3	1.2E+06	1295	
100 kW	**Avg.**	**1.2E+06**	**1297**	**905.5**
	Run 1	8.5E+05	943	
	Run 2	8.5E+05	943	
	Run 3	8.6E+05	949	
75 kW	**Avg.**	**8.6E+05**	**945**	**905.5**
	Run 1	5.7E+05	635	
	Run 2	5.7E+05	635	
	Run 3	5.8E+05	639	
50 kW	**Avg.**	**5.8E+05**	**636**	**905.5**

[a] Reported LHV is the average of three fuel gas samples collected on September 10, 2007

2.1.2. Long Term Test Results

Measurements necessary to determine electrical and thermal performance and efficiency were collected over a period from September 2009 through September 2010. The heat recovery measurements account for heat made available for facility operations, but do not reflect recovered heat energy actually used at the facility. However, since the average heat recovered from the CHP array during full load operations (approx. 3 MMBtu/hr) is only 1.5 times higher than the output rating of one of BOCES's five boilers (approx. 2 MMBtu/hr), the facility is easily capable of using all of the recovered heat.

Table 2-6 provides a summary of the results. During normal operations at the BOCES facility, the cogeneration array operates in response to electrical demand. As such, the array typically operates at nearly full load during weekdays, with partial load at nights and on weekends. Full load conditions are characterized by power generation rates over 300kW, and night/weekend conditions are characterized by generation rates less than 300 kW. The cogeneration array operated nearly continuously throughout the year of monitoring, with only one brief period of down time (43 hours) in late June 2010.

Table 2-5. Extended Test Results Summary

	Average *Net* Power Output (kW)	+/-	Average Heat Recovery (MMBtu/hr)	+/-	Average Thermal Efficiency (%)	+/-	Average *Net* Electrical Efficiency (%)	+/-	Average Total Efficiency (%)	+/-
Annual Average	293	0.7%	2.26	4.4%	53.7	4.9%	23.5	3.0%	77.2	3.5%
Full Load - (Weekday) (>=300kW)	394	0.7%	2.98	4.4%	60.4	4.9%	25.8	3.0%	86.2	3.5%
Partial Load - (Night) (<300kW)	211	0.7%	1.68	4.4%	48.2	4.9%	21.3	3.0%	69.5	3.5%

Reported uncertainties by measurement error propagation per GVP.

Gross electrical efficiency during the extended test was 24.1 percent on an annual basis, 26.4 percent at full load conditions, and 22 percent at partial load conditions. Parasitic loads accounted for 2 to 4 percent of power production depending on load conditions. As can be seen in Table 3, the electrical and thermal efficiency of the system is somewhat lower at partial load than at full load. The lower thermal efficiency at partial load may be due to system heat losses - which amount to a greater proportion of the total heat recovered at partial load than at full load.

The lower electrical efficiency at partial load is not fully explained by the data. However, at the very lowest loads (occurring during weekend daytimes), fuel consumption was consistently observed to increase as power output decreased. This could be due to the cogeneration array running in an inefficient operating range at the lowest load conditions. During the controlled tests with only one of six units operating, electrical efficiency decreased slightly at the 50 percent load condition, but not as much as was observed during extended monitoring of the full cogeneration array.

2.2. POWER QUALITY PERFORMANCE

Power quality measurements planned for the controlled test period included frequency, power factor, and voltage and current THD. During the controlled testing, a data logger malfunction corrupted the power quality data from the power meter, so these data were not obtained. This is not considered to have a significant impact on the verification, as power quality is proven to be acceptable for grid interconnection and use at the BOCES facility. A utility will not allow grid interconnection if the power supplied is not of acceptable quality.

2.3. EMISSIONS PERFORMANCE

2.3.1. Emissions Test Results

Stack emission measurements were conducted during each of the controlled test periods in accordance with the methods described above. Following the GVP, the SUT was maintained in a stable mode of operation during each load condition based on PTC-17 variability criteria. Results are summarized in Table 2-6. Emissions results are reported in units of parts per million volume for CO, CO_2, THC, and NO_X. Measured pollutant concentration data were converted to mass emission rates using EPA Method 19 and are reported in units of pounds per hour (lb/h). The emission rates are also reported in units of pounds per kilowatt hour electrical output (lb/kWh). They were computed by dividing the mass emission rate by the electrical power generated during each test run.

Table 2-6. Tecogen Emissions During Controlled Test Periods

Test ID		Gross Power (kW)	CO Emissions			CO2 Emissions		
			ppm	**lb/hr**	**lb/MWh**	**Volume %**	**lb/hr**	**lb/MWh**
100kW	Run 1	98	175	0.17	1.8	9.3	91	930
	Run 2	97	162	0.16	1.6	9.2	90	927
	Run 3	98	168	0.16	1.7	9.2	91	928
	Avg.	**98**	**168**	**0.17**	**1.7**	**9.2**	**91**	**928**
	95% CI		**1.7%**			**0.02%**		
75 kW	Run 1	72	44	0.04	0.5	9.1	80	1113
	Run 2	72	81	0.08	1.1	9.1	85	1182
	Run 3	73	96	0.09	1.2	9.1	86	1180
	Avg.	**72**	**74**	**0.07**	**0.9**	**9.1**	**84**	**1158**
	95% CI		**5.3%**			**0.06%**		
50 kW	Run 1	47	not reported*	0.06	1.4	9.2	52	1095
	Run 2	47	not reported*	0.08	1.7	9.2	59	1250
	Run 3	48	not reported*	0.09	1.8	9.2	63	1328
	Avg.	**47**		**0.08**	**1.6**	**9.2**	**58**	**1224**
	95% CI					**0.07%**		
Test ID		**Gross Power (kW)**	**THC Emissions**			**NOx Emissions**		
			ppm	**lb/hr**	**lb/MWh**	**ppm**	**lb/hr**	**lb/MWh**
100kW	Run 1	98	5.7	0.006	0.06	12.8	0.013	0.1
	Run 2	97	4.8	0.005	0.05	12.9	0.013	0.1
	Run 3	98	4.9	0.005	0.05	13.1	0.013	0.1
	Avg.	**98**	**5.1**	**0.005**	**0.05**	**12.9**	**0.013**	**0.1**
	95% CI		**1.2%**			**2.5%**		
75 kW	Run 1	72	8.8	0.008	0.11	8.4	0.007	0.1
	Run 2	72	8.5	0.008	0.11	8.3	0.008	0.1
	Run 3	73	8.7	0.008	0.11	7.8	0.007	0.1
	Avg.	**72**	**5.8**	**0.008**	**0.11**	**5.6**	**0.008**	**0.1**
	95% CI		**2.3%**			**4.0%**		
50 kW	Run 1	47	273	0.154	3.2	843	0.475	10.0
	Run 2	47	288	0.185	3.9	881	0.567	12.0
	Run 3	48	292	0.201	4.2	881	0.608	12.8
	Avg.	**47**	**284**	**0.180**	**3.8**	**869**	**0.550**	**11.6**
	95% CI		**1.5%**			**1.6%**		

*Carbon monoxide results for the 50 percent load condition are not reported because the instrument failed the span drift check at the conclusion of the testing at this condition and the results appeared suspect upon examination (concentrations during the run were frequently recorded as negative values).

THC and NO_x emissions at the 50kW load condition are elevated. This is due to poor engine performance at partial load – an abnormal operating condition. In normal operations, the units are run at greater than 60 percent load and individual units are taken on and off line in response to facility electrical demand.

Uncertainties given in this table were determined by calculating a 95 percent confidence interval over the mean of all three runs at each load condition. The higher uncertainty for CO emissions at the 75kW load condition is due to a a greater degree of fluctuation in CO concentration observed at the lower load conditions.

2.4. ESTIMATION OF ANNUAL NO_X AND CO_2 EMISSION REDUCTIONS

The approach for estimating the annual emission reductions that may result from use of the Tecogen CHP units at this facility was outlined above (section 1.3.6). The Tecogen emissions were compared to both the New York State and national power system average emissions as published in EPA's eGRID database. The results of this analysis are given in Table 2-7 below.

Table 2-7. Estimation of Emission Reductions at BOCES

Regional Power System Scenarios	Annual SUT Emissions[a] (tpy)		Baseline Case Annual Emissions (tpy)						Estimated Annual Emission Reductions (tpy)	
			Avoided Grid Emissions[b]		Boiler Emissions Offset[c]		Total Baseline Emissions			
	NO_X	CO_2	NO_X	CO_2	NO_X	CO_2	NO_X	CO_2	NO_X	CO_2
New York State	0.1554	1121	1.07	1000	0.92	1104	1.99	2103	1.83	983
National	0.1554	1121	2.34	1604	0.92	1104	3.26	2708	3.10	1588

[a] Based on the SUT's performance during the verification period, an expected availability of 95 percent, and the average measured power output for the full cogen array.

[b] From eGRID 2007

[c] From AP42 Table 1.4-1

3.0 DATA QUALITY ASSESSMENT

During the unusually long period of time between approval of the TQAP for this verification and commencement of field work, a number of minor changes to the test plan became necessary due to personnel and instrumentation changes. These changes were documented in a memorandum dated 9/7 2009, before the beginning of field measurement activity. The impact on data quality of all of the changes is assessed in this memorandum. None of the changes were found to have any negative effect on data quality.

3.1. DATA QUALITY OBJECTIVES

Under the ETV program, the GHG Center specifies DQOs for each verification parameter before testing commences as a statement of data quality. The DQOs for this verification were developed based on past DG/CHP verifications conducted by the GHG Center, input from EPA's ETV QA reviewers, and input from both the GHG Centers' executive stakeholders groups and industry advisory committees. As such, test results meeting the DQOs will provide an acceptable level of data quality for technology users and decision makers. The DQOs for electrical and CHP performance are quantitative, as determined using a series of measurement quality objectives (MQOs) for each of the measurements that contribute to the parameter determination:

Verification Parameter	DQO (relative uncertainty)
Electrical Performance	±0.7 %
Electrical Efficiency	±3.0 %
CHP Thermal Efficiency	±4.9 %

Each test measurement that contributes to the determination of a verification parameter has stated MQOs, which, if met, demonstrate achievement of that parameter's DQO. This verification is based on the GVP which contains MQOs including instrument calibrations, QA/QC specifications, and QC checks for each measurement used to support the verification parameters being evaluated. Details regarding the measurement MQOs are provided in the following sections of the GVP:

§ 8.1 Electrical Performance Data Validation
§ 8.2 Electrical Efficiency Data Validation
§ 8.3 CHP Performance Data Validation

The DQO for emissions is qualitative in that the verification will produce emission rate data that satisfies the QC requirements contained in the EPA Reference Methods specified for each pollutant. Details regarding the measurement MQOs for emissions are provided in the following section of the GVP:

§ 8.4 Emissions Data Validation

Controlled Test Data Capture
Completeness goals for this verification were to obtain valid data for 90 percent of the test periods (controlled test period and extended monitoring).

For the controlled test period, three 30-minute test runs were planned at each load condition, or a total of 90 minutes data collection at each load condition. Due to time constraints imposed by site operations (the testing had to be completed at night), this goal was revised in the field as 60 minutes data collection at each load condition. A total of 59 minutes data were collected at both the 100kW and 75kW loads. The 50kW load test was cut short at 39 minutes as normal facility operations were due to re-start. Thus, the completeness goal for controlled test data collection was not met. However, examination of the data clearly shows that sufficient emissions and electrical and thermal efficiency results were obtained at each load condition to adequately characterize operations. Therefore, the impact on data quality of this goal not being met is considered insignificant.

Some of the emissions measurements were not recorded by the PEMS, or were deemed invalid upon inspection of the data and QC checks. For the 100kW runs, only 64% of the THC data were valid. For the 75kW runs, only 46% of the CO data, 62% of the THC data and 80% of the NOx data were valid. For the 50kW runs, only 22% of the CO data were valid. All other data met the 90% valid data capture goal. Careful examination of the data shows that sufficient data were captured to adequately characterize emissions at each load condition, except that the average CO results for the 50kW runs cannot be considered fully representative as negative values were recorded and the analyzer failed a drift check at the conclusion of the run. The impact on overall data quality of this is small, however, since CHP unit operations at the 50kW load condition are not representative of normal operations.

Long Term Test Data Capture

The RTDs installed on the supply and return sides of the CHP heat recovery loop for long term monitoring proved unreliable and failed to provide useful data after the end of November 2009. Valid data were obtained from these sensors for approximately two months from 9/23/2009-11/25/2009 excepting a period from 11/2-13/2009. To address this, Southern obtained supply and return temperature and flow data from the BES building management system that was archived commencing on 11/7/2009 and extending through 9/30/2010. The BES data were examined and compared with an overlapping period of Southern's data from November 17-24 2009 and compare reasonably well (average percent difference between delta_T from CDH and BES data is on the order of 10%). Long term results based on the BES sensors are considered acceptable. Thus, valid long term thermal efficiency data were obtained for the period from 9/23/2009 through 9/20/2010. Power output and fuel consumption data collection ceased on 8/31/2010. Thus, valid electrical efficiency data were collected starting 9/10/2009 and extending through 8/31/2010.

3.2. DOCUMENTATION OF MEASUREMENT QUALITY OBJECTIVES

The field team leader reviewed collected data for reasonableness and completeness while in the field. The field team leader also reviewed data from each of the controlled test periods to verify that variability criteria specified below (see Table 2-1) were met. The emissions testing data were validated by reviewing instrument and system calibration data and ensuring that those and other reference method criteria were met. Calibrations for fuel flow, pressure, temperature, electrical and thermal power output, and ambient monitoring instrumentation were reviewed on site to validate instrument functionality. Other data such as fuel LHV analysis results were reviewed, verified, and validated after testing had ended. All collected data was classified as either valid, suspect, or invalid upon review, using the QA/QC criteria specified in the TQAP. Review criteria are in the form of factory and on-site calibrations, maximum calibration and other errors, audit gas analyses, and lab repeatability. Results presented here are based on measurements which met the specified data quality objectives (DQOs) and QC checks, and were validated by the GHG Center.

3.2.1. Electrical Generation Performance

Table 3-1 summarizes the MQOs for electrical generation performance.

Table 3-1. Electrical Generation Performance MQOs

Measurement	QA/QC Check	When Performed	Allowable Result	Result Achieved
kW, kVA, kVAR, PF, I, V, f(Hz), THD	Power meter National Institute of Standards and Technology (NIST) traceable calibration	18-month period	± 2.0%	Meets spec.
	CT documentation	At purchase	ANSI Metering Class 0.3%; ± 1.0% to 360 Hz (6^{th} harmonic)	Meets spec.
V, I	Sensor function checks	Beginning of load tests	V: ± 2% I: ± 3%	Meets spec.
	Power meter crosschecks	Before field testing	± 0.1% differential between meters	Meets spec.
Ambient temperature	NIST-traceable calibration	18-month period	± 1 ^oF	Meets spec.
	Ice and hot water bath crosschecks	Before and after field testing	Ice water: ± 0.6 ^oF Hot water: ± 1.2 ^oF	Meets spec.
Barometric pressure	NIST-traceable calibration	18-month period	± 0.1 "Hg or ± 0.05 psia	Meets spec.

All of the MQOs met the performance criteria. Following the GVP, the MQO criteria demonstrate that the DQO of ±1% relative uncertainty for electrical performance was met.

3.2.2. Electrical Efficiency Performance

Table 3-2 summarizes the MQOs for electrical efficiency performance.

Table 3-2. Electrical Efficiency MQOs

Measurement	QA/QC Check	When Performed	Allowable Result	Result Achieved
Gas meter	NIST-traceable calibration	18-month period	± 1.0% of reading	meets spec.
	Differential pressure check	Prior to testing	< 0.1"	Meets spec.
Gas pressure	NIST-traceable calibration	18-month period	± 0.5% of FS	Meets spec.
	Crosscheck with ambient pressure sensor	Before and after field testing	± 0.08 psia differential between sensors	Meets spec.
Gas temperature	NIST-traceable calibration	18-month period	± 1.0% of FS	Meets spec.
	Ice and hot water bath crosschecks	Before field testing	Ice water: ± 0.6 °F Hot water: ± 1.2 °F	Meets spec.
Fuel Gas LHV	NIST-traceable standard gas calibration	Weekly	± 1.0 % of reading	Meets spec.
	ASTM D1945 duplicate sample analysis and repeatability	Each sample	Within D1945 repeatability limits for each gas component	Meets spec.

Following the GVP, the MQO criteria in Tables 3-1 and 3-2 demonstrate that the DQO of ±3.0 % relative uncertainty for electrical efficiency was met.

3.2.3. CHP Thermal Efficiency Performance

Table 3-3 summarizes the MQOs for CHP thermal efficiency performance.

Table 3-3. CHP Thermal Efficiency MQOs

Description	QA/QC Check	When Performed	Allowable Result	Result Achieved
Flow	Sensor function checks	At installation	Passes mfg. function checks and sensor to data loop check	Meets spec.
T_{supply} and T_{return} sensors	NIST-traceable calibration	18-month period	± 0.6 °F between 100 and 210 °F	Meets spec.
	Ice and hot water bath crosschecks	Before field testing	Ice water: ± 0.6 °F Hot water: ± 1.2 °F	Meets spec.

All of the MQOs met the performance criteria. Following the GVP, the MQO criteria in Tables 3-1, 3-2, and 3-3 demonstrate that the DQO of ±4.9 % relative uncertainty for CHP thermal efficiency was met.

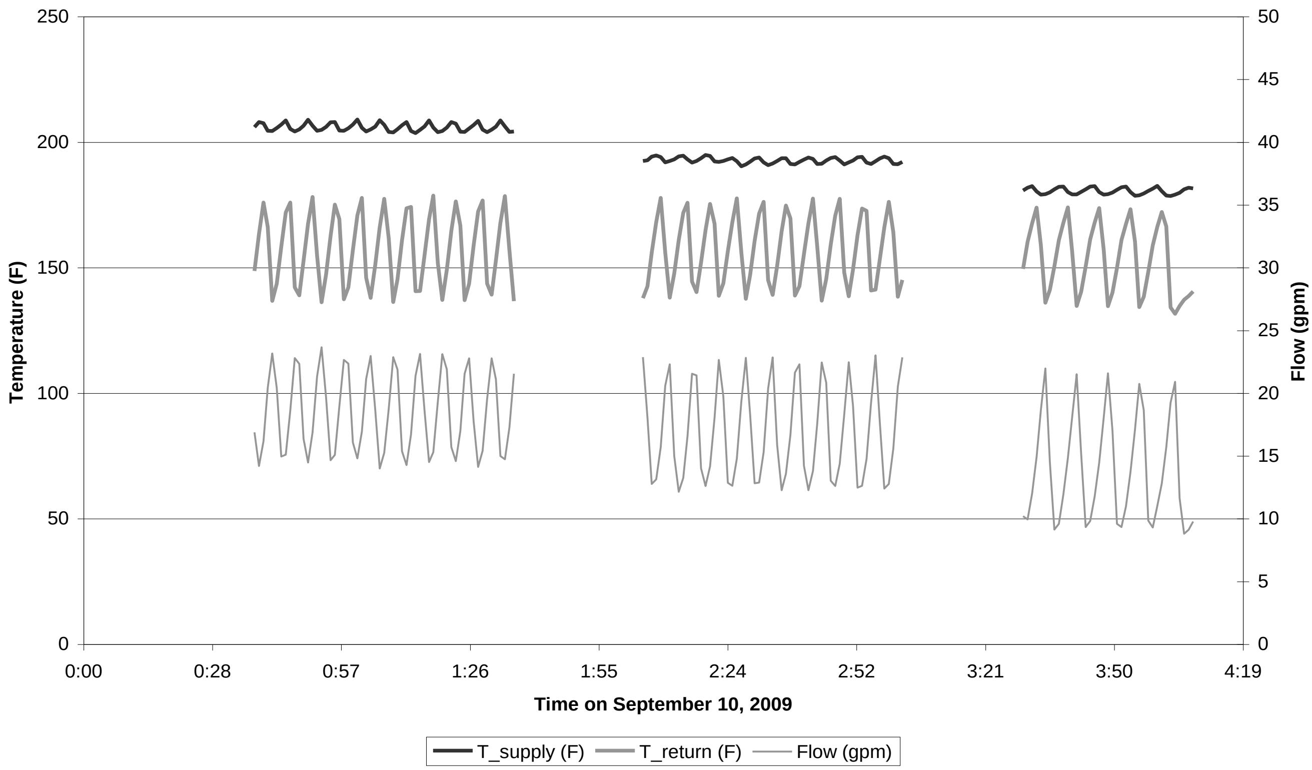
The thermal performance measurements for the controlled test period are not considered representative for several reasons and are not reported. An assessment of the results and test configuration leading to this conclusion is given in the following paragraphs.

The heat recovery fluid flow measurement is not considered reliable because the flow velocities with only a single unit operating were at or below the velocity at which the instrument accuracy rapidly deteriorates. The fluid velocity at the nominal flow rate with only a single unit operating (40 gpm in a 4 inch pipe) is about 1 foot per second. This is at the lower limit at which the Controlatron ultrasonic meter used during the controlled tests may be considered to provide acceptably accurate results. At velocities lower that 1 foot per second, the accuracy of the instrument deteriorates rapidly.

System controls, which seek to maintain the return temperature to the cogeneration array at a constant level, did not appear to be able to operate as intended with only a single unit operating, resulting in cycling of flow rate and return temperature. This is illustrated in Figure 2-1. The cause of this cycling has been exhaustively investigated but cannot be determined with certainty from the data available. Data from the building management system was sought in an attempt to determine cause, but was not available. Building data archives started in November 2009.

The system controls seek to keep the return temperature constant. It is hypothesized that at the low heat recovery fluid flows associated with operation of only one of the six CHP units, the controls were not able to stabilize the return temperature, resulting in the cyclic behavior observed.

Figure 3-1: Periodic Variation in Controlled Test Heat Recovery Data



Finally, heat losses with only a single unit operating are disproportionately high compared to normal operations with up to six units operating.

3.2.4. Emissions Measurement MQOs

Sampling system QA/QC checks were conducted in accordance with GVP and TQAP specifications to ensure the collection of adequate and accurate emissions data. The reference methods specify detailed sampling methods, apparatus, calibrations, and data quality checks. The procedures ensure the quantification of run-specific instrument and sampling errors and that runs are repeated if the specific performance goals are not met. Table 3-4 summarizes relevant QA/QC procedures.

Table 3-4. Summary of Emissions Testing Calibrations and QA/QC Checks

Description	QA/QC Check	When Performed	Allowable Result	Result Achieved
CO, CO_2, O_2	System zero drift test	After each test run	± 2% of analyzer span	All calibrations, system bias checks, and drift tests were within the allowable criteria except that the CO measurement failed the span drift check for the 50 percent load condition.
	System span drift test	After each test run	± 4% of analyzer span	
NO_x	System zero drift test	After each test run	± 2% of analyzer span	All criteria were met for the NO_X measurement system.
	System span drift test	After each test run	± 4% of analyzer span	
THC	System zero drift test	After each test run	± 2% of analyzer span	All criteria were met for the THC measurement system.
	System span drift test	After each test run	± 4% of analyzer span	
Ambient temperature	Temperature within allowable range	After each test run	Within ± 10°F	Within the allowable criteria
Barometric pressure	Barometric pressure within allowable range	After each test run	Within ± 1" Hg	Within the allowable criteria

Satisfaction and documentation of each of the calibrations and QC checks verified the accuracy and integrity of the measurements and that reference method criteria were met for each of the parameters.

3.3. AUDITS

An independent Technical Systems Audit was conducted during the controlled test period on September 10, 2009 by David A. Gratson of Neptune and Company, Inc. and Robert S. Wright, Quality Assurance Manager, Air Pollution Prevention and Control Division, NRMRL EPA. An audit report was received September 15, 2009. The auditors main findings were (1) that the ultrasonic flow meter used during the controlled tests may not give reliable readings due to low flow and possible lack of turbulence and (2) that the heat transfer fluid samples showed some discoloration and may not have been solely water. Examination of the data showed that the lowest heat recovery fluid velocities recorded were near the low end of the ultrasonic meter's range. Based on this, and other factors, thermal efficiency was not reported for the controlled test (see section 3.2.3). Southern confirmed with BES that the heat recovery fluid is water.

Southern's QA manager also conducted an audit of data quality. This consisted of verifying computations and traceability from the raw data collected through final results reported and verifying that all required QA/QC checks were conducted and documented. The audit found the results to be of acceptable quality.

4.0 REFERENCES

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