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Condensing Boiler Assessment: Peachtree Summit Federal Building Atlanta, Georgia

S.A. Parker

J. Blanchard

The Green Proving Ground program leverages GSA's real estate portfolio to evaluate innovative sustainable building technologies and practices. Findings are used to support the development of GSA performance specifications and inform decision-making within GSA, other federal agencies, and the real estate industry. The program aims to drive innovation in environmental performance in federal buildings and help lead market transformation through deployment of new technologies.

DISCLAIMER

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For more information contact:

Kevin Powell
Program Manager
Green Proving Ground
Office of the Commissioner
Public Buildings Service
U.S. General Services Administration
555 Battery Street, Room 518
San Francisco, CA 94708
Email: kevin.powell@gsa.gov

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I. Executive Summary

This report is divided into five sections. The first section describes the background and opportunity for condensing boilers to reduce energy consumption by the U.S. General Services Administration (GSA). The second section discusses the condensing boiler technology and how it reduces energy consumption. The third section introduces a demonstration of the technology. The fourth section provides a more detailed overview of the demonstration application, how the heating boiler system operates, and how the new heating technology was monitored for comparison to a baseline condition. The fifth section presents the results of the monitoring activity, documents the performance and resulting energy savings, and presents the results of a life-cycle cost analysis. This section also presents additional opportunities to further improve the performance of the condensing boiler technology based on the observations and lessons learned. The final section draws conclusions from the demonstration results and projects how GSA may best benefit from its application. Several best practices are discussed to assist GSA in designing applications that take advantage of the efficiency benefits offered by this technology, including a discussion of the barriers and enablers to adoption, as well as some recommended changes to GSA Facilities Standards for the Public Buildings Service (GSA 2010).

BACKGROUND

In the U.S., space heating accounts for the largest end-use of energy in buildings. Achieving energy and greenhouse gas reduction goals means this significant demand for energy needs to be optimized. Within U.S. office buildings, boilers provide space heating for 34.5% of the total floor space (EIA 2003a). Therefore, a more efficient boiler technology holds significant opportunity for reducing annual energy consumption for GSA. Condensing boilers offer the potential for higher thermal efficiency, thereby reducing annual energy consumption.

OVERVIEW OF THE TECHNOLOGY

Boilers combust fuel, mixed with oxygen from the air, to release the fuel's heat energy. The boiler's heat exchanger is then used to transfer the heat energy from the products of combustion to a fluid (typically water or a water-glycol solution). The heat transfer fluid is then circulated through the facility to provide space heating where it is needed. The products of combustion for natural gas (mostly methane, CH_4) include carbon dioxide (CO_2) and water (H_2O). In a conventional boiler, the exhaust gas temperature is kept elevated to prevent the water vapor from condensing in the boiler or exhaust stack. Unfortunately, water vapor contains a significant amount of heat energy—on the order of 1000 Btu per pound of water. The amount of heat energy contained within the water vapor is equal to the difference between the fuel's higher heating value and its lower heating value. In the case of natural gas with a higher heating value of 1050 Btu/ft^3 and a lower heating value of 950 Btu/ft^3, this means the water vapor holds 9.5% of the fuel's total heat energy. This limits the efficiency of non-condensing boilers to around 80%. Condensing boilers are equipped with high-efficiency heat exchangers designed to extract more of the heat energy released by the combustion process. Extracting more heat energy lowers the temperature of the combustion gases, to the point where the water vapor condenses, thereby allowing the boiler to recover both more sensible heat energy (energy associated with a change in temperature) as well as the latent heat energy (energy associated with a phase change in the material—*e.g.*, vapor to liquid) released in the combustion process. This allows the efficiency of condensing boilers to reach into the mid- to high-90s. Because the condensing moisture is corrosive in nature, condensing boilers are constructed using corrosion-resistant materials, such as stainless steel. While using more exotic metals in place of conventional carbon steel allows the condensing boiler to withstand the corrosive nature of the condensate, thereby extending the life of the boiler, it also accounts for the more expensive cost of the technology over the conventional, non-condensing boiler.

Condensing boilers, however, require the right conditions to operate in the condensing mode. While different manufacturers offer different designs, generally speaking condensing boilers require a low entering water temperature, typically below 130 to 120°F, to operate in a condensing mode. The low entering water temperature allows the heat transfer fluid to lower the temperature of the exhaust gases to below its dew point, thereby releasing the latent energy contained in the water vapor. When the entering water temperature is above 130°F, a condensing boiler will operate in a non-condensing mode and be limited in efficiency.

STUDY DESIGN AND OBJECTIVES

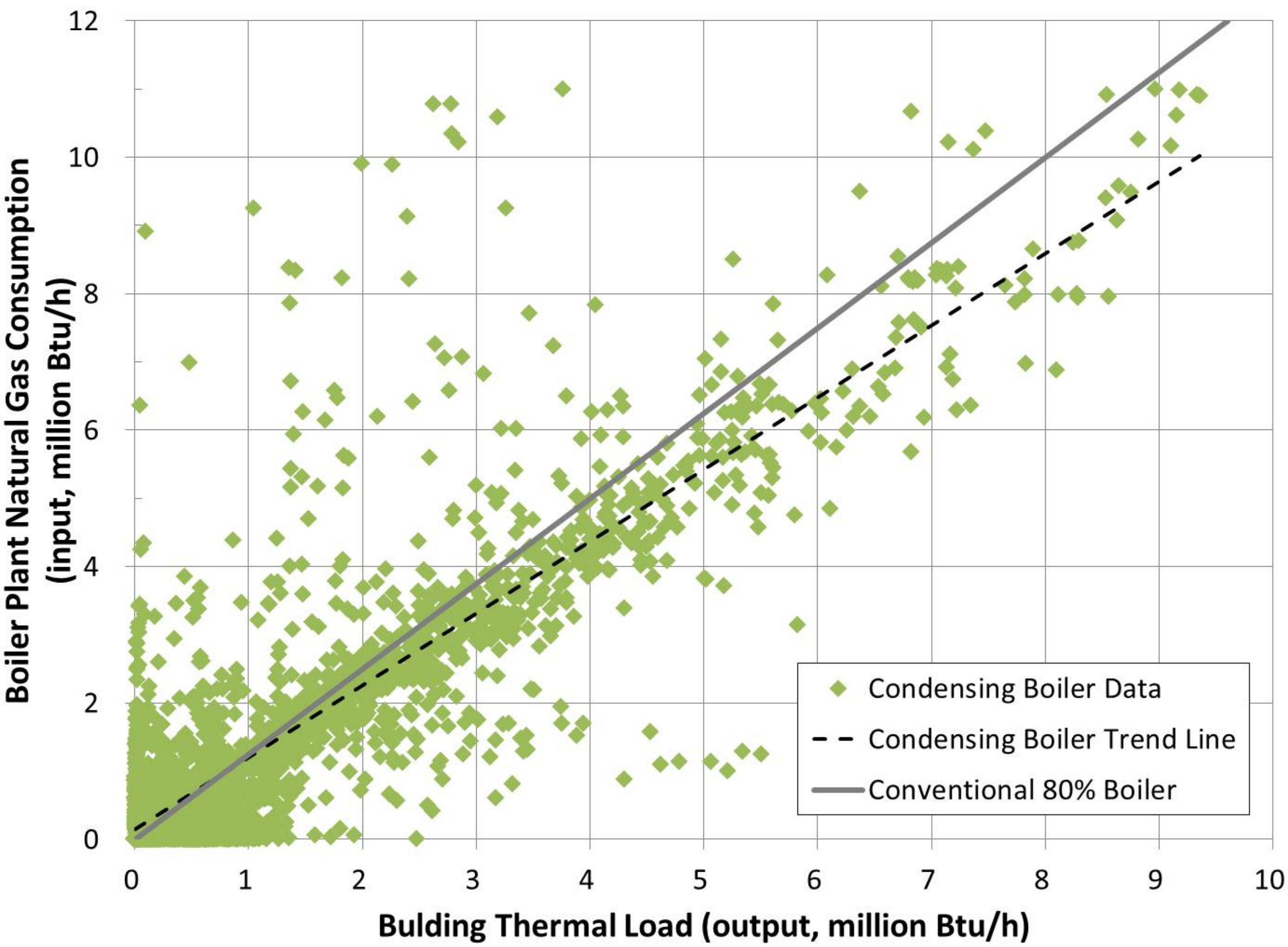
GSA identified the Peachtree Summit Federal Building as the demonstration location for condensing boilers. The 31-story Federal office building is located in the heart of Atlanta, Georgia. Space heating is served from a hot-water boiler plant located on the roof of the building. During 2010, two natural-gas-fired non-condensing fire-tube boilers (nominal input capacity of 5 million Btu/h each) were removed and replaced with four natural-gas-fired condensing boilers (nominal input capacity of 2.5 million Btu/h each). The new condensing boilers became operational in October 2010. In August 2011, GSA hired the Pacific Northwest National Laboratory (PNNL) to monitor and assess the performance of the condensing boiler plant at the Peachtree Summit Federal Building for GSA Green Proving Ground.

The purpose of the study was to assess operation of the condensing boiler heating plant, quantify the operational performance of the heating plant, quantify the load profile for the building application, apply the measured performance to estimate the normalized energy savings compared to the expectations of a conventional non-condensing boiler heating plant, assess (to the extent possible) the technology's broader application within GSA portfolio, and report the findings and conclusions. The monitoring plan included recording the natural gas consumption (input) of the boiler plant, which was separately submetered, as well as monitoring and recording the parameters required to quantify the thermal load (thermal output) on the boiler plant. As a result of the sensors available, the boiler plant was monitored as a single system rather than as a collection of four individual boilers. The condensing boiler plant was monitored from December 14, 2011, through May 11, 2012. The monitored data allowed for determining the operational thermal performance profile of the boiler plant, as well as determining the thermal load profile of the building as it related to occupancy status and weather conditions. The development of these two profiles supported the weather-normalized assessment of annual energy savings for the condensing boiler plant at the Peachtree Summit Federal Building in Atlanta.

PROJECT RESULTS/FINDINGS

Analysis of the monitored data showed the boiler plant performance is, in general, greater than the expectations of a conventional, 80% efficient, non-condensing boiler plant. Figure ES-1 shows the condensing boiler plant performance profile resulting from the monitored data. The wide variance illustrated by the data results from both boiler cycling effects, as well as the impact from the natural gas meter being located in the basement, 32-stories below the boiler plant. The long pipeline between the natural gas meter location and the boiler plant resulted in a compression/expansion effect on the correlation between metered gas consumption and the metered load on the boiler plant. The dashed line illustrates the average trend line from the monitored data. The trend line illustrates that, on average (but not always), the condensing boiler plant operates around 93.5% efficient. The red line illustrates the performance of a nominal 80% efficient boiler plant. Data points below the red line illustrate lower gas consumption from the monitored boiler plant compared to a nominal 80% efficient boiler plant. Because the trend line is below the red line, the monitored boiler plant is (typically) more efficient than the 80% nominal boiler plant.

Figure ES-1. Condensing Boiler Plant Thermal Performance



On a weather normalized basis, the resulting analysis estimates the condensing boilers have reduced natural gas consumption from 92,033 therms/yr to 79,014 therms/yr for a savings of 13,019 therms/yr, or 14%, which is within the range of energy savings expected with the condensing boilers. The results of the life-cycle cost analysis indicate that condensing boilers can be cost-effective for new construction and replace-on-failure projects. However, because of the high capital costs, retrofitting a boiler plant is unlikely to be cost effective when the boilers have remaining economic life.

CONCLUSIONS

Condensing boilers are an effective technology and can produce energy savings compared to non-condensing boilers in space heating applications. The efficiency of the system benefits from lower entering water temperature. Condensing boilers operate in the condensing mode when the entering water temperature is below 120°F to 130°F. With higher entering water temperatures, condensing boilers operate in a non-condensing mode. Therefore, design and operating strategies that lower the return water temperature are most beneficial. Potential strategies include designing heating systems for lower supply water temperature, using variable-speed pumps, eliminating by-pass operation, higher temperature drops across heating coils, and, most importantly, load-based hot water supply temperature reset control. Condensing boilers do have one new maintenance item and that is the condensate neutralizer, but annual recharge requirements are inexpensive relative to the efficiency gains. The market potential within GSA portfolio is significant, and it is recommended that condensing boilers be assessed as part of all future energy evaluations of GSA facilities.

II. Background

A. INTRODUCTION

Energy consumption for space heating accounts for 35% of the total energy consumption in office buildings in the United States, according to the U.S. Energy Information Administration (EIA 2003b). This makes space heating the largest end-use energy consumer in office buildings.[1] Further, space heating in office buildings is provided by boilers in 34.5% of the total heated floor space in office buildings (EIA 2003a). This makes boilers the largest provider of space heating in heated office buildings by total floor space. Because condensing boilers are expected to offer higher thermal efficiency compared to conventional (non-condensing) boilers, the use of condensing boilers is expected to reduce on-site energy consumption, thereby assisting GSA in achieving the energy-use intensity reduction requirements as identified in the Energy Independence and Security Act of 2007 (EISA 2007)and Executive Order 13423. This report will assess the energy performance from one installation of condensing boilers in a space heating application and draw conclusions on how the application of condensing boilers may contribute to further reductions in heating energy at GSA facilities.

Condensing boilers have the potential to reduce space heating energy consumption because their rated thermal efficiency is higher than that of the conventional, non-condensing, boiler. Nameplate efficiency ratings on non-condensing boilers are 80%. Condensing boilers, however, can be found to have rated thermal efficiencies ranging from the high-80s to the high-90s. If condensing boilers could be installed and operated under these ideal conditions, condensing boilers could result in reductions in heating fuel by between 9 and 19%.

B. OPPORTUNITY

There are several alternatives for providing space heating to commercial spaces. These include steam boilers, hydronic boilers, furnaces, air-source heat pumps, ground-source heat pumps, district heating, solar thermal (both active and passive systems), plus an assortment of hybrid configurations. The Commercial Buildings Energy Consumption Survey (CBECS) estimated that boilers are used in 32% of commercial buildings (by number of buildings) (EIA 2003a). However, an Environmental Protection Agency (EPA) study estimated that boilers provide heat to an estimated 15% of all commercial buildings and 29% of U.S. building floor space area (EPA 2008). As noted in the previous section, boilers are estimated to account for 34.5% of the total heated floor space in office buildings. Each of these estimates illustrates that boilers are responsible for a considerable amount of energy consumption in GSA portfolio.

Condensing boilers have been commercially available for over 30 years. However, the equipment has progressed in design since the first generation. Condensing boilers today have higher turn-down ratios, fully modulating burners, high-efficiency heat transfer designs, and fully integrated controls. The Consortium for Energy Efficiency (CEE) estimated the total market for commercial boiler units sold in the United States in 1999 was 35,000 units (CEE 2001). Of that, the market for commercial condensing boilers was estimated to

[1] Based on site energy.

be 700 boilers (± 250 units), or around 2% of total sales. CEE went on to project that market penetration for condensing boilers was around 15 to 25% in 2009 (Horsey 2009).

Based on the above information, it is assumed that the most common incumbent heating technology in GSA facilities is the conventional, non-condensing, boiler. The typical nameplate-rated efficiency for conventional boilers is 80%. The current market penetration of condensing boilers within the GSA portfolio is small but starting to grow. A recent report by Cutler, Dean and Acosta (2012) reports that GSA's Denver Federal Center has converted all but one boiler plant over to condensing boilers. Condensing boilers, either as a system-wide integrated alternative to the current heating system design, or as a simple equipment replacement alternative to the conventional, non-condensing, boiler, offers potential energy savings across the GSA portfolio.

III. Methodology

A. TECHNOLOGY DESCRIPTION

A space heating boiler is a pressure-rated vessel consisting of a fuel burner, furnace chamber, heat-transfer fluid chamber, heat exchanger, exhaust system, and controls. A boiler is designed to transfer the heat energy released through the combustion of a fuel to a heat transfer fluid, which for a hydronic boiler is water or a water-glycol solution. The combustion of fuel within the boiler's furnace chamber releases the chemical energy contained within the fuel molecule. The amount of heat energy released depends on the chemical composition of the fuel. For fuels that contain hydrogen, part of the heat energy released is contained within the water vapor that forms as the hydrogen in the fuel combines with oxygen during the combustion process. The heat energy contained within the water vapor is called the latent heat energy and accounts for the difference between a fuel's higher-heating value (HHV) and its lower-heating value (LHV). Latent heat energy can account for over 10% of the total heat energy released by hydrogen-rich fuels, such as natural gas.

In a conventional, non-condensing boiler, only the sensible[2] heat energy of the fuel is recoverable to elevate the temperature of the heat transfer fluid used in the space heating system. The unrecovered portion of the sensible heat energy and all of the latent[3] heat energy are lost as the products of combustion (exhaust gases) are vented to the atmosphere.

There are several different configurations of condensing boilers. Condensing boilers are available in fire-tube configurations (where the hot combustion gases flow through tubes surrounded by the heat transfer fluid), as well as water-tube configurations (where the heat transfer fluid flows through tubes while the hot combustion gases flow over the tubes). Figure 1 illustrates cut-away views for 3 different condensing boilers.

Condensing boilers are equipped with high-efficiency heat exchangers to recover sufficient heat energy from the products of combustion, which results in the temperature of the combustion gases dropping below the condensing temperature of the water vapor. As the water vapor condenses, the latent heat energy is released and absorbed by the heat transfer fluid. The result is an increase in the thermal efficiency of the heating system.

Condensing boilers have been available in the commercial market for a wide range of capacities for several years. Condensing boilers are common in the European market, and have been required by (European) building energy codes for several years. Market penetration within the United States is lower than in Europe, but growing. Condensing boilers are commercially available in capacities up to 4 million Btu/h. The technology category has approved testing standards and is covered by Energy Star and the U.S. Department of Energy (DOE), Federal Energy Management Program (FEMP) designated products.[4]

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[2] Sensible heat transfer is heat exchanged by a thermodynamic system based solely on a change in temperature.
[3] Latent heat transfer is heat exchanged by a thermodynamic body based on a phase change, such as vapor condensing into liquid.
[4] See Covered Product Category: Commercial Boiler at http://www1.eere.energy.gov/femp/technologies/eep_boilers.html last accessed on 07/05/2012.

Figure 1: Cut-away View of Three Different Condensing Boilers. (Images courtesy of Harsco Industrial Patterson-Kelley, Lochinvar, and Cleaver Brooks [from left to right, respectively], used with permission)

There are many case studies available on the application of condensing boilers in space heating applications. In one article by Durkin (2006), the retrofit of 20 school boiler plants to condensing boilers reported (weather normalized) energy reductions ranging from between 33% and 76%. A few federal agencies have performed tests and demonstrations on condensing boilers. The National Renewable Energy Laboratory recently published a report commissioned by GSA Region 8 assessing a series of condensing boilers installed in buildings at the Denver Federal Center (Cutler *et al*. 2012). In addition, the Navy Technology Validation (Techval) program recently demonstrated a natural-gas-fired condensing boiler installed at a child development center in southern California and is currently demonstrating a fuel-oil-fired condensing boiler in a Navy facility located in northern Maine.[5] The Navy is also demonstrating condensing boilers in service (potable) water heating applications at two additional locations.

B. TECHNICAL OBJECTIVES

It is the purpose of this study to assess the operation of a condensing boiler heating plant, quantify the operational performance of the heating plant, quantify the load profile for the building application, apply the measured performance to estimate the normalized energy savings compared to the expectations of a conventional non-condensing boiler heating plant, assess (to the extent possible) the technology's broader application within GSA portfolio, and report the findings and conclusions.

There are several recognized measures for boiler performance. The most comprehensive, and most useful for field monitoring, is generally thermal efficiency. As used in this study, thermal efficiency is derived by measuring the useful thermal energy delivered by the boiler plant (output) divided by the fuel energy consumed (input). Given the configuration of the boilers in the heating plant selected, it is impractical to

[5] The report, when completed, will not be publicly available, but results may be requested through the Navy Techval program (Paul.Kistler@Navy.mil).

measure the parameters required for thermal efficiency of the individual boilers. Therefore, the boiler heating plant was monitored as a whole system rather than four individual boilers.

Data from meters and sensors was collected through an independent data acquisition system (DAS). Data from the meters and sensors was scanned every second with data averages stored in 5-minute and 1-hour tables. In addition to monitoring the boiler plant's output, fuel consumption was also measured and recorded. The stored data was used to both determine the performance profile of the boiler heating plant, as well as determine a thermal (heating) load profile model for the building. Data was collected from December 2011 through May 2012. The boiler plant performance profile, building thermal load model and typical meteorological year (TMY) data were used to estimate normalized energy savings associated with the condensing boiler system. The results were used to develop an assessment of the installation economics.

C. DEMONSTRATION PROJECT LOCATION

GSA identified the Peachtree Summit Federal Building as the demonstration location for condensing boilers. Located in Atlanta, Georgia, the 31-story, 769,200 ft^2, Federal office building is home to several Federal agencies, including the Social Security Administration and the Internal Revenue Service. The facility, constructed in 1975, is unique in that it has three sides. A photo of the Peachtree Summit building is shown in Figure 2. Atlanta is located in climate zone #3, as defined by the DOE and the International Energy Conservation Code (IECC 2012). The area is also classified as a mixed-humid climate zone. While the climate region description tends to focus on the summer cooling aspects of the area, the TMY for Atlanta experiences over 4,600 hours below 65°F, resulting in 3,095 heating-degree days (HDD, 65°F basis). The winter heating design temperature for Atlanta is 22°F. Therefore, it is assumed that Atlanta's winter would provide a reasonable location for examining the potential benefits associated with condensing boilers.

The installation of the condensing boilers was funded through the American Recovery and Reinvestment Act of 2009[6] (ARRA). The project was awarded in two phases: the scope of work was a design-build project awarded to AGL (Atlanta Gas Light) Resources, the procurement was made as a task order against an existing area wide utility contract using the utility energy service contract (UESC) procedure.[7] The boiler design cost was $51,975[8], and the cost of the installation phase was $677,780[9], including the removal of the previous boilers.

[6] Public Law 111-5.
[7] Solicitation Number: GS-04P-10-BV-C-0026.
[8] E-mail communication from R. Poole, GSA Energy Engineer, dated 8-28-2012.
[9] As reported in FedBizOps, see https://www.fbo.gov/index?s=opportunity&mode=form&id=0dc15c13173a3b9983c5d811699caaa4&tab=core&_cview=0, last accessed 07/06/2012.

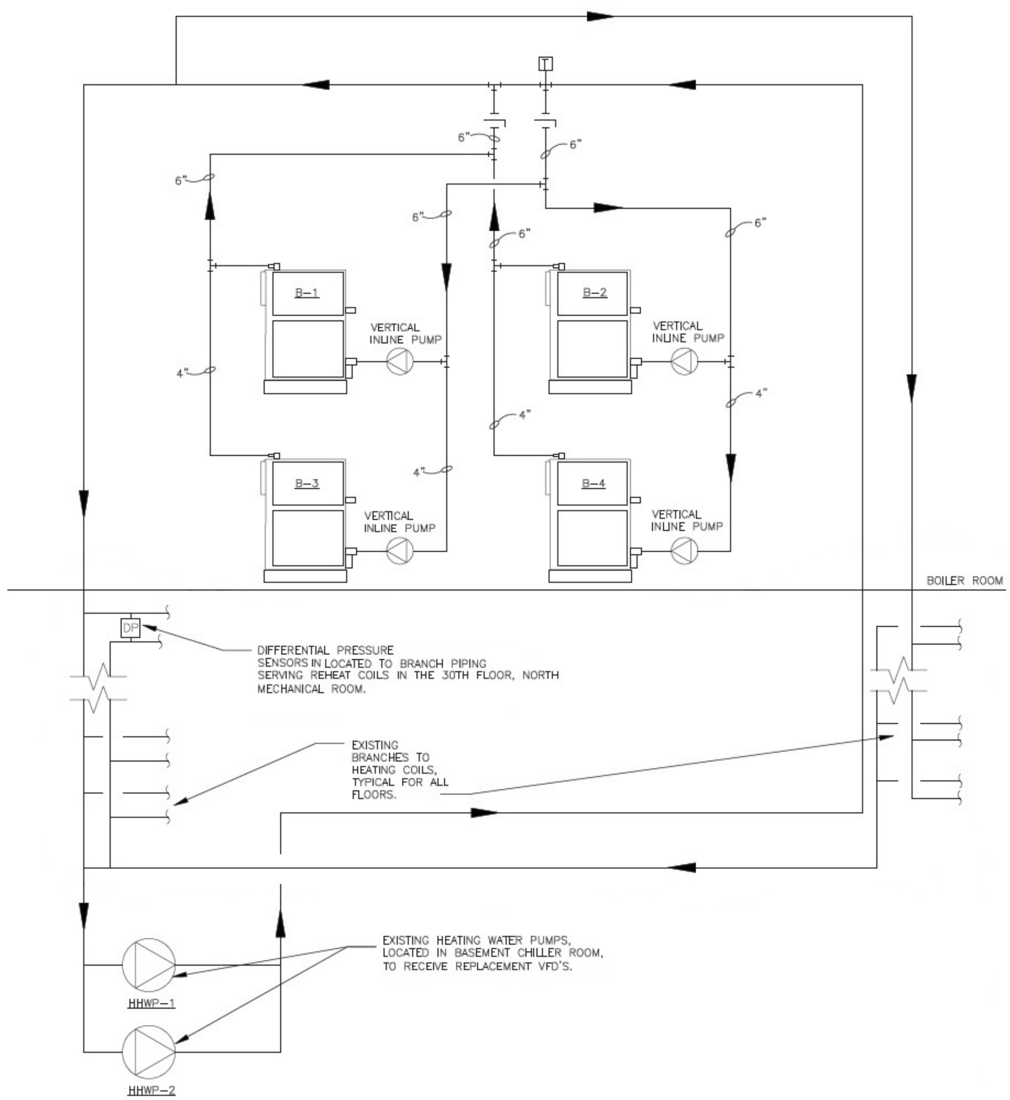
Figure 2: View of the Peachtree Summit Federal Building, Atlanta, Georgia.

IV. M&V Evaluation Plan

A. FACILITY DESCRIPTION

The Peachtree Summit Federal Building is a 31-story Federal office building located in the heart of Atlanta, Georgia. The boiler room is located in a penthouse mechanical room on the roof of the building. The hot water circulation pumps are located in a lower-level basement mechanical room. Figure 3 illustrates the heating system for the building. Natural gas enters the building in the basement mechanical room. There are three natural gas meters in the basement serving different loads in the building. One of the natural gas meters serves the boiler heating plant.

Figure 3: Peachtree Summit Federal Building Heating System One Line Diagram



Because this Green Proving Ground (GPG) program assessment was identified one year after the conventional, non-condensing, boilers were replaced with new condensing boilers, there was no opportunity to assess the original baseline conditions. For this reason, the measured performance of the condensing boilers was compared to a nominal 80% efficiency rating for a conventional non-condensing boiler system.

B. TECHNOLOGY SPECIFICATION

Space heating requirements are served from four natural gas-fired condensing boilers. The condensing boilers were installed in October 2010, replacing two conventional, non-condensing, natural gas-fired boilers. The four condensing boilers are identical, each rated at 2,500,000 Btu/h input, 2,375,000 Btu/h output (approximately 71.9 boiler horsepower), with a rated thermal efficiency of 95%. Technical specifications for the boiler are listed in Table 1. The operating sequence for the condensing boilers, as identified in the construction drawings, is described in Table 2.

Table 1: Technical Specifications

Ratings and Capacities

Fuel	Natural gas
Input (Btu/h)	2,500,000
Output (Btu/h)	2,375,000
Boiler hp	71.9
Inlet gas pressure (max/min)	14” w.c./ 4” w.c.
Electrical requirements:	120-v, 1-ph, 60-Hz, 17-amp
Operating weight (lbs)	1550
Water content (gal)	19

A.S.M.E. Section IV data

Max pressure (psig)	125
Max allowable temperature (°F)	200
Max operating temperature (°F)	194
Flow rate @ 20°F ΔT (gpm)	238
Flow rate @ 40°F ΔT (gpm)	119

Boiler Controls

Integrated boiler control
Main gas train
Operating thermostat 70 to 195°F
High limit thermostat, manual reset 100 to 210°F
Low water cut-off, probe type, manual reset
Combustion blower, variable speed 1100 watt

Table 2: Operating Sequence for the Peachtree Summit Federal Building Heating Plant

Step	Hot Water Reset
A	The hot water supply temperature set point (HWSTSET) shall be reset (see schedule below) by the reading taken from the existing plant Btu meter.
	Btu — Temperature ≤ 936,000 Btu — HWSTSET = 110°F ≥ 8,010,000 Btu — HWSTSET = 180°F
Step	**System Start-up**
A	When the heating system is enabled, B-1 shall start. When B-1 has a firing rate of 90%, B-2 shall start.
B	B-1 and B-2 shall increase their firing rate together to maintain the leaving water supply temperature equal to HWSTSET.
C	When B-1 and B-2 both are at 90% of their full firing rate, B-3 shall start.
D	B-1, B-2 and B-3 shall increase their firing rate together to maintain the leaving water supply temperature equal to HWSTSET.
E	When B-1, B-2, and B-3 are at 90% of, or above, their full firing rate, B-4 shall start and all four boilers shall modulate at the same firing rate.
F	At any time a boiler does not start or fails during operation, an alarm shall be sent to the operators' work station giving the alarm condition and the associated boiler. The next boiler in sequence shall be energized as required.
Step	**System shut-down**
A	When all four boilers are firing at, or below, 65% for 30 continuous minutes, B-4 shall be shut-down.
B	B-1, B-2, and B-3 shall decrease their firing rate together to maintain the leaving hot water temperature equal to HWSTSET.
C	When B-1, B-2 and B-3 are at 55% of, or below, their full firing rate, B-3 shall be shut-down.
D	B-1 and B-2 shall decrease their firing rate together to maintain the leaving hot water temperature equal to HWSTSET.
E	When B-1 and B-2 are at 45% of their full firing rate, B-2 shall be shut-down.
Step	**Duty Cycling**
A	The firing controller shall stage the boilers according to run hours. The boiler with the least amount of run hours shall be lead. The boiler with the greatest amount of run hours shall be the last boiler sequenced on.
Step	**Heating System Pumps**
A	Two existing system pumps pump hot water throughout the building.
B	Each pump's speed shall be controlled by a variable-frequency drive (VFD). The VFD speed signal shall increase or decrease as required to maintain differential pressure as sensed by an existing differential pressure transmitter in the loop. The transmitter's location shall be close to the system's most remote equipment.

C. TEST PLAN

At the start of this activity, the condensing boilers had already been installed for 1 year. Therefore, there was no opportunity to monitor the original natural gas boiler system. Measured results for the condensing boiler system are compared to expectations of a non-condensing boiler system. The condensing boilers were monitored to develop system performance and the building load profile.

The fuel flow (*i.e*., natural gas consumption), supply and return hot water temperatures, and hot water circulation flow rate were monitored from December 14, 2011 through May 11, 2012. The data collected was used to determine the thermal efficiency of the boiler system under various load conditions. The data for determining thermal efficiency was monitored and stored using both a central DAS in addition to a few remote portable data loggers. The time clocks of all data collection devices were synchronized. Thermal efficiency is calculated consistent with recognized methods of testing commercial and industrial boilers.[10] Because testing standards are based on steady-state controlled conditions, the method of testing used in this field demonstration deviated as required to assimilate data under dynamic field conditions. Further, testing standards are based on cold inlet water temperatures. The purpose of this monitoring activity was to capture actual operating conditions.

Data was collected through two means. A central DAS, located in the penthouse mechanical room, collected interval data relative to the boiler output. The interval data was transferred to PNNL through the use of a Campbell Scientific SC115, flash memory drive. In addition, a portable pulse data logger was installed on the natural gas submeter located in the basement mechanical room. The portable data loggers were periodically swapped with a replacement logger to allow periodic data transfer to PNNL for review and analysis. The flash drive and replacement data loggers were periodically shipped between GSA site point-of-contact and PNNL. As a precaution, a back-up data logger was installed on the natural gas submeter and left installed for the duration of the monitoring activity. The back-up pulse data logger ensured no data was lost during the interim data transfer process.

Because the plant was monitored as a system, thermal efficiency is calculated for the boiler plant rather than for the individual boilers. The heating plant's thermal efficiency is determined by the ratio of energy output to energy input. The energy input Q_{in}, in Btu, is defined as

$$Q_{in} = q_f \, HHV \qquad \text{(equation 1)}$$

where q_f is the fuel flow, in standard cubic foot (scf), and HHV is the fuel higher heating value[11], in Btu/scf. Fuel flow was collected using a remote data logger that stored the cumulated fuel flow data in 5-minute intervals. Using the interval data collected through the logger, the result of using equation #1 would represent energy consumed during the 5-minute interval. To achieve units of Btu/h, the value from equation #1 would need to be multiplied by 12. The energy output Q_{out}, in Btu/h, is defined as

[10] For commercial packaged boilers, ASHRAE Standard 90.1-2007, Table 6.8.1F Gas- and Oil-Fired Boilers, Minimum Efficiency Requirements, references the test procedure documented in 10CFR431. 10CFR431.86 references BTS-2000, second edition (Rev 06.07) from the Hydronics Institute Division of AHRI.

[11] For analysis, the energy content for the local gas supply is assumed to be 1,050 Btu/scf (HHV) for Atlanta.

$$Q_{out} = \dot{q}_{HW}\, \rho_{HW}\, C_p\left(T_{sup} - T_{ret}\right) 60 \qquad \text{(equation 2)}$$

where $\dot{q}_{HW}$, is the hot water flow rate, in gal/min, ρ_{HW} is the hot water density, in lb/gal, C_p is the specific heat of water, in Btu/lb-°F, and T_{sup} and T_{ret} are the supply and return temperatures, in °F, respectively, and 60 min/h is used to achieve the desired units (Btu/h). The thermal efficiency, $\eta_{thermal}$, in percent, is given as

$$\eta_{thermal} = 100\, \frac{Q_{out}}{Q_{in}} \qquad \text{(equation 3)}$$

D. INSTRUMENTATION PLAN

A Campbell Scientific CR1000 DAS was located in the main boiler room in a penthouse mechanical room on the building roof. Data collected was limited to sensors that are directly used to determine thermal efficiency. A few additional sensors were installed as back-up to the primary sensors used in the analysis. The primary sensors included a surface-mounted ultrasonic transit-time flow meter and surface-mounted[12] thermocouples. The DAS was mounted on the wall in the boiler room near a wall outlet power supply. Power supply for the DAS and the flow meter were from an existing 120-volt wall outlet. The ultrasonic flow meter was installed on the main hot water return line entering the boiler room on the longest straight run of pipe. A small section of pipe insulation was removed to accommodate the surface-mounted flow meter. Two surface-mounted thermocouples were also installed at this location. Thermal compound was used to ensure a reasonable temperature reading from the thermocouples. An insulated thermal blanket was installed around the flow meter and thermocouples. The second set of surface-mounted thermocouples were installed on each of the two hot water supply pipelines. A small section of insulation was removed to allow for the installation of the thermocouples. Thermal compound was used to ensure a reasonable temperature reading from the thermocouples. The insulation was replaced over the thermocouples. In addition, a removable insulated thermal blanket was installed over the cuts made in the original insulation to allow for potential future access.

Natural gas consumption was monitored using the existing natural gas submeter located in the basement mechanical equipment room, which is owned by Atlanta Gas Light (AGL) Resources. A pulse signal from the natural gas submeter was used to log natural gas consumption in time-series records synchronized to the upstairs DAS. AGL Resources installed the pulse generator on the existing meter, shown in Figure 4, and provided the multiplier to convert pulses to standard cubic foot.

Sensor data was recorded in 5-minute intervals. The DAS also stored hourly data. Table 3 identifies the systems monitored by the DAS. Table 4 identifies the systems monitored using remote data loggers.

[12] Insertion temperature sensors provide more accurate absolute temperature readings than surface-mounted temperature sensors but because temperature difference is the desired product, surface-mounted temperature sensors provide sufficient accuracy and are better suited to temporary monitoring activities.

Figure 4: Photo of Natural Gas Meter located in the Basement that serves the Boiler Plant.

Table 3: Sensors used with the Primary Data Acquisition System

Parameter	Sensor	Units	Signal
Hot water flow rate	EMCO flow transit-time ultrasonic flow meter	gpm	Pulse
Hot water supply temperature (boiler room supply to building)	Type T surface-mounted thermocouple (redundant sensors used on both supply lines)	°C	Voltage differential
Hot water return temperature (boiler room return from building)	Type T surface-mounted thermocouple (redundant sensors used)	°C	Voltage differential
Outside air dry-bulb temperature	Campbell Scientific CS215 temperature and relative humidity (RH) sensor with solar radiation shield	°C % RH	Voltage differential

Table 4: Sensors used with Portable Data Loggers

Parameter	Sensor	Units	Signal
Natural gas flow	AGL natural gas meter with pulse output and MadgeTech pulse logger (P101A). Also installed a back-up MadgeTech pulse logger.	scf	Pulse
Hot water circulation pump #1	WattNode pulse power meter, 20-amp current transformers and MadgeTech pulse logger (P101A)	kW	Pulse
Hot water circulation pump #2	WattNode pulse power meter and MadgeTech pulse logger (P101A)	kW	Pulse

V. Results

The results section is divided into four subsections. The first subsection describes the performance profile of the condensing boiler plant resulting from the monitored data. The second subsection describes the building thermal load profile also resulting from the monitored data. The third subsection brings the two profiles together to determine the resulting benefit of the condensing boiler plant compared to a conventional, non-condensing, boiler plant for a normalized TMY. The results from the third subsection are also used to determine the economic assessment of the condensing boiler plant. Finally, the fourth subsection extrapolates from the observed data and findings to identify additional opportunities for further improving the performance of the condensing boiler plant, both for the monitored location as well as potential other applications in GSA portfolio.

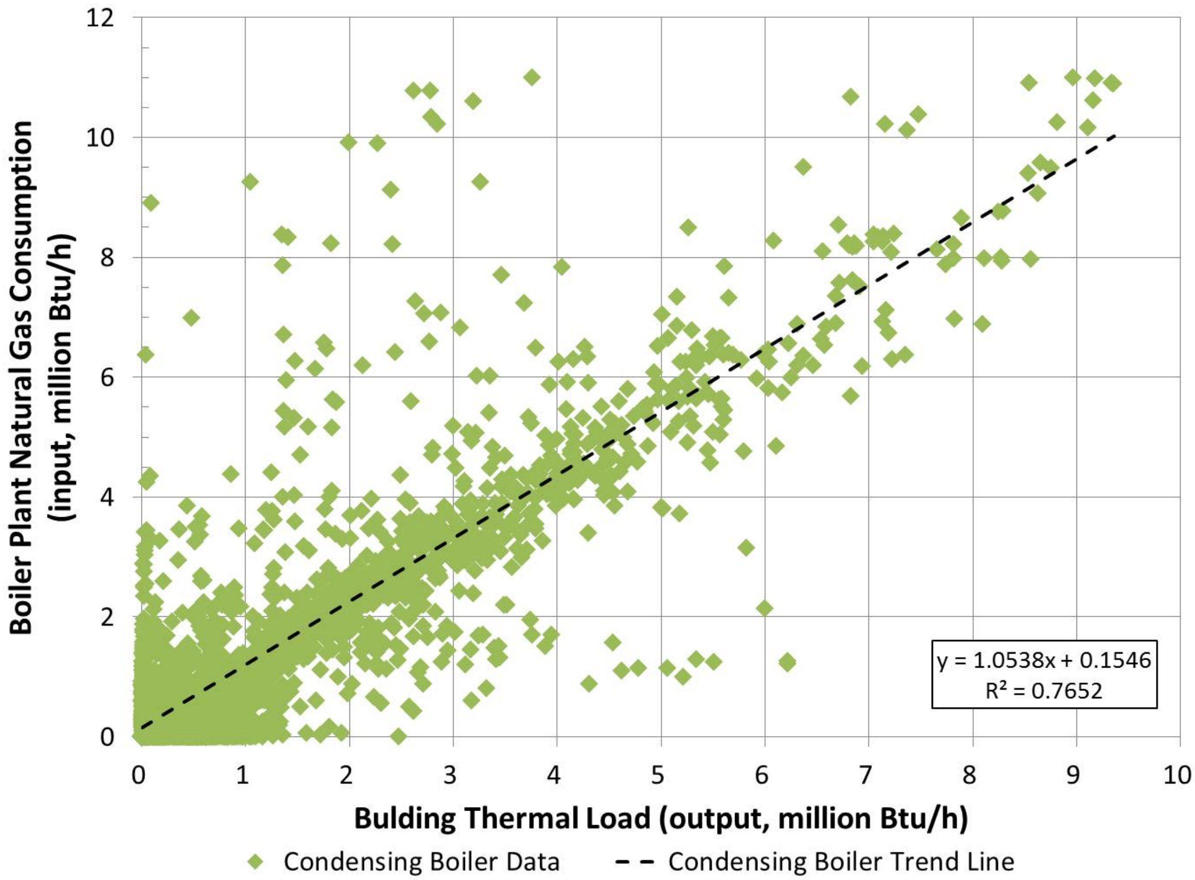
A. BOILER PLANT PERFORMANCE PROFILE

The data acquisition system and portable loggers collected data from December 14, 2011, through May 11, 2012. Applying the collected interval data to equations #1 (natural gas input) and #2 (building thermal load output) result in the boiler plant performance, which is illustrated in Figure 5. The linear trend line equation, shown in the figure and determined using Microsoft Excel, illustrates that the boiler can operate around 93.5% at full load, which is close to the rated 95%.[13] The wide variance illustrated by the data in Figure 5 results from both boiler cycling effects, as well as the impact resulting from the natural gas meter being located in the basement, 32-stories below the boiler plant. There is an offset between the natural gas consumed in the boiler plant and measurement of natural gas by the natural gas submeter resulting from the compressibility of natural gas, particularly at low pressure and in such a tall standpipe. The trend line, however, averages out the delayed impact from the interval data.

In general, the boiler plant has a higher operating efficiency than would be expected from a conventional, non-condensing, boiler plant (93.5% versus 80, excluding shell losses). Additional findings related to when the boiler operates efficiently and how it might operate more efficiently will be discussed in more detail later in this report.

[13] Using the trend line equation at full load output, thermal efficiency = (output)/(input) = (9.5 x 10^6 Btu/h) /([(1.0538(9.5x10^6)+(154559) Btu/h] = 0.935 or 93.5%.

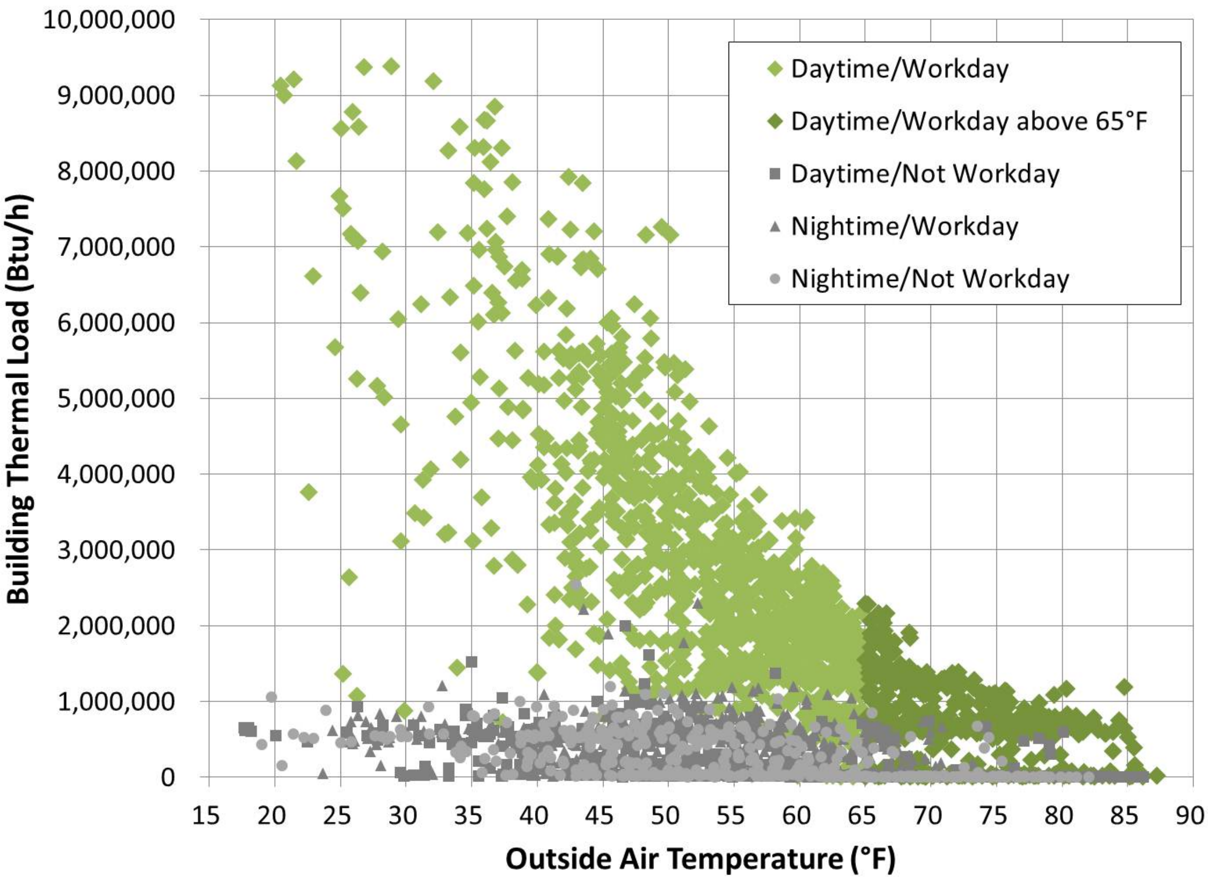
Figure 5: Condensing Boiler Plant Performance Profile Resulting from the Measured Data



B. BUILDING THERMAL LOAD PROFILE

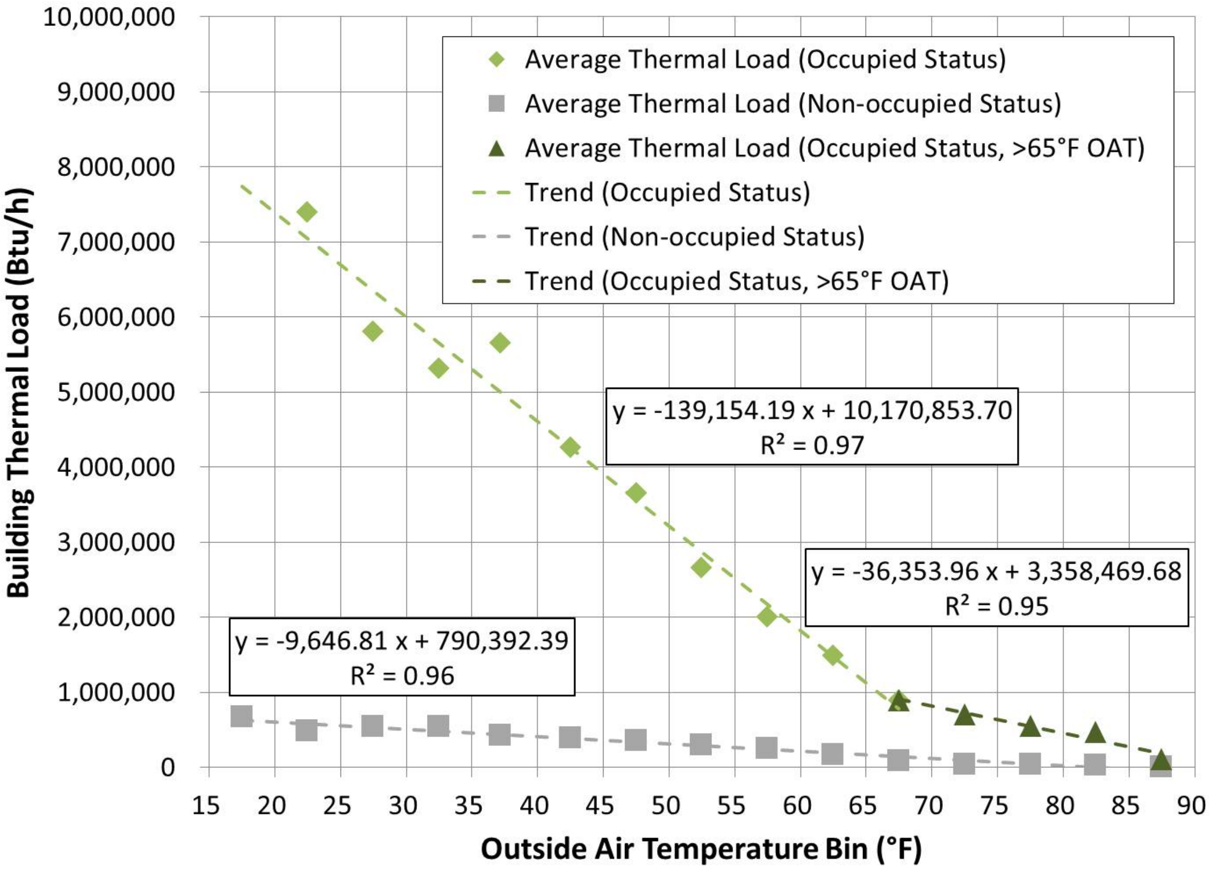
The data from equation #2 (thermal load) plotted versus outside air temperature can also be used to determine the thermal load profile for the application—space heating for the Peachtree Summit Federal Building. Figure 6 illustrates the building thermal load for the measured parameters. Examination of the thermal load clearly shows that there are multiple operating profiles for the building, which is illustrated in Figure 6 using different markers. The distinction between "occupied" and "unoccupied" profiles during workdays is very evident within Figure 6, as well as when examining the interval data sets for both thermal load and natural gas consumption. Transition between the two periods occurs around 5:00 AM and 7:00 PM, Monday through Friday. Further analysis revealed that the various "non-occupied" periods (*e.g.*, workday unoccupancy period, weekends [both daytime and nighttime], and holidays [both daytime and nighttime]) could be combined into one primary "unoccupied" operating profile. In addition to occupied and unoccupied profiles, there was also a third profile—when the outside temperature was above 65°F. GSA's facility description did not include the use of reheat (therefore, we had assumed the facility did not use hot water for reheat) and the site also reported the boilers are taken offline during the summer. Nevertheless, there is a different thermal load profile for the building when the ambient outside air temperature is above 65°F.

Figure 6: Building Thermal Load versus Outside Air Temperature



The monitoring period, winter of 2011-2012, was not a typical winter. While the winter did experience the normal range of temperatures, it was brief. However, the monitored data may be used to develop typical building thermal load profiles, which can then be applied to TMY data to achieve a normalized winter. The data from Figure 6 for each of the operational periods was divided into conventional 5°F temperature bins and averaged for the corresponding bin and occupancy status. The result is illustrated in Figure 7. The resulting bin data from Figure 7 was used to develop trend line equations, which result in a building thermal load model based on occupancy status and outside air temperature.

Figure 7: Average Building Thermal Load versus Outside Air Temperature for Bin Data Analysis



C. NORMALIZED ANNUAL ENERGY AND ECONOMIC ASSESSMENT

A weather-normalized estimate of annual heating energy consumption for the condensing boiler plant can be determined using the boiler plant performance profile in conjunction with the building thermal load profiles and applying TMY data. TMY3[14] data for Atlanta Hartsfield International Airport was used in this analysis (Wilcox and Marion 2008). Further, based on information provided by GSA site staff, it is assumed the heating plant operates from October through April, inclusive. As noted earlier, baseline measurements for a conventional, non-condensing, boiler plant were not possible. To develop a baseline profile, an 80% boiler thermal efficiency with an additional fixed heat loss of 1.5% (to account for typical shell thermal losses) was assumed. The results are shown in Table 5. Normalized for TMY data, the conventional, non-condensing, boiler plant is estimated to consume 92,033 therms/yr natural gas, while the condensing boiler plant is estimated to consume 79,014 therms/yr natural gas, a savings of 13,019 therms/yr, or 14.1%, which is within the range of energy savings expected with condensing boilers.

[14] TMY3 refers to a third update of TMY data for 1020 locations based on data from 1991 to 2005.

Table 5. Weather-Normalized Energy Assessment of Condensing Boiler Plant for the Peachtree Summit Federal Building

Tempera-ture Bin	Average Bin Temper-ature	TMY3 Total Observa-tions	TMY3 Total Observa-tions	Average Facility Thermal Heat Load[1]	Average Facility Thermal Heat Load[2]	Baseline Natural gas Consump-tion[3]	Baseline Natural gas Consump-tion[4]	Post-Installation Natural gas Consump-tion[5]	Post-Installation Natural gas Consump-tion[6]	Baseline Natural gas Consump-tion[7]	Post-Installation Natural gas Consump-tion[8]
A	B	C	D	E	F	G	H	I	J	K	L
–	–	Occupied	Unoccu-pied	Occupied	Unoccu-pied	Occupied	Unoccu-pied	Occupied	Unoccu-pied	–	–
(°F)	(°F)	(h/yr)	(h/yr)	(Btu/h)	(Btu/h)	(Btu/h)	(Btu/h)	(Btu/h)	(Btu/h)	(therms/yr)	(therms/yr)
85 to 89°F	87.5	1	0	0	0	0	0	0	0	0	0
80 to 84°F	82.5	56	12	359,265	0	599,081	0	533,152	0	335	299
75 to 79°F	77.5	127	40	541,035	42,765	826,294	203,457	724,702	199,625	1,131	1,000
70 to 74°F	72.5	131	91	722,805	90,999	1,053,506	263,749	916,251	250,454	1,620	1,428
65 to 69°F	67.5	211	199	777,959	139,233	1,122,449	324,042	974,372	301,283	3,013	2,655
60 to 64°F	62.5	305	410	1,473,729	187,467	1,992,161	384,334	1,707,575	352,112	7,652	6,652
55 to 59°F	57.5	284	431	2,169,499	235,701	2,861,874	444,627	2,440,777	402,941	10,044	8,668
50 to 54°F	52.5	279	437	2,865,269	283,935	3,731,586	504,919	3,173,979	453,770	12,618	10,838
45 to 49°F	47.5	151	314	3,561,039	332,169	4,601,299	565,212	3,907,182	504,599	8,723	7,484
40 to 44°F	42.5	221	373	4,256,809	380,403	5,471,011	625,504	4,640,384	555,428	14,424	12,327
35 to 39°F	37.5	212	279	4,952,579	428,637	6,340,724	685,797	5,373,587	606,257	15,356	13,083
30 to 34°F	32.5	86	135	5,648,349	476,871	7,210,436	746,089	6,106,789	657,086	7,208	6,139
25 to 29°F	27.5	56	115	6,344,119	525,105	8,080,149	806,382	6,839,992	707,915	5,452	4,644
20 to 24°F	22.5	33	70	7,039,889	573,339	8,949,861	866,674	7,573,194	758,744	3,560	3,030
15 to 19°F	17.5	7	13	7,735,659	621,573	9,819,574	926,967	8,306,396	809,573	808	687
10 to 14°F	12.5	0	8	8,431,429	669,807	10,689,286	987,259	9,039,599	860,402	79	69
5 to 9°F	7.5	0	1	9,127,199	718,041	11,558,999	1,047,552	9,772,801	911,231	10	9
Total	–	2,160	2,928	–	–	–	–	–	–	92,033	79,014

1) For above 65°F, determined using the trend line equation from Figure 7, (column E) = [(-36,353.96) * (column B) + 3,358,469.68]. For below 65°F, determined using the trend line equation (column E) = [(-139,154.19) * (column B) + 10,170,853.70].
2) Determined using the trend line equation from Figure 7, (column F) = [(-9,646.81) * (column B) + 790,392.39]
3) Determined using the equation (column G= [(1/0.80) * (column E) + (150,000)], which assumes 80% efficiency plus 1.5% thermal shell losses
4) Determined using the assumption (column H) = [(1/0.80) * (column F) + (150,000)], which assumes 80% efficiency plus 1.5% thermal shell losses
5) Determined using the trend line equation from Figure 5, (column I) = [(1.0538) * (column E) + (154,559)]
6) Determined using the trend line equation from Figure 5, (column J) = [(1.0538) * (column F) + (154,559)]
7) Determined using (column K) = [(column G) * (column C)] + [(column H) * (column D)]) / (100,000 therms/Btu)
8) Determined using (column L) = [(column I) * (column C)] + [(column J) * (column D)]) / (100,000 therms/Btu)

Local natural gas cost for the location was $0.798/therm, resulting in annualized energy cost reduction of $10,389.[15] As reported by GSA, installation of the condensing boilers, including design, demolition, equipment, and installation, cost a total of $729,755. It is noted, however, that the heating plant is located in a penthouse mechanical room on the roof of a 31-story building. The difficult-to-access location added to the installation cost of the boilers. Also adding to the cost was converting the heating plant from two fire-tube boilers to four modular condensing boilers; although the total heating plant capacity remained the same. Further, the Peachtree Summit condensing boiler project was funded through the area-wide agreement between GSA and the local utility, AGL Resources. This turnkey approach also may have contributed to the higher-than-average project installation cost. As a basis for comparison, Cutler *et al*. (2012) reported the installation costs for 5 condensing boiler projects at GSA Denver Federal Center (DFC). Table 6 shows a comparison of actual installation costs for the condensing boiler installation projects.

Table 6: Installation Cost Comparison

Location	Number of Boilers	Boiler Capacity (MBtu/h)	Heating Plant Capacity (MBtu/h)	Total Installed Cost	Installed Cost per MBtu/h
Peachtree Summit	4	2,500	10,000	$729,755	$72.98
DFC Building 25	6	2,500	15,000	$618,057	$41.20
DFC Building 45(1)	3	1,500	4,500	$1,458,469	$324.10
DFC Building 54	5	2,500	12,500	$506,389	$40.51
DFC Building 710A(2)	2	1,500	3,000	$361,347	$120.45
DFC Building 810	6	2,500	15,000	$570,748	$38.05

(1) Cost includes converting facility from a steam to a hot water distribution system.

(2) Installation cost for this facility was high as a result of building configuration, unique design and ventilation requirements, and limited access.

To support the life-cycle cost analysis, PNNL developed a series of cost estimates for the various alternatives. RSMeans (2011a, 2011b) provides a basis for estimating the installed cost of a conventional hot-water boiler system, as well as demolition and removal of the previous boiler system, for a typical installation. However, RSMeans does not address costs associated with high-efficiency hot-water boilers, such as those meeting FEMP Designated Products requirements, nor does RSMeans address costs associated with condensing boilers in the larger capacity range of commercial-sized systems. For these costs, PNNL referred to costs researched and developed in support of DOE rule-making processes related to commercial

[15] According to the Energy Information Administration, the U.S. average consumer price for natural gas for commercial facilities was $0.947/therm (2010), $0.893/therm (2011) and $0.813/therm (2012 year-to-date). Reference: http://www.eia.gov/naturalgas/monthly/pdf/table_03.pdf, last accessed 9/4/2012. For more information on natural gas costs see Appendix D.

packaged boilers[16], as well as equipment price quotes from a hot-water boiler manufacturer. The result was a series of cost estimates for typical installation of a hot water boiler system for a configuration and capacity as described for the Peachtree Summit Federal Building (4 units with an input rating of 2.5 million Btu/h each), as shown in Table 7. These cost estimates may be considered reasonably typical for basic hot-water boiler plants with similar quantity and capacity boilers. Because economies of scale are to be expected, these cost estimates may not be appropriate for other capacities and configurations. Applying relative cost factors ($/million Btu/h) for different boiler capacities derived from RSMeans (2011b), it might be reasonable to assume that for smaller capacity boilers, with a unit boiler capacity of 1 million Btu/h, installed costs should be expected to be 55% greater on a cost per capacity basis. Similarly, for larger capacity boilers, with a unit capacity of 4 million Btu/h, installed costs should be expected to be 15% less on a cost per capacity basis.

The installation at the Peachtree Summit Federal Building should not be considered typical. As noted earlier, the boiler plant is located in a difficult to access location. Further, boiler installation was procured through GSA area-wide agreement using a general contractor and subcontractors. This combination of factors accounts for the actual installed costs being greater than a typical installation. In this case, the actual cost was 71% greater than the cost estimate for a typical installation. Applying this escalation factor to the other installation scenarios results in the final cost estimates used in the life-cycle cost analysis, also shown in Table 7.

Table 7: Scenario Cost Estimates for the Peachtree Summit Federal Building

Description	Units	Conventional boiler	High-efficiency boiler	Condensing boiler
Number of boilers	Each	4	4	4
Capacity, input	1,000 Btu/h	2,500	2,500	2,500
Capacity, output	1,000 Btu/h	2,000	2,100	2,375
Rated efficiency	%	80%	84%	95%
Cost estimate, typical(1)	Lot	$353,900	$384,800	$426,100
Cost/capacity, typical	$/1000 Btu/h (input)	$35.40	$38.50	$42.60
Escalation factor(2)	%	Not applicable	Not applicable	+71.3%
Cost estimate, Peachtree	Lot	$606,200	$659,100	$729,755

(1) Cost includes estimate for removal of previous boilers, design, plus equipment, materials, installation labor, contractor overhead and profit.

(2) Determined as [1 - (actual installation cost)/(typical cost estimate)] x 100%

[16] DOE Rulemaking Commercial Heating, Air Conditioning, and Water Heating Equipment (i.e., ASHRAE Equipment) Final Rule, 2008. See http://www1.eere.energy.gov/buildings/appliance_standards/commercial/ashrae_final_rile.html.

An assessment of the economics for the condensing boiler heating plant at the Peachtree Summit Federal Building was performed. Table 8 includes a summary of the economic assessment, including the resulting net present value (NPV), savings-to-investment ratio (SIR), and simple payback.[17] Two strategies were included in the assessment: retrofit and replace-at-end-of-life. Retrofit is defined as when the existing non-condensing boilers have considerable useful life remaining, so replacement is optional. The economics of this option are driven by the total cost of replacing the existing non-condensing boilers with new condensing boilers. The resulting energy cost reduction is used to justify the total installation cost of the retrofit. Replace-at-end-of-life is defined as when the existing non-condensing boilers are at the end of their useful economic life and need to be replaced. This option is sometimes called replace-on-failure. The economics of this option are driven by the additional cost of the condensing boilers over the cost of the non-condensing boilers because the boilers need to be replaced in any event. Therefore, the resulting energy cost reduction is used to justify the additional cost of the condensing boilers.

There are additional operation and maintenance (O&M) costs to be expected from a condensing boiler plant. Specifically, condensing boilers typically require the installation of condensate neutralizers. The acidic condensate that forms when the exhaust gases are cooled below the dew point are collected from the boiler and from the exhaust stack and piped to a condensate neutralizer, where the pH is raised to a point where it may be dumped to a sewage drain line. The neutralizer needs to be recharged or replaced periodically to maintain this capability. Neutralizer kits are available in an assortment of capacities designed to match boiler capacities. Typical O&M requirements are to replace/recharge the neutralizers annually.

[17] Net present values are calculated according to the National Institute of Science and Technology (NIST) Handbook 135. Boiler life is assumed to be 25 years consistent with the DOE FEMP Covered Product Category for Commercial Boiler (FEMP 2012).

Table 8: Economic Assessment Results for the Peachtree Summit Federal Building

Description	Non-condensing boilers(1) (original)	Non-condensing boilers(2) (new)	Condensing boilers(3) (new)
Energy consumption	92,033 therm/yr	87,981 therm/yr	79,014 therm/yr
Energy cost	$73,442/yr	$70,209/yr	$63,053/yr
Additional maintenance	Not applicable	Not applicable	$400/yr
Retrofit option			
Installed cost	$606,200	$659,100	$729,755
Energy cost reduction	Baseline	$3,233/yr	$10,389
Simple payback	Baseline	204 yr	73.1 yr
Net-present value	Baseline	$-599,156	$-544,121
SIR	Baseline	0.09	0.25
Replace-at-end-of-life option			
Additional installed cost	Not applicable	Baseline	$70,655
Energy cost reduction	Not applicable	Baseline	$7,156/yr
Simple payback	Not applicable	Baseline	9.9 yr
Net-present value	Not applicable	Baseline	$55,035
SIR	Not applicable	Baseline	1.78

(1) Annual energy estimate based on 80% thermal efficiency, as shown in Table 5.

(2) Annual energy estimate based on FEMP designated product minimum performance requirement of 84%.

(3) Annual energy estimate based on measured performance, as shown in Table 5.

D. WAYS TO FURTHER IMPROVE BOILER PERFORMANCE

There are ways to improve the performance of condensing boilers. These methods are discussed relative to observations made of the Peachtree Summit Federal Building boiler plant operation, but should be considered relative to any application.

The efficiency of a condensing boiler is considered highly related to the entering water temperature (Durkin 2006). Therefore, the lower the heating system's return water temperature, the better for efficient operation of the condensing boilers. Typical design practice for a conventional hydronic heating system has been to supply 180°F to 200°F hot water at design full load or peak design winter conditions.[18] Further, typical design practice is to select heating coils designed for a 20°F temperature drop in hot water temperature across the coil. This conventional design practice results in a return water temperature of 160°F under design conditions, which will result in a condensing boiler operating as a conventional boiler and not condensing.

System performance can be improved by designing the heating system to operate more frequently in the condensing mode. First, the system can be designed to operate with a lower heating supply water temperature, such as 150°F to 160°F, under peak design conditions. This will reduce heat loss in the distribution system, saving additional energy through reduced load on the boilers. Further, heating coils can be selected to operate with larger temperature drops, such as 40°F instead of the conventional 20°F. These two recommended design practices will result in larger heating coils, which will add to the initial cost of the overall heating system. However, the result will be a return water temperature of 110°F to 120°F during design conditions, which is within the condensing regime of the condensing boiler. The two design strategies just outlined are most applicable for new construction, when the heating system is being designed from the ground up. In retrofit applications, replacing heating coils is likely to be cost prohibitive.

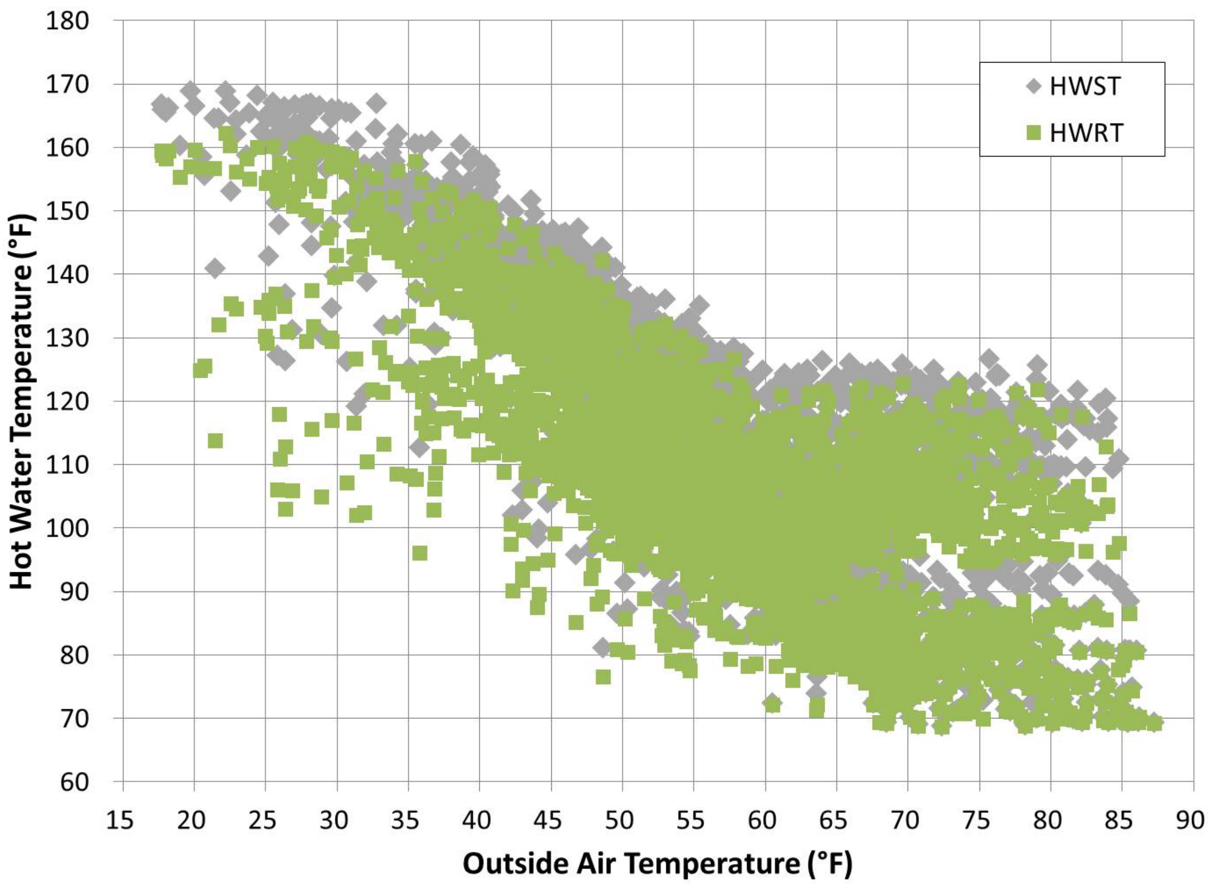
Additional savings are also possible through the application of hot water supply temperature reset, an operating strategy available with most building automation systems (BAS). In general, a supply temperature reset control strategy will reset the hot water supply temperature set point based on the load (demand) on the boiler. The higher hot water supply temperature of 180°F may be required under design winter conditions (22°F for Atlanta), but is not required under milder winter conditions. Generally, no heating is expected to be required with outside air temperatures greater than 65°F. Therefore, the hot water supply temperature can be lowered as the load on the boiler lowers. The reset strategy may also have upper and lower limits related to boiler load, outside air temperature, or other factors. When decreasing the hot water supply temperature results in lowering the return water temperature, boiler efficiency may improve. Once the return hot water temperature drops below 120 to 135°F (depending on the manufacturer, make and model), the condensing boiler will begin to condense.

The Peachtree Summit Federal Building employs a hot water supply temperature reset strategy. As noted in Table 2, the hot water supply temperature is set to 180°F when the system load is above 80% and set to 110°F when the system load is below around 10%. Between these two loads, the BAS interpolates the hot

[18] The Peachtree Summit Federal Building's heating system is designed to operate with a peak supply water temperature of 180°F (see Table 2), although the highest observed supply temperature was 170°F (shown in Figure 8).

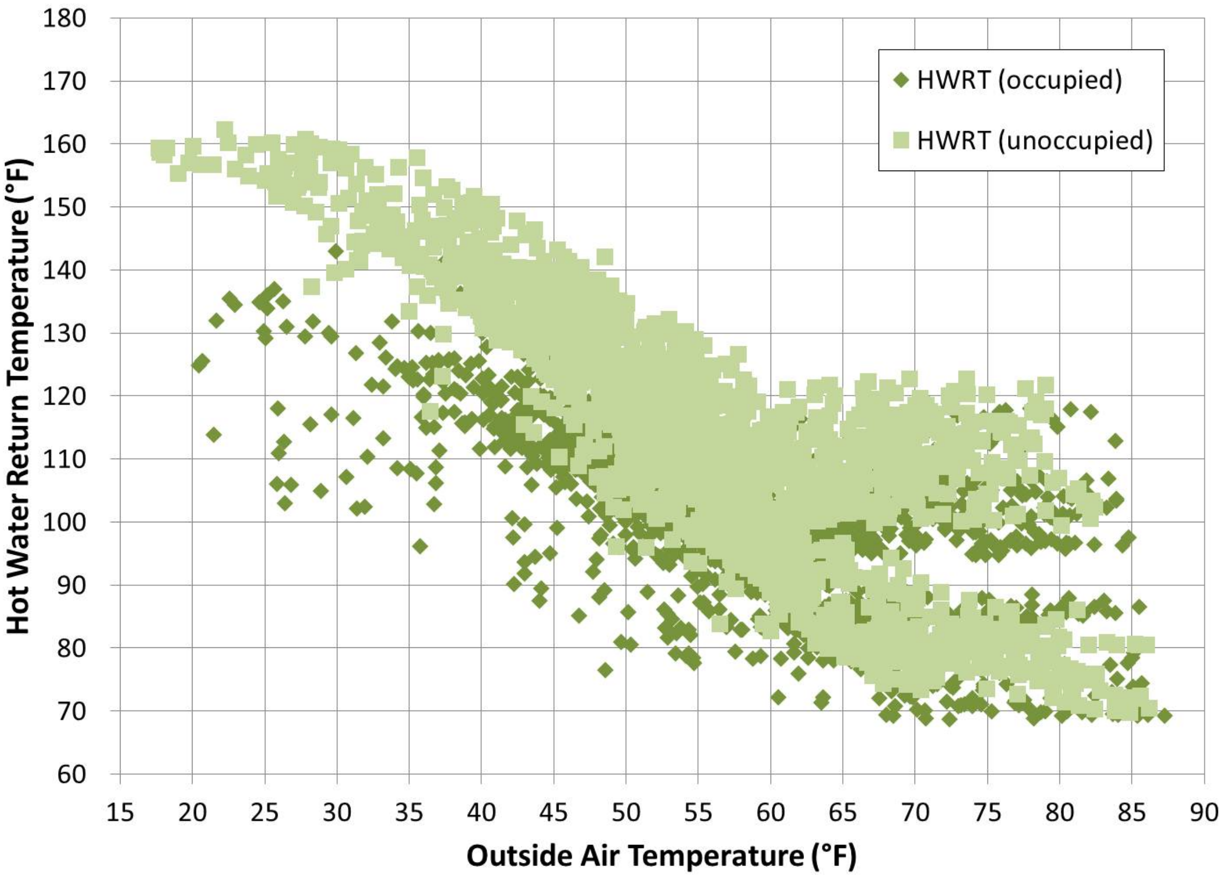
water supply temperature using a linear algorithm. The measured result of the variable hot water supply temperature is shown in Figure 8.

Figure 8: Hot Water Temperature (Supply and Return) versus Outside Air Temperature



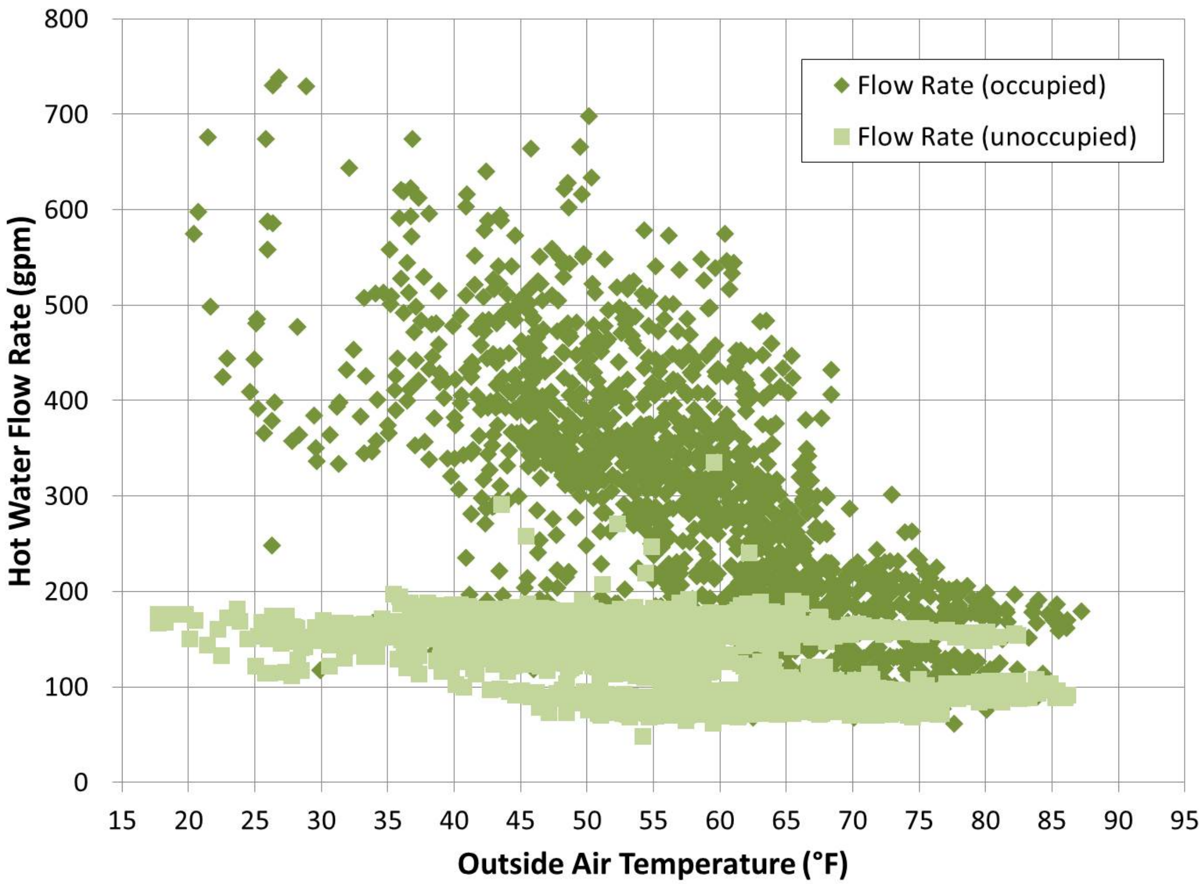
While this strategy does save energy, and is responsible for when the boilers operate in the condensing mode, examination of the data shows the opportunity for additional improvement. Figure 8 also shows the measured return water temperature, which more directly impacts the efficiency of the condensing boiler. Figure 9 shows the hot water return temperature versus outside air temperature for both occupied and unoccupied operating status. Figure 9 shows more clearly that during the occupied status, the boiler spends considerable time operating with a return water temperature below 120°F, resulting in condensing operation. However, during unoccupied status, which accounts for 35% more operating hours than the occupied status, the boiler operates relatively more time with a hot water return temperature above 120°F, resulting in non-condensing operation. Along with the higher hot water return temperature during the unoccupied status is a lower temperature difference between the supply and return temperature. One possible solution to this condition could be to reduce the hot water flow rate during the unoccupied status.

Figure 9: Hot Water Return Temperature (HWRT) versus Outside Air Temperature for Occupied and Unoccupied Operating Status



The hot water flow rate is controlled by a differential pressure sensor located in the hot water distribution loop. The BAS is programmed to increase or decrease the hot water supply pump flow rate by changing the speed of the variable-frequency drives as required to maintain a differential pressure set point as sensed by an existing differential pressure transmitter in the loop. The result is the hot water flow rate does reduce notably between the occupied and unoccupied periods, as shown in Figure 10. The BAS program that controls the flow rate, however, does not differentiate between the occupied and unoccupied status, but could. To lower the return water temperature further during the unoccupied status, the options are to reduce the supply water temperature further or reduce the hot water flow rate further. Given the extreme low load conditions observed during the unoccupied status, a combination of both is likely warranted. Modifying the BAS program to further reduce the hot water supply temperature and lower the hot water flow rate would result in lowering the hot water return temperature, which would result in increasing the further operation of the boilers in the condensing mode, thereby saving more energy.

Figure 10: Hot Water Flow Rate versus Outside Air Temperature for Occupied and Unoccupied Operating Status



A note on thermal shock—thermal shock can be defined as the expansion and contraction that occurs within a boiler when exposed to rapid or large temperature differentials, such as when a cold boiler is exposed to hot water (*i.e.*, such as when adding an isolated cold boiler to an active heating system) or when a hot boiler is exposed to cold water (*i.e.*, such as may occur during start-up when recovering from an overnight setback mode). Thermal shock, as a term, is a misnomer in that the event is not sudden (as the word *shock* would imply), but rather it is the result of long-term stresses from being exposed to repeated expansion and contraction. Thermal shock can occur when a boiler is exposed to rapid or large temperature changes, uneven temperature changes, or parts of the boiler expanding or contracting more rapidly than other parts. Many conventional (non-condensing) boiler designs are susceptible to thermal shock concerns (*i.e.*, cast iron, scotch marine, or firebox boilers). Condensing boilers, however, are designed and constructed to be highly resistant to thermal shock. Many of the operating strategies presented in this report to improve the performance of condensing boilers may not be appropriate for conventional (non-condensing) boilers because of the concern for the potential impact of thermal shock. Condensing boilers, however, are designed to accept low return water temperatures and respond quickly to cold starts without concern for thermal shock. (Pilaar 2007, Vastyan 2011, 2012)

VI. Summary Findings and Conclusions

A. OVERALL TECHNOLOGY ASSESSMENT AT DEMONSTRATION FACILITY

The application of condensing boilers offers the potential for reducing energy consumption through improved efficiency. Conventional boilers can be found to operate between 75% and 83% efficiency, with conventional nameplate ratings typically based on 80% nominal efficiency (output/input). Condensing boilers, designed for use with natural gas, are commercially available from a number of manufacturers with rated efficiencies ranging from the low- to high-90s. With the right design and applications, GSA could significantly reduce natural gas energy consumption in building heating systems.

Based on the performance data collected and evaluated from the Peachtree Summit Federal Building application, the condensing boiler technology is capable of achieving performance claims. However, results will greatly depend on the proper application and operation. High operating efficiency is achieved when the boiler operates in the condensing mode, which generally requires a lower entering water temperature (typically below 120 to 130°F). As shown in Figure 9, the heating system serving the Peachtree Summit Federal Building did operate with a return water temperature below 120°F, but mostly during unoccupied hours or when the heating plant would be expected to have low load.

The installation cost of the condensing boilers at the Peachtree Summit Federal Building was high, $729,755 for design and installation. However, the cost was mostly associated with the installation rather than the added cost of the condensing boilers compared to that of conventional boilers (additional cost of the four condensing boilers alone was $28,000 over the cost of equivalent capacity non-condensing boilers). For difficult to install applications, replace-on-failure or replace-on-end-of-life is probably the most cost-effective strategy. For new construction, the additional cost associated with condensing boilers is recoverable through reduced energy operating costs.

It is important to understand that condensing boilers operate differently than conventional boilers and, to realize some of the potential energy savings achievable with condensing boilers, designers and operators may need to modify their approach. Most important is to investigate ways to reduce the hot water return temperature, whenever possible and to the maximum extent possible. For retrofit applications, this could be accomplished by reducing the hot water supply temperature, when the thermal load allows. This may also be accomplished by reducing the hot water flow rate, again, when the load allows; thereby increasing the temperature drop through the heating coils. In new construction, designers may consider selecting heating coils that can deliver design heat loads with lower hot water supply temperatures, as well as increased temperature drop through the heating coils. For new construction projects, it may be cost effective to select heating coils designed to improve the operation of a condensing boiler plant. For retrofit projects, replacing heating coils throughout the heating system is likely cost prohibitive.

B. BEST PRACTICE

A boiler system needs to be capable of meeting the building's peak thermal heating demand, as well as operate efficiently under part-load conditions. Designing the right system configuration and specifying the proper boiler capacities requires an understanding of both the peak thermal demand and thermal load profile. When the range of building thermal loads is highly variable, as is common in commercial buildings and clearly shown in the previously presented data in Figure 6, designers should consider specifying and installing multiple modular boilers, in addition to boilers that have fully modulating burners. During periods of low thermal demand, some of the boilers can be isolated from the system to reduce standby losses or cycling losses while off-line. Modular boilers can also be automatically staged so the system as a whole is running at its most efficient operating point, while minimizing unnecessary boiler cycling. These types of best practices are applicable to condensing boiler heating systems, but are also beneficial when applied to conventional, non-condensing, boiler systems.

However, having modular condensing boilers with fully modulating burners is still not a guarantee of efficient operation. Condensing boilers will operate as non-condensing boilers when the conditions are not right for condensing operation. The following best practices are identified to assist in maximizing the frequency of operational conditions that provide for optimum efficiency.

Hot water supply temperature reset—Hot water boilers should have the capability for hot water supply temperature reset. This control strategy, available with most BAS and central boiler control systems, can be based on the outside air temperature, or the return water temperature, or in the case of the Peachtree Summit Federal Building, based on system load. In general, when the thermal load is reduced, the hot water supply temperature set point is reduced. While this does reduce the heating capacity of the heating coils, the demand is already reduced. The result is the return water temperature is reduced further, which improves the efficiency of the condensing boilers.

Modulating burners with high turn-down ratio—The boilers specified should have the capability to vary their heating output by modulating the burner. Thermal demand is almost always below the peak design load, even when multiple boilers are used. Rather than cycling boilers on and off to meet demand, which has a severe energy penalty, fully modulating boilers will vary the firing rate, operating continuously, to meet current thermal demand requirements. A minimum turn-down ratio of 4:1 is recommended by FEMP for gas/water boilers.[19] However, some condensing boilers are designed to operate with greater turn-down ratios, such as 10:1 to 20:1. The greater the turn-down ratio, the less frequently a boiler may be required to cycle off and on. In addition, many condensing boilers are designed to operate more efficiently at partial load.

Optimum start control—An optimum start control brings boilers on line so that it fires just in time to heat up and meet an increase in thermal demand, such as increasing the temperature in a building that has been in temperature set-back mode overnight. Similarly, optimum stop control is used to take boilers off-line when the building is preparing to enter a temperature set-back mode of operation.

Low mass—Boilers with a low quantity of internal water are referred to as “low-mass” boilers. Contrast this with conventional fire tube or “Scotch” marine boilers that contain significant volumes of water (high mass). Because boilers can cycle on and off and it takes time (and energy) to bring a high-mass boiler up to operating temperature, using low-mass boilers will reduce energy consumption and increase response time. Some boilers can be brought on-line quickly, thereby avoiding the need to keep a boiler on hot standby.

[19] See FEMP, Commercial Boiler, Buyer Tips at http://www1.eere.energy.gov/femp/technologies/eep_boilers.html, last accessed 7/10/2012.

Heating coil selection—As noted earlier, selecting larger heating coils designed to provide the required heat transfer rate, but with greater temperature drop across the coil and a lower supply water temperature, will result in a much lower return water temperature. This, in turn, will reduce the condensing boiler's entering water temperature, which results in more frequent operation in the condensing mode, and improves the system efficiency. Best practices for heating coil selection for use with condensing boilers include designing systems to operate with temperature drops of at least 40°F to as high as 60°F under design conditions. It is noted that *GSA Facilities Standards for the Public Buildings Service* (also called the P100), Section 5.12, Primary Heating Systems, specifies that total system temperature drop must not exceed 30°F and that the temperature drop for terminal unit heating coils must be 20°F (GSA 2010). It is recommended that GSA update the P100 to allow for more optimal integration of condensing boilers in new construction.

Primary versus primary-secondary distribution system—The distribution system installed at the Peachtree Summit Federal Building and illustrated in Figure 3 is a primary-secondary distribution system. The primary distribution system, operating with constant-speed pumps, circulates water through the individual boilers during firing. The secondary distribution system, operating with a variable-speed pump (using a variable-frequency drive), circulates water through the building between the boiler plant and the heat delivery system (heating coils). According to Cutler *et al.* (2012), primary-secondary distribution systems are not generally recommended for use with condensing boiler heating plants. The concern with primary-secondary distribution system is when the boiler circulation flow rate and the thermal load (building) circulation flow rate do not match. When the boiler circulation flow rate is greater than the building circulation flow rate, some of the heated water from the boiler output bypasses the building and mixes with the return water, resulting in an increase in the boiler's entering water temperature. This, in turn, reduces the efficiency of the condensing boiler. When the boiler circulation flow rate is less than the building circulation flow rate, the water heated by the boilers is mixed with return water that bypasses the boilers. This, in turn, results in a lower hot water supply temperature. A heating system that uses heating coils selected for high temperature drop operates best when there is a minimum of mixing of the supply and return water. A primary-only distribution system is best suited for use with heating systems designed with coils selected for high temperature differentials.

While the Peachtree Summit Federal Building monitored in this demonstration was a simple boiler retrofit and did not involve a redesign of heating coils for higher temperature differentials, examination of the data during unoccupied hours does show the negative impact of a primary-secondary distribution system. The primary pumps are rated at 165 gpm (at 25-feey of head pressure). Examination of the building (secondary) circulation flow rate, illustrated in Figure 10, shows considerable operation below the primary rated flow rate. The result is the heated water from the boiler bypasses the building distribution loop flowing back into the return water line. The boiler's entering water temperature then increases, which results in a lowering of the boiler's thermal efficiency.

Reducing the primary flow rate during the unoccupied, low load, periods could improve the overall efficiency of the condensing boiler plant. Of course, it is important to not reduce the boiler's flow rate below the manufacturer's minimum flow rate requirement. [As noted in Table 1, the installed condensing boilers at the Peachtree Summit Federal Building are designed to operate at 119 gpm at 40°F ΔT.]

Variable-speed pump control—The hot water supply pump distributes the heating energy from the boiler plant through the building to the zones calling for heat. The use of variable-speed drives on circulation pump motors, in place of by-pass control valves, can significantly reduce pumping power. In addition, lowering the circulation flow rate can be used as a tool for enhancing the temperature drop through the system, thereby reducing the hot water return temperature. Reducing the return water temperature also reduces the boiler's entering water temperature, which improves the operating efficiency of the condensing boiler. Lower limits should be placed on the circulation flow rate so that the boiler's minimum flow rate is not compromised.

Master boiler management controller—For a boiler plant consisting of multiple boilers, the master controller stages the boilers, controls sequencing, and modulates the firing rates to achieve the highest operating efficiency. Condensing boilers operate differently than non-condensing boilers. For example, with non-condensing boilers, plant efficiency is typically optimized by keeping the fewest number of boilers on-line as possible to meet the load. However, with condensing boilers, efficiency is frequently optimized by keeping as many boilers on line as possible. Condensing boilers are more efficient at low load; the greater residence time (of combustion gases in the heat exchanger) allows more condensation to occur within the boiler. The master controller also acts as the interface between the boiler plant and the BAS. The master controller should generally be specified to be provided by the boiler manufacturer. Because there are several manufacturers of condensing boilers, each with unique characteristics, the master controller needs to be compatible with the condensing boilers, as well as the BAS. Further, the control sequence for multiple boilers is dependent on how the heating system is piped. The manufacturer or vendor representative should be involved in the design process to ensure the control system configuration matches the piping arrangement.

Remote monitoring capability—Remote monitoring capability is useful to manage boiler operation and to detect any malfunctions in a timely manner. This capability enhances the O&M function, which, in turn, can save energy.

Cutler *et al.* (2012) identifies additional design and operating practices that can result in a more efficient condensing boiler plant.

C. BARRIERS AND ENABLERS TO ADOPTION

One of the greatest barriers to adoption is concern for the condensate that forms. As water vapor in the products of combustion condenses, the condensate becomes acidic. The amount of condensate that forms is relative to the firing rate, but is expected to be around 0.2 gpm per million Btu/h with a pH between 2 and 4. This raises two issues. First, the exhaust stack needs to be constructed of corrosion resistant material. Second, the acidic condensate needs to be neutralized prior to disposal. While these are acknowledged concerns, they can be addressed.

The use of dual-wall stainless steel exhaust stack material is the most common recommended practice. Stainless steel, while thinner and lighter, is more expensive than conventional carbon steel exhaust stacks, which adds to the overall cost of the condensing boiler system. Some condensing boilers lower the exhaust temperature to the point where the exhaust stack may be constructed from non-metallic material. This is not a common practice and may not be allowed by local codes.

The acidic condensate is found in two locations. Within the boiler, condensate that collects in the heat exchanger is routed through a collection chamber and then piped outside the boiler. Additional condensate is collected at the base of the exhaust stack. Condensate that is collected from the boiler and from the base of the exhaust stack should be piped to a condensate neutralizer. Smaller neutralizer kits can be plumbed in line with the condensate pipe on its way to the sewer drain. Larger systems may be located behind the boiler and include float valves and neutralizing chambers with an overflow to drain. Figure 11 shows two photos of in-line neutralizers installed on condensing boilers. The photo on the left shows an in-line condensate neutralizer installed on a 2 million Btu/h condensing water heater. The in-line canister is about 4-inches in diameter. Flexible tubing (3/4-inch) routes the condensate from the boiler and exhaust stack to the neutralizer. Downstream of the neutralizer, the flexible tubing transitions to 3/4-inch PVC piping and is routed to a sewer drain. The photo on the right shows a 3-inch diameter in-line condensate neutralizer installed on a 600,000 Btu/h condensing boiler used for space heating. The neutralizer is connected via flexible tubing, but hard pipe (out of photo) routes the neutralized condensate to drain. The capacity of condensate neutralizers is typically designed for annual maintenance. Therefore, the condensate neutralizer adds to both the first cost, as well as the annual maintenance cost of a condensing boiler.

Figure 11. In-line Condensate Neutralizer Kits Installed on Condensing Boilers

D. MARKET POTENTIAL WITHIN GSA PORTFOLIO

Almost any space heating system can be designed for optimal use with condensing boilers. For new construction, the hydronic heating system can be designed to take advantage of the efficiency benefits offered from condensing boilers. [This will require some modifications to the P100 with regard to the allowable design temperature drop through the heating system components.] On a retrofit basis, there are several circumstances that may not allow for optimal use of condensing boilers and, therefore, may not be cost effective as a stand-alone retrofit project. These systems, however, should be assessed near the end of current space heating boiler equipment life and when preparing for major facility modernization.

Insufficient information is available to identify properly the number of cost-effective candidates throughout GSA portfolio of buildings. It is recommended that condensing boilers be a required technology assessment during facility energy evaluations, which are required by EISA for every covered GSA facility every four years[20] (EISA 2007). It is estimated that the market potential within GSA for the application of condensing boilers could reduce annual energy consumption by around 93 to 140 billion Btu/yr. This equates to potential energy savings of between 0.7% and 1.0% of GSA's FY2007 total energy consumption. This estimate is based on the following assumptions:

- space heating accounting for 35% of GSA's annual energy consumption [consistent with CBECS (EIA 2003a)]
- boilers providing space heating in 34.5% of GSA's facilities [consistent with CBECS (EIA 2003b)]
- condensing boilers reducing boiler energy consumption by an estimated 10 to 15% (consistent with the findings in this report), and
- based on GSA's reported energy consumption during FY2007 (FEMP 2010).

E. RECOMMENDATIONS FOR INSTALLATION, COMMISSIONING, TRAINING, AND CHANGE MANAGEMENT

It is recommended that a thermal load calculation be performed by a qualified engineer to determine whether the heating plant is designed to meet the thermal load without excessive overcapacity. Similarly, for existing facilities, the actual thermal load and profile could be measured to validate proper equipment sizing. As noted by Cutler *et al.* (2012), relying on the size of the previous heating plant capacity is not an acceptable sizing strategy. Given the energy reduction achievements by GSA, as well as other improvements in modern design techniques, previous equipment may have excess capacity and be oversized to meet current loads. For example, examination of Figures 6 and 7 illustrate that the heating plant at the Peachtree Summit Federal Building can meet the measured building's thermal load at the winter design temperature with three of the four boilers. This sizing does meet with the intent of the n+1 equipment sizing required in the P100.

[20] EISA Section 432 requires agencies to identify their facilities that constitute at least 75% of the agency's facility energy use, also referred to as "covered facilities," and complete comprehensive energy and water evaluations of 25% of covered facilities each year, so that an evaluation of each facility is completed at least once every four years (Reference: FEMP web site at http://www1.eere.energy.gov/femp/regulations/eisa.html).

VII. APPENDICES

A. ABBREVIATIONS AND ACRONYMS

The following is a list of abbreviations, acronyms, and terms as used in this report.

Term	Description
AGL	Atlanta Gas Light, an AGL Resources company
AGL Resources	a utility energy services company
AHRI	Air Conditioning, Heating and Refrigeration Institute
Amp	ampere (electric current)
ARRA	American Recovery and Reinvestment Act of 2009
ASHRAE	American Society of Heating, Refrigerating, and Air Conditioning Engineers
ASME	American Society of Mechanical Engineers
BAS	building automation system
Btu	British thermal unit
Btu/h	British thermal units per hour
CBECS	Commercial Buildings Energy Consumption Survey
CEE	Consortium for Energy Efficiency
CFR	U.S. Code of Federal Regulations
CH_4	methane, a primary component of natural gas
CO_2	carbon dioxide
C_p	specific heat (of a fluid at constant pressure)
DAS	data acquisition system
DFC	Denver Federal Center
DOE	U.S. Department of Energy
EIA	U.S. Energy Information Administration
EISA	Energy Independence and Security Act of 2007
EPA	U.S. Environmental Protection Agency
FEMP	U.S. DOE Federal Energy Management Program
gal	gallons (of water)
GPG	Green Proving Ground
gpm	gallons (of water) per minute
GSA	U.S. General Services Administration
h	hour
H_2O	water
HDD	heating-degree days (base 65°F)
HHV	higher-heating value
hp	horsepower
HWRT	hot water return temperature
HWST	hot water supply temperature
HWSTSET	hot water supply temperature set point

Term	Description
Hz	hertz (frequency)
IECC	International Energy Conservation Code
lb, lbs	pounds
kW	kilowatt
LHV	lower-heating value
max	maximum
MBtu/h	1000 Btu/h
min	minimum
min	minute
NREL	National Renewable Energy Laboratory
O&M	operations and maintenance
ph	Phase (electric)
pH	Measure of alkalinity ranging from 2 to 14, 7 being neutral
P100	Facilities Standards for the Public Buildings Service, P100, U.S. General Services Administration, Washington DC
PNNL	Pacific Northwest National Laboratory
psig	pounds per square inch gage pressure
PVC	polyvinyl chloride
q_f	fuel flow
$\dot{q}_{HW}$	hot water volumetric flow rate
Q_{in}	energy input
Q_{out}	energy output
RH	relative humidity
scf	standard cubic foot (of natural gas)
therm	100,000 Btu
TMY	typical meteorological year
TMY3	a third update of TMY data for 1020 locations based on data from 1991 to 2005
T_{ret}, T_{return}	return temperature
T_{sup}, T_{supply}	supply temperature
UESC	utility energy service contract
v	voltage (electric potential)
VFD	variable-frequency drive
yr	year
ΔT	temperature difference
$\eta_{thermal}$	thermal efficiency
ρ_{HW}	density of hot water
" w.c.	inches of water column, a measure of pressure

B. GLOSSARY

The following is a glossary of advanced terminology in support of this report.

Terminology	Description
Active (chilled beam)	A chilled beam system in which forced air is used to deliver the cooling into the space.
Affinity laws	A set of three mathematical equations that define the relationship between rotational speed, flow rate, pressure rise, and brake horsepower for centrifugal systems.
Air-cooled chiller	A refrigerating machine in which heat removal is accomplished entirely by heat absorption by air flowing over condensing heat exchanger surfaces (condenser is air cooled).
Air-handling unit	A device used to condition and circulate air as part of a heating, ventilating, and air-conditioning (HVAC) system
Annual load profile	A measure of the time distribution of thermal or other energy loads, such as Btu/h, for a system over the course of a year.
Back up	An additional, redundant, piece of equipment used to increase the operational reliability or availability of a system.
BACNet	A communications protocol for building automation and control networks. It is an ASHRAE, ANSI, and ISO standard protocol.
Baseline	Typically referring to an energy profile, model or characteristics, or any combination, before changes have been made to a system for the purpose of modeling the original operating condition, derived from measurements taken over a period of time and used as a basis for comparison to one of more options or alternatives.
Bin data	A data pre-processing technique used to reduce observation errors.
boiler (hot water)	A closed pressure vessel that consumes energy for the purpose of heating water or other fluids.
Boiler horsepower	An antiquated boiler output capacity term equal to 33,475 Btu/h.
Building automation system (BAS)	A computerized network of electronic devices designed to monitor and control the mechanical, electronics, and lighting systems in a building.
Capacity	Intended technical full-load (a.k.a., maximum) sustained output of a facility, system, or device. Typically quantified as a power rating or rate of energy transfer. May also be known as nameplate capacity, rated capacity, nominal capacity, or installed capacity.

Terminology	Description
Central chiller plant	A single or common chilled-water facility consisting of one or more chillers used to serve one or more facilities.
Centrifugal compressor	A dynamic (or non-positive-displacement) compressor that uses rotational (centrifugal) forces to raise pressure in the refrigerant system.
Chilled-water pumps	Pump and motor system used to circulate chilled water for space or process cooling distribution systems.
Chilled-water return temperature	The temperature of the chilled water entering the evaporator or returning from the facility distribution system.
Chilled-water supply temperature	The temperature of the chilled water leaving the evaporator or being supplied to the facility distribution system.
Chilled-water temperature reset	An operating strategy in which the chilled water supply temperature set point is varied in response to a control signal or varying sensor input.
Chiller	A machine that removes heat from a liquid via a vapor-compression or absorption refrigeration cycle.
Climate zone	A region with similar weather characteristics.
Coefficient of Performance (COP)	The ratio of the heating or cooling provided divided by the electrical energy consumed, as a unitless measure. The COP provides a metric of performance for heat pumps that is analogous to thermal efficiency for power cycles.
Commission (commissioning process)	A quality focused process for enhancing the delivery of a project. The process focuses upon verifying and documenting that the facility and all of its systems and assemblies are planned, designed, installed, tested, operated, and maintained to meet the Owner's Project Requirements.
Condenser	The part of a refrigerant system where refrigerant is liquefied by removal of heat through use of a heat sink.
Condenser-water temperature	The temperature of the water departing the cooling tower or entering the water-cooled condenser, or both.

Terminology	Description
Condenser-water temperature reset	An operating strategy in which the condenser-water temperature set point is varied in response to a control signal or varying sensor input.
Condensing boiler	A boiler designed to extract sufficient heat energy that, under the right set of operating conditions, the moisture resulting from the products of combustion may condense from vapor to liquid allowing the heat energy released to be absorbed and recovered by the heat transfer fluid.
Condensing coil	A heat exchanger in which the refrigerant rejects heat to the point where the refrigerant condenses from vapor to liquid.
Condenser-water pump	Motor-driven pump used to circulate water through the condensing system
Constant speed	A motor system in which the motor's rotational speed remains (relatively) constant--may be applied to a pump, fan or chiller.
Constant volume (pumping system)	A pumping system in which the pump speed remains (relatively) constant.
Constant-air volume	A type of HVAC system that delivers supply air at a constant flow rate, but in which the supply temperature will vary to meet variable thermal loads.
Cooling tower	A heat removal device used to transfer (reject) heat to the atmosphere via the evaporation (mass transfer) of water.
Cooling-tower-water temperature reset	An operating strategy in which the condenser-water temperature (water temperature returning from the cooling tower) set point is varied in response to a control signal or varying sensor input.
Current transformer	Sensor used to measure the electric current in a wire
Cycling losses (boiler)	Energy loss that occurs as a result of a boiler cycling on and off, mostly as a result of the burner's pre-purge and post-purge process.
Dashboard	A display capable of providing operational data or information on a system or unit of equipment, either in real time or near real time.
Data Acquisition System (DAS)	A computer-based device that records results of input signals from meters or sensors, or both.

Terminology	Description
Dedicated outdoor air system (DOAS)	A type of HVAC system that consists of two parallel systems: a dedicated outdoor air ventilation system that handles latent loads and a parallel system to handle sensible loads.
Dehumidification	The act of removing moisture (from air).
Dehumidifier	A device that removes moisture (from air).
Dehumidify	The removal of moisture from air.
Design conditions	Specified environmental conditions, such as temperature and humidity, required to be produced and maintained by a system.
Design load	The thermal load expected to occur under design conditions.
Dew point	The temperature below which the water vapor in a volume of humid air at a constant barometric pressure will condense into liquid water.
Direct expansion (DX)	Evaporator arrangement whereby liquid refrigerant is fed through an expansion device and evaporates completely before leaving as vapor.
Displacement ventilation	A room or air distribution strategy where conditioned outdoor air is supplied at floor level and extracted above the occupied zone, usually at ceiling height.
Down time	Period of time in which equipment is not operating or off-line.
Dry-bulb temperature	The temperature of air measured by a thermometer freely exposed to the air, but shielded from radiation and moisture. Dry-bulb temperature is the temperature that is usually thought of as air temperature.
Economizer (HVAC)	A duct and damper arrangement and automatic control system that together allow a cooling system to supply outdoor air to reduce or eliminate the need for mechanical cooling during mild or cold weather.
Efficiency	Typically, energy output divided by energy input, but may also be defined as useful energy output divided by consumed energy input.
Electronically commutated motor (ECM)	Also known as brushless direct-current (DC) motors, are synchronous motors powered by a DC electric source via an integrated inverter/switching power supply, which produces an AC electric signal to drive the motor. ECM motors are much more efficient than other fractional horsepower motor types.

Terminology	Description
Energy-efficiency ratio (EER)	A ratio of the net refrigerating capacity in Btu/h to the power input value in Watts at a given set of rating conditions, expressed in Btu/(h · W).
Energy savings Performance Contract (ESPC)	An alternative financing mechanism in which a customer can procure turnkey energy efficiency products and services from an energy service company in which the cost of the products and services are repaid over time and come with a certain level of performance guarantee.
Energy service company (ESCO)	A company that provides turnkey energy services and products.
Energy-use intensity (EUI)	A metric determined as energy consumed within an facility divided by the gross square foot of the facility, expressed as Btu/ft2-yr.
Entering water temperature	The temperature of water, or heat transfer fluid, entering the device or equipment.
Enthalpy wheel	A heat recovery device used to exchange both sensible and latest heat energy between two (air) streams.
Fan coil unit	A small air-handling unit consisting of a heating or cooling coil, or both, and a fan used to serve a single space (control zone) without a ducted air distribution system. The coils are typically designed for use with heated or chilled water and used to condition air recirculated within the space.
FEMP Designated Product	Products that meet FEMP-designated efficiency requirements and are in the upper 25% of their class in energy efficiency.
Fire-tube boiler	A boiler in which the hot combustion gases flow through the inside of the heat transfer tubes and the heat transfer tubes are immersed in the water being heated.
Footprint	The floor area required for placement.
Full load	The nominal peak load that a piece of equipment is designed to carry under design conditions.
Grain (of moisture)	A unit of measure of water vapor; 7,000 grains of moisture per pound of water.
Ground-source heat pump	A heat pump using a brine solution circulating through a subsurface piping loop that functions as a heat source/heat sink.

Terminology	Description
Ground-water-source heat pump	A heat pump using water pumped from a well, lake, or stream functioning as a heat source/heat sink.
Heat pump	A thermodynamic heating/refrigerating system used to transfer heat. The condenser and evaporator may change roles to transfer heat in either direction.
Heating-degree day	The difference in temperature between the outdoor mean temperature over a 24-hour period and a given base temperature. For heating degree-days, includes data when the mean daily temperature is below the given base temperature. Unless otherwise noted, the base temperature is typically 65°F.
Heat-transfer fluid	A fluid, such as water or water-glycol solution used to transfer heat from the heat source (equipment) to the heat sink (load).
Higher-heating value	The total amount of heat energy released during the combustion of a specified amount of fuel that takes into account the latent heat of vaporization of water in the combustion products.
Hot-water return temperature	The temperature of the hot water returning from the facility distribution system.
Hot-water supply temperature	The temperature of the hot water being supplied to the facility distribution system.
Hot-water supply temperature reset	An operating strategy in which the hot-water supply temperature set point is varied in response to a control signal or varying sensor input.
Humidity ratio	A measure of the absolute humidity in moist air, expressed as the mass of water contained per mass unit of dry air.
Impeller	The device inside a pump or fan used to increase pressure, and thereby induce flow, when in rotation.
Integrated energy-efficiency ratio (IEER)	A partial-load efficiency measure, calculated with the sum of weighting factors applied to tested efficiencies at four part-load conditions: (EER at 25%) X 0.125 + (EER at 50%) X 0.238 + (EER at 75%) X 0.617 + EER at 100%) X 0.02.

Terminology	Description
Integrated part-load value (IPLV)	A single-number metric based on part-load EER, COP, or kW/ton, expressing part-load efficiency for air conditioning and heat pump equipment on the basis of weighted operation at specific increments of load capacities for the equipment. Typically used for ARI rating purposes.
Interval data	Data collected with a uniform time period.
Kilowatt	An electric power term, meaning a rate of electric energy consumption.
Kilowatt-hour	An electric energy term, equal to 3412 Btu and 1,000 watt-hours.
latent heat energy	Heat exchanged by a thermodynamic body based on a phase change, such as water condensing into liquid or liquid evaporating into vapor.
Least-squares regression	A statistical model that relates the dependent (y-axis) to the independent (x-axis) variable by minimizing the summed square of the difference between the observed x-y data and the regression.
Leaving water temperature	The temperature of the water, or heat transfer fluid, leaving the device or equipment.
Life-cycle cost	The total discounted dollar costs of owning, operating, maintaining, and disposing of a building or building system over the study period.
Load factor	Actual load or average load divided by full load, typically expressed as a percentage of full or design-full load.
LONworks	Short for local operation network, it is a networking platform created to address the needs of control applications. The platform is built on a protocol created by Echelon Corporation for networking devices over media such as twisted pair, power lines, fiber optics, and radio frequency. The protocol is also one of several data link/physical layers of the BACnet ASHRAE/ANSI standard for building automation.
Lower-heating value	The amount of heat energy released during the combustion of a specified amount of fuel that does not account for the latent heat of vaporization of water in the combustion products
Magnetic bearings	Magnetic levitation used to prevent surface to surface (metal on metal) contact.
Meter	A sensor used for measurement.

Terminology	Description
Mixed-humid climate	As defined by U.S. DOE, a region that receives more than 20 inches (50 cm) of annual precipitation, has approximately 5,400 heating degree days (65°F basis) or fewer, and where the average monthly outdoor temperature drops below 45°F (7°C) during the winter months.
Modular configuration	An assembly consisting of multiple smaller units to provide a larger system capacity.
Modulating (burner)	Capable of operating at a variable rate from full-load down to a minimum load.
Monitoring system	A computer- or electronic-based device that observes or displays, but does not necessarily record, the results of input signals from meters or sensors, or both.
Net-present value	Future costs discounted to today's value.
Nominal (capacity)	The capacity reported by the manufacturer for a specified device under general conditions or recorded and reported by a given test.
Non-condensing boiler	A boiler designed such that, under the intended operating conditions, the moisture resulting from the products of combustion will not condense in the boiler or exhaust system.
Non-standard part-load value (NPLV)	A single number part load efficiency figure of merit calculated and referenced to conditions other than IPLV conditions for units that are not designed to operate at ARI Standard Rating Conditions.
Occupied (period)	A period in which a facility is typically occupied as a result of the normal business process.
Original Equipment Manufacturer (OEM)	Refers to the company that originally manufactured the finished product. Also refers to a company that may purchase for use in its own products a component made by a second company.
Passive (chilled beam)	A chilled beam system in which natural convection and buoyancy are used to drive airflow through the cooling coil and into the space.
pH	A figure expressing the acidity or alkalinity of a solution on a logarithmic scale in which 7 is considered neutral, lower values are more acidic, and higher values are more alkaline.

Terminology	Description
Plenum	According to ASHRAE, a compartment or chamber to which one or more ducts are connected, that forms a part of the air distribution system, and that is not used for occupancy or storage. A plenum often is formed in part or in total by portions of the building. An air compartment that is attached to, or is an integral part of, a forced-air furnace, which is designed to either distribute the heated air after it leaves the heat exchanger in the case of a supply plenum or collects air that enters the return inlet in the case of a return plenum. A component forming an interface between a ductwork and one or more air terminal devices; by virtue of its design or by the inclusion of accessories, it can also be used to equalize the pressure/velocity across the air terminal device.
Positive-displacement compressor	A compressor type that raises the pressure of a gas by trapping a fixed amount (volume) and forcing (displacing) that trapped volume into the discharge.
Post installation (period)	A period of time after a change to the system, typically compared or in contrast to a baseline period.
Power	The rate at which energy is transferred, used, or transformed; also the rate at which this work is performed. Power is determined as energy divided by time.
Power Input per Capacity	The ratio of the power input supplied to the unit in kilowatts [kW], to the net refrigerating capacity in tons refrigeration at any given set of rating conditions, expressed in kW/ton
Primary distribution system	A chilled- or hot-water distribution system in which the circulation flow through the facility is coupled with the circulation flow through the chilled-water or hot-water generators.
Primary-boost distribution system	A (water) distribution system in which multiple circulation pumps may be installed in series.
Primary-secondary distribution system	A chilled- or hot-water distribution system in which the circulation flow through the facility is de-coupled from the circulation flow through the chilled-water or hot-water generators.
Qualified engineer	A sufficiently trained and experienced engineer; may also include certification from an accredited professional organization or registered as a licensed professional engineer through a state regulatory agency.

Terminology	Description
Rate tariff	The schedule of charges and fees charged by a provider of energy services, such as a utility.
Reciprocating compressor	A positive-displacement compressor that uses pistons to raise the pressure of a gas or vapor.
Refrigerant head pressure	The pressure of a refrigerant system, typically at the discharge of the compressor.
Replace-at-end-of-life	Used in life-cycle cost analysis as a replacement alternative when the existing equipment is at the end of its useful life, so replacement is not optional. This option may also be called replace-on-failure. This type of life-cycle cost analysis is equivalent to the new construction analysis.
Retrofit	Used in life-cycle cost analysis as a replacement alternative when the existing equipment has considerable useful life remaining, so replacement is optional.
Roof-top unit	A packaged HVAC system designed to be mounted on the roof.
Rotary-screw compressor	A positive-displacement compressor type that uses a rotating mechanism of one or more screws to raise pressure of a vapor or gas.
Scroll compressor	A positive-displacement compressor type that uses two interleaving scrolls to raise pressure of a vapor or gas. One of the scrolls may be fixed, while the other orbits eccentrically without rotating, thereby trapping and compressing pockets of fluid between the scrolls. Another method for producing the compression motion is co-rotating the scrolls, in synchronous motion, but with offset centers of rotation. The relative motion is the same as if one were orbiting.
Sensible heat energy	Heat exchanged by a thermodynamic system based solely on a change in temperature.
Sensor	A device that measures a physical quantity and converts it into a signal that can be read by an observer or electronic instrument or system.
Sequencing	The strategy that defines how equipment will operate, such as loading and unloading and when a piece of equipment is placed on-line and taken off-line.
Service life	The expected usable or economic life (years) from a piece of equipment or system. The period of time over which a system continues to generate benefits.

Terminology	Description
Simple payback	The time in which an investment is recovered, or repaid, through the accumulation of savings, determined as installed cost divided by savings; however, the result must be less than or equal to the service life of the project.
Soft start	A method used with electric motors to reduce temporarily the load and torque in the powertrain of the motor during start-up. Normal start-up process is extended from less than a second to several seconds for the purpose of reducing the stress than may occur during the starting process.
Specific heat (of water)	Heat capacity per unit of mass. For water, the specific heat is 1 Btu/lbm-°F.
Split system	A packaged HVAC system consisting of two primary components; an indoor system for delivering heating, cooling and ventilation to the control zone and an outdoor system for heat rejection.
Stacked	As used in this report, the use of multiple modular components to create a larger system.
Standard cubic foot (natural gas)	The volume of a gas at 60°F and 1 atmosphere of pressure (~14.7 psia).
Standby losses (boiler)	Energy loss through the shell that occurs as a result of the boiler being warmer than ambient.
Static pressure	The pressure at a specific point as can be measured using a pressure sensor. (To avoid potential ambiguity when referring to pressure in fluid dynamics, many authors use the term static pressure to distinguish it from total pressure and dynamic pressure. Static pressure is identical to pressure.)
Temperature bin	An interval range of temperature data used for energy analysis.
Testing standard	Common and repeated use of rules, conditions, guidelines or characteristics for products, equipment or systems; methods of measuring capacity, or other aspects of operation, of a specific unit or system of a given class of equipment, together with a specification of instrumentation, procedure, and calculations, typically set forth by a professional technical association.
Therm	A quantity of thermal energy equal to 100,000 Btu.

Terminology	Description
Thermal compound	A viscous fluid substance that increases the thermal conductivity of a thermal interface by filling microscopic air-gaps present due to the imperfectly flat and smooth surfaces of the components; used to improve the accuracy and responsiveness of temperature sensors.
Thermal cooling load	The heat energy needed to be removed from a space to maintain the desired space temperature set point.
Thermal efficiency	A dimensionless performance metric for a device, determined by useful thermal energy output divided by added thermal energy input.
Thermal shock	The expansion and contraction that occurs within equipment when exposed to rapid or large temperature differentials. The term is a misnomer in that the event is not sudden (as the word shock would imply) but rather it is the result of long-term stresses from being exposed to repeated expansion and contraction or uneven temperature changes.
Thermocouple	A thermoelectric device used to measure temperatures accurately, consisting of two dissimilar metals joined so that a potential difference generated between the points of contact is proportional to the temperature difference between the points.
Ton (cooling)	A unit of measure equal to 12,000 Btu/h, the equivalent energy absorbed by melting 1-ton of ice from solid to liquid at 32°F in a 24-hour period.
Trend line	An approach to modeling the relationship between a scalar dependent variable, Y, and one or more explanatory variables denoted, X. Typically the result of a best-fit regression analysis.
Turn-down ratio	The ratio of maximum to minimum operating load factor for a modulating piece of equipment.
Typical meteorological year (TMY)	A typical meteorological year (TMY) is a collation of selected weather data for a specific location, generated from a data bank much longer than a year in duration. It is specially selected so that it presents the range of weather phenomena for the location in question, while still giving annual averages that are consistent with the long-term averages for the location in question.

Terminology	Description
Ultrasonic flow meter	A transit-time ultrasonic flow meter is a device that utilizes two transducers, which function as both ultrasonic transmitters and receivers, to measure the velocity of a fluid (in a pipe) by measuring the difference in time response of sonic signals through the fluid in both up-stream and down-stream measurements.
Unoccupied (period)	A period outside of normal business-occupancy time. Although the facility may still have occupancy, the occupancy level is significantly below what is considered normal during the business process.
Utility	An energy-service provider.
Utility program	An incentive or support program sponsored by a serving utility company.
Variable speed	A system in which the (rotational) speed can vary as a result of changing control parameters.
Variable-air volume	A type of HVAC system in which the supply air flow rate to the conditioned space varies to meet variable thermal loads.
Variable-frequency drive	A type of adjustable-speed drive used in electro-mechanical drive systems to control AC motor speed and torque by varying motor input frequency and voltage.
Water-cooled chiller	A chiller in which water is used in the refrigerant condensing process.
Water-side economizer (HVAC)	A heat exchanger that uses the condenser water side of the system for cooling without requiring the operation of the chiller when conditions are favorable.
Water-source heat pump	A heat pump using a pre-conditioned water source (*e.g.*, cooling tower or boiler) as a heat source/heat sink.
Water-tube boiler	A boiler in which the hot combustion gases flow over the heat transfer tubes and the water flows through the inside of the heat transfer tubes.
Weather normalized	A statistical analytical technique that allows the comparison of corresponding normalized values for different datasets in a way that eliminates the effects of certain gross influences, in this case weather conditions.

Terminology	Description
Wet-bulb temperature	The (thermodynamic) wet-bulb temperature, also known as the adiabatic saturation temperature, is the temperature a volume of air would have if it were cooled adiabatically to saturation (100% relative humidity) by the evaporation of water into it, with the latent heat being supplied by the volume of air. The wet-bulb temperature is the lowest temperature that can be reached under current ambient conditions by the evaporation of water only.
Zone (thermal control zone, HVAC)	A space (or group of spaces) within a building with heating or cooling requirements that are sufficiently similar so that desired conditions can be maintained throughout using a single controlling device.

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D. HISTORICAL CONSUMER PRICE FOR NATURAL GAS FOR COMMERCIAL FACILITIES

Figure 12 illustrates the historical consumer price of natural gas for commercial consumers for Georgia compared to the U.S. average from 1995 to 2012 (latest data available). As shown, natural gas prices vary considerably based on seasonality, as well as market factors. The facility's reported average natural gas cost of 0.798/therm ($7.98/Mcf) is around 10% below the Georgia 2012 low.

Figure12. Consumer Price Comparison for Natural Gas for Commercial Facilities
(Reference: EIA, http://www.eia.gov/dnav/ng/ng_pri_sum_a_EPG0_PCS_DMcf_m.htm)