New York State Energy Research and Development Authority

The Wild Center Renewable Heating Demonstration:

High-Efficiency, Commercial-Scale, Wood-Pellet Boiler Integrated with a Solar Thermal System

Final Report

March 2013

NYSERDA Report 13-08

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The Wild Center Renewable Heating Demonstration: High-Efficiency, Commercial-Scale, Wood-Pellet Boiler Integrated with a Solar Thermal System

Prepared for:

New York State Energy Research and Development Authority
Albany, NY

Ellen Burkhard, Ph.D., Senior Project Manager
Nathan Russell, Associate Project Manager

Prepared by:

The W!ld Center
Natural History Museum of the Adirondacks
Stephanie Ratcliffe, Executive Director
Dave St. Onge, Facilities Manager

and

Clarkson University
Potsdam, NY
Philip K. Hopke, Ph.D.,
Director of the Center for Air Resources Engineering and Science and
Director of the Institute for a Sustainable Environment

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Preface

This project is a technology demonstration of the first Made-in-New York commercial pellet boiler by Advanced Climate Technologies (Schenectady, NY). This pellet-fired heating system is integrated with a solar-thermal hot water system, thus allowing for improved system efficiency and a zero emissions heating mode during late spring, summer and early fall when heating demand is low. The demonstration was an important engineering accomplishment for this emerging technology, and included a rigorous third-party scientific evaluation of the efficiency and emissions performance of the boiler by Clarkson University. This heating system is also part of a comprehensive educational display at the Wild Center, allowing thousands of visitors to learn about these emerging technologies.

NYSERDA’s Biomass Heating Program is a joint effort of the Environmental R&D and Building R&D Programs to develop a high-efficiency biomass heating market of technologies with acceptable emissions performance in New York State.

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Summary

The use of biomass fuel combustion for residential and commercial heating has gained attention due to the fluctuating price of fossil fuels and the desire to use renewable energy. However, conventional wood burning systems in the U.S. tend to have relatively low efficiency and high emissions of CO and particulate matter (Gammie and Snook 2009). In Europe, a number of advanced combustion systems have been developed that are reported to provide substantially higher thermal efficiency and lower emissions than conventional U.S. systems (New York State Energy Research and Development Authority (NYSERDA 2010a). These advanced systems use staged combustion units with sensors and process control systems that provide high thermal efficiency above 85% at steady state output when the demand in the building is about 100% and also greatly reduced emissions of pollutants from the stack when compared with conventional wood fired boilers. Thus, in 2008, NYSERDA initiated a series of studies on these high-efficiency wood boiler systems.

The Wild Center is the natural history museum of the Adirondacks (Figure S-1). It is science-based, and its experiences, exhibits and programs are designed to open new ways to look into the latest discoveries made by natural scientists. There may be no more important issue facing humankind than discovering better ways to coexist with the rest of the natural world, and there may be no better place to understand that effort than in the Adirondacks. The Center is the place to see and appreciate the natural side of that vital story. It is the first LEED® Certified museum in New York State. Through "green" building programming, the Center offers a model of sustainable living approaches. The boiler system has been integrated into a core educational component – which is featured in workshops, conferences, publications and tours reaching hundreds of people every year – in this "green building" program, in addition to functioning to save the Center energy dollars each year. The Wild Center heating system uses an innovative combination of renewable energy solutions, integrating a solar thermal hot water system with a 1.7 MMBtu/h pellet boiler. The boiler system is the first highly efficient, commercial-sized, gasification wood-pellet boiler of its kind and size manufactured and installed in New York State. The main objective of this study was to evaluate the energy performance of the wood boiler system and to monitor the combined performance of the wood-pellet boiler coupled with a solar hot water system during the winter and shoulder heating seasons.

Figure S-1. The Wild Center is located in Tupper Lake, NY.

Source: Wild Center

S.1 High-Efficiency Pellet Boiler and Solar-Thermal Integrated Heating System

The 1.7 MMBtu/hr boiler (Figure S-2) is manufactured by Advanced Climate Technologies LLC (ACT) of Schenectady, NY under license from Hamont Consulting and Engineering in Austria. This boiler was tested for gaseous and particle emissions and thermal efficiency by researchers at Clarkson University during the period from spring 2010 and 2011. The integrated pellet boiler and solar hot water heating system performance were monitored for the entire heating season.

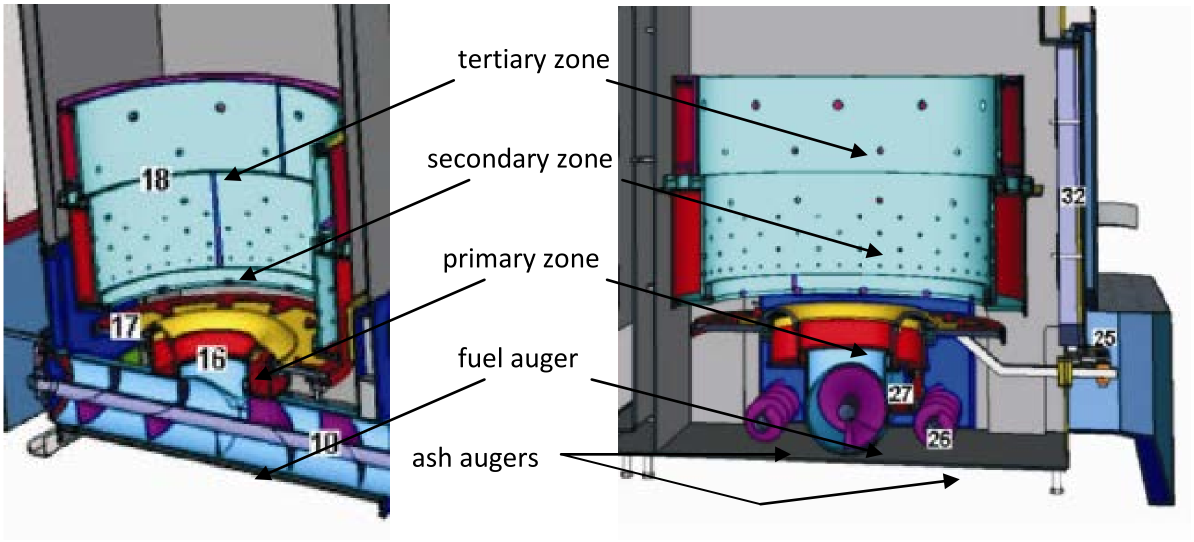
Figure S-2. The pellet boiler at the Wild Center was manufactured by Advanced Climate Technologies of Schenectady, NY.

Source: Wild Center

The ACT boiler shown in Figure S-2 is an automated boiler with a large heat exchanger surface area. Figure S-3 shows an illustration of the fuel feed auger, ash auger and combustion zones of the Hamont boiler. The boiler uses wood pellets as fuel. It has an automated fuel feed system and uses a triple air staging process that promotes complete combustion of the fuel. The primary air is injected into the fuel bed at a low air to fuel ratio (λ) to de-volatilize but not combust the fuel. Secondary and tertiary air streams are injected at higher λ values to burn the pyrolysis gases and achieve complete combustion. In order to ensure optimum excess air delivery into the different combustion stages, the boiler was equipped with an accurate process control system (CO/ λ control system) that varies the λ by measuring CO and λ using sensors in the combustion chamber. Because of good mixing of combustion air with pyrolysis gases, the boiler operates at low excess air levels, thus enabling the boiler to operate at higher temperatures in the combustion zone with high combustion efficiency (Nussbaumer 2003).

Figure S-3. Detailed view of the fuel feed auger, ash augers, and combustion zones of a Hamont Boiler.

Source: Reprinted with permission from Hamont European Operating Manual for CATfire 150-1.7 MMBtu/hr Wood Boilers.

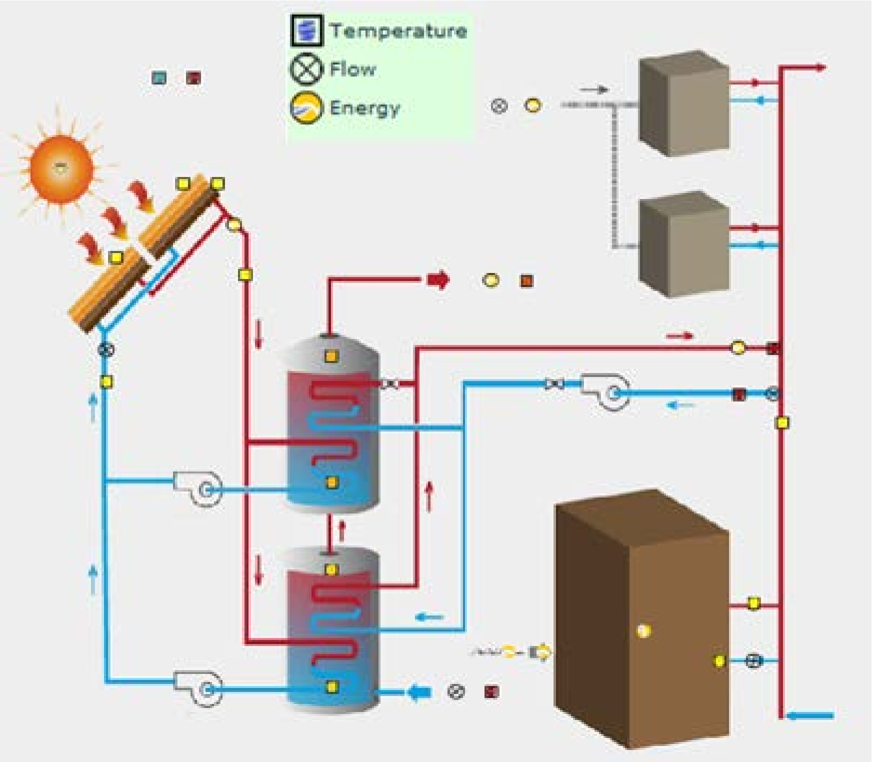


The Wild Center solar thermal system is an active indirect system as shown in Figure S-4. It consists of two types of solar collectors mounted on the south side of the wood-pellet container roof. Four flat plate collectors manufactured by Alternate Energy Technologies operate in parallel with 100 Viessman 200-T evacuated tubes.

Figure S-4. Solar-thermal plate collectors and evacuated tubes are mounted on the roof of the pellet storage container at the Wild Center.

Solar heated water was pumped and stored in two Steibel Eltron SBB 600 Plus storage/heat exchange vessels having a combined capacity of 320 gallons. Additionally, the Wild Center’s existing well insulated hydronic piping loop provided additional storage capacity of approximately 600 gallons (a part of building design) once the two Steibel tanks reached their pre-determined maximum temperature. The collectors have the potential of harvesting up to 300,000 Btus per day for use in the Wild Center’s kitchen (domestic water) and space heat (hydronic loop). The pumped solar energy collection fluid was mixed with glycol to prevent freezing in the closed outdoor pipe loop. Figure S-5 represents the schematics of The Wild Center boiler and solar hot water system.

Figure S-5. Schematic of Wild Center Boiler.



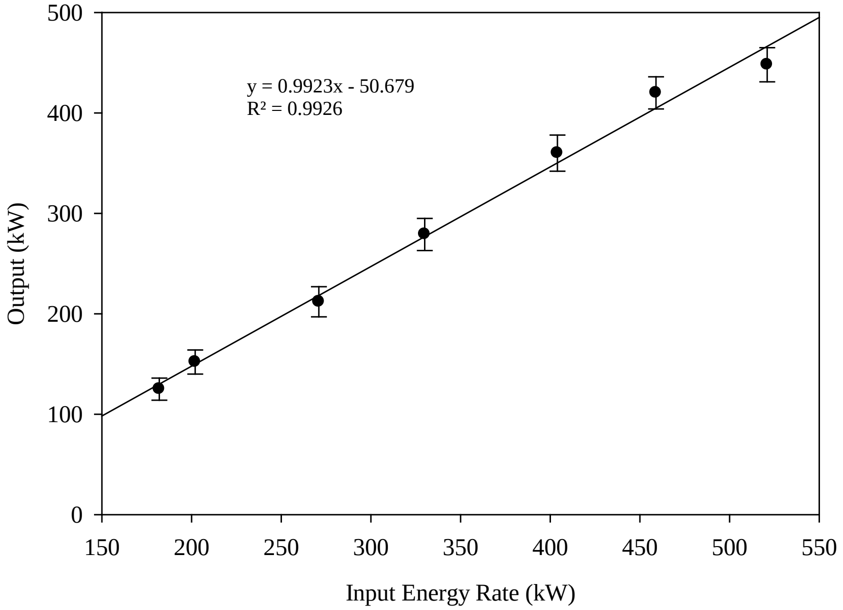
S.2 Efficiency Performance

Thermal efficiency is the ratio of heat output to the heat input. The thermal efficiency of the boiler at The Wild Center was determined using the new provisional protocol American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) Standard 155p. This method provides a different approach for determining the thermal efficiency that includes the partial load efficiency of individual commercial scale boilers. It examines a linear relationship between the input and output at full load and part load conditions. This standard includes methods for interpolating and extrapolating data and provides rating conditions to be executed in tests. It also provides a method for determining application-specific seasonal efficiency under steady-state conditions through flow loss rate and idling energy input rate of individual boilers.

The thermal efficiency of The Wild Center boiler ranged from 61% to 80% during spring 2010 and from 65% to 91% during spring 2011 over a boiler thermal capacity of 50% to 100%. The lowest feed rate (57.1%) was the manufacturer’s recommended minimum feed rate. The measured highest efficiency was 91% (spring 2011) at steady state that is slightly higher than the value from the European measurements. The optimal parameters for the operation of the boiler were also determined. The major parameters that affect the performance of the boiler were outlet water temperature, demand in the building and fuel feed rate.

Figure S-6 presents a plot of the thermal energy input and output for The Wild Center boiler. The plot shows a linear relationship between the boiler input and output. The efficiency drops when the boiler is not running at maximum load.

Figure S-6. Thermal energy input rate versus output rate of The Wild Center boiler (input rate calculated using the gross calorific value).



The efficiency of the boiler was also compared with respect to building demand (Figure S-7). The demand in the building increased as the temperature dropped during colder days and nights. The maximum efficiency measured was 91% for The Wild Center boiler at a load of 98% and maximum outlet water temperature.

The building demand is affected by a number of parameters. In addition to the outdoor temperature, the wind velocity, the solar gain, the presence of machines or equipment that radiate heat and the number of persons present in the building have to be considered. However, the most dominant factor affecting the energy consumption is the outdoor temperature (Pilat detto Braïda, 2010), which can be used to estimate the building demand roughly. In this analysis, the building demand was calculated using only the average outdoor temperature and the estimated building temperature (18 degrees Celsius) as follows in Equation S-1:

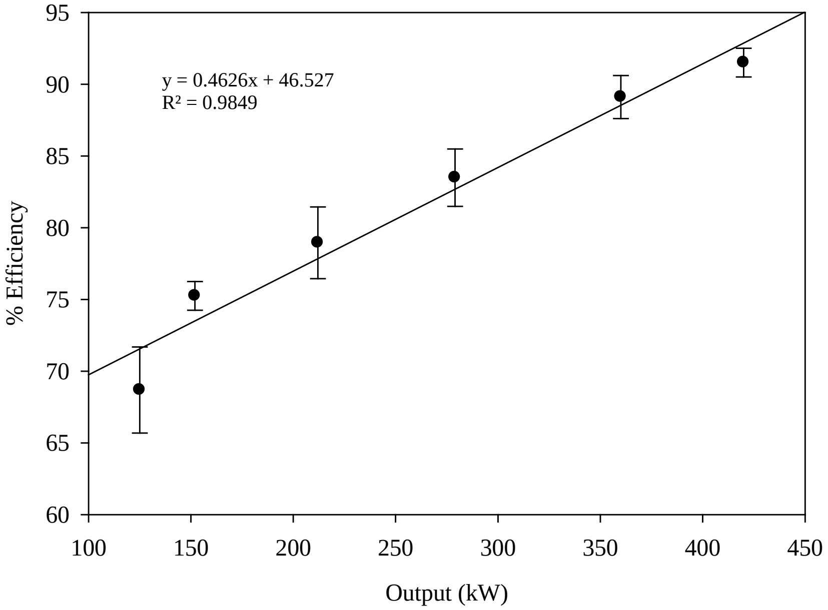
$$\%bd = \frac{(Tset - Tavg)}{T_{set}} * 100 \qquad \text{(Equation S-1)}$$

where

- bd is the building demand (%)
- T_{avg} is the average ambient temperature (degrees Fahrenheit [°F])
- T_{set} is the set temperature in the building (usually 65 °F)

During shoulder heating season when the heating demand in the building is low, the efficiency of the boiler decreases because of increased cycling. This cycling increases the fuel consumption because the system does not operate at steady-state.

Figure S-7. Thermal efficiency of Wild Center boiler for various building heat demand using the gross calorific value with 95% confidence intervals.



The installation of the solar hot water system was effective in satisfying the building heating demands during shoulder heating season. The intended purpose of the system was to: 1) satisfy the domestic hot water (DHW) requirements of the Waterside Café and 2) supplement the output of the boiler in meeting the space heating loads.

S.3 Emissions Performance

The measurements of The Wild Center boiler included emissions sampling and analysis. Stack gases were drawn through a dilution stack sampling system conforming to U.S. Environmental Protection Agency's (EPA) conditional test method CTM-039 using a $PM_{2.5}$ cut-point cyclone. Diluted stack gas samples were drawn through the sampling ports to obtain semi-continuous measurements of carbon monoxide (CO), nitrogen oxides (NO_x), sulfur dioxide (SO_2), and $PM_{2.5}$. Ultrafine particle size distributions were also measured in the stack emissions. $PM_{2.5}$ was collected on 142-mm baked quartz filters. It also included simultaneous emission testing using EPA Method 5 for filterable particulate matter (FPM), OTM-28 for condensable particulate matter and dilution sampling with the CTM-039 for ultrafine particles, $PM_{2.5}$ and CO, CO_2, NO_x, and SO_2. Although loads of 25%, 50%, 75% and 100% were targeted, the boiler could only operate at 100% by constantly varying the temperature parameters given the low heat demand in April 2010 with relatively warm ambient temperatures.

Three sets of measurements were conducted during this campaign. During the second and third measurements, the boiler was mostly operating in an unsteady state. The CTM-039 measurements during these periods were not included in the analysis and therefore, lower emission factors were estimated in comparison to the EPA Method 5 results (see Table S-1). Table S-1 represents some of the emission factors from the stack measurement. CO from the pellet boiler measured 1.21 lb/MMBtu (1015 parts per million (ppm)). CO emissions for a No. 6 stack test were not available but for comparison but a No.2 oil-fired system is typically 0.026 lb/MMBtu (33 ppm) and the American National Standards Institute (ANSI) limit in flu gas is 400 ppm.

The particulate matter values from the pellet boiler (0.06 lb/MMBtu) are higher than those from a measure of a large commercial oil-fired boiler using number six oil (0.016 lb/MMBtu). $PM_{2.5}$ was found to be comprised primarily of inorganic salts (K^+ and SO_4^{2-}), which have a lower cell toxicity than organic-based particles.

Table S-1. Emission factors from stack measurements.

Emission Species	1.7 MMBTU/hr Wood boiler		
	Wood Pellets (g/kg) Method CTM-039	Wood Pellets (lb/MMBtu) Method CTM-039	Wood Pellets (lb/MMBtu) EPA Method 5
PM	0.47	0.06[a]	0.07
SO_2	0.005	0.001	-
NO_x	0.42	0.07	-
CO	7.62	1.21	-

[a] Data collected using in-stack $PM_{2.5}$ cyclone

S.4 Boiler Performance, Cost Savings, and Thermal Storage Optimization

The fuel consumption and cost are compared before and after installation of the wood-pellet boiler at the Wild Center in Table S-2. The LPG consumption was prior to wood boiler installation from April 2009 to March 2010. The wood boiler was fired April 2010. The LPG consumption after wood boiler installation was from April 2010 to March 2011.

Table S-2. Comparison of fuel utilization with respect to cost.

Parameter	Prior to Wood boiler installation	After WoodBoiler installation
LP G flow (Gallons)	38,208	5,472
Total Cost of LPG	$65,702	$10,394
Pellets consumption	-	$23,655
Total Cost fuels	$65,702	$34,049
Savings after 1 year	-	$31,653
Degree days	-	7,863[a]

[a] From August 2010 until April 2011. Data were available only from August 2010.

Operating the wood boiler at low building demands during the shoulder heating seasons not only resulted in low efficiency but increased operating costs. To reduce the boiler cycling and increase its efficiency, thermal storage of about 1,000 gallon capacity could be installed that would store excess energy and allow the boiler to operate at 85 to 90% efficiency. Table S-3 represents a return on investment calculation suggesting a simple payback period of less than five years comparing the boiler operating at 65% and 85% efficiency with increased thermal storage capacity.

Table S-3. Economics of adding a storage tank.

Parameter	Wood-Pellet Boiler	
	Efficiency 85%	**Efficiency 65%**
Fuel Heat content	16.3 MMBtu/ton	16.3 MMBtu/ton
Fuel consumed, when operated at 100% load per heating season[a]	~ 98 tons (reduced cycling)	~127 tons
Fuel Cost	$185/ton	$185/ton
Annual Fuel cost $ (1st year)	18,130	23,495
Annual Fuel cost (2nd year) Fuel consumption 80 ton[b]	$14,800	$14,800
Thermal storage unit costs $ (1000 Gallon)	15,000	-
Total costs	47,930	38,295
Cost after 5 heating seasons	$87,320	$108,780
Savings After 5 heating seasons	$21,460	-
Simple Payback period (year)	<5	-

[a] Estimated based on efficiency

[b] The boiler was down late in January and February for three weeks for repairs, plus the winter was very mild.

S.5 Solar-Thermal Enhancements

In addition, boiler operation can be reduced by doubling the size of the solar collector. The current solar collector capacity is 300,000 Btu/day and the capacity of the storage tanks is 200,000 Btu (for a temperature difference of 75 °F between the inlet water (city water) and domestic hot water (DHW)). This amount of energy is equivalent to that in two gallons of fuel oil. For the shoulder heating season month (during April), the calculated temperature difference averaged about 50 °F while for May and June, the calculated temperature difference exceeded 75°F. The temperature difference of 50 °F contributes 133,333 Btu (calculated from energy balance and interpolation) and that is about 67% of the tank's capacity for the inlet water at 165°Fand outlet water temperature ranging between 240 °F and 260 °F. By doubling the collector size to 600,000 Btu/day, excess solar energy can be harvested and stored in the thermal storage units that can be used for space heating during night and early morning hours. This additional collector system would cost $15,000 more than the thermal storage unit. However, it would be economical on a long term basis reducing pellet consumption and its related cost.

There are few operating and maintenance costs for the solar hot water system. It requires the operation of two coolant pumps and one space heat injection pump that demand a total of about 3 amps (a capacity of three 100 watt bulbs) when they operate. There is no need to cover the panels in July because the Wild Center's existing well insulated hydronic piping loop provides an additional storage capacity of approximately 600 gallons (a part of building design initially). The heating loop runs through the air handlers. During summer when the building needs some heating overnight and early in the morning, warmer ambient air is brought in to preheat the large hydronic loop during the previous day and retain that heat energy overnight. The boiler would, in theory, cycle less in the morning. The museum always maintains a minimum temp of 150 ˚F in the loop, even in the summer, as it could have been needed for heating on any given morning since summer morning temperatures can be in the 40s, with daytime highs in the 70s.

S.6 Summary and Recommendations

The first Made-in-NY commercial wood-pellet boiler manufactured by Advanced Climate Technologies, LLC of Schenectady, NY was installed at The Wild Center in April 2010 and integrated with a solar-thermal hot water system. The boiler was tested for efficiency and emissions performance by researchers at Clarkson University.

- The thermal efficiency of The Wild Center boiler ranged from 61% to 80% during spring 2010 and from 65% to 91% during spring 2011 over a boiler thermal capacity of 50% to 100%.
- Efficiency performance was best when the boiler was operating at full load in steady-state.
- The PM emissions from the pellet boiler stack at full load were 0.06 and 0.07 lb/MMBtu by Method CTM-039 and EPA Method 5 respectively or 0.47 g/kg of wood pellets. In comparison, a number 6 oil-fired boiler was measured in another study at 0.016 lb/MMBtu.
- CO from the pellet boiler measured 1.21 lb/MMBtu or 1015 ppm in contrast to CO emissions from number 2 oil-fired systems which are typically 0.026 lb/MMBtu or 33 ppm and the American National Standards Institute limit in flu gas of 400 ppm.
- SO_2 and NO_x emissions were 0.001 and 0.07 lb/MMBtu and 0.005 and 0.42 g/kg respectively.
- Emissions of carbonaceous derived species (organic carbon, elemental carbon, poly-cyclic aromatic hydrocarbons, and organic compounds) during high-load, steady-state operation were all relatively low because of the nearly complete combustion.
- The Wild Center heating costs following the installation of the ACT pellet-fired boiler and solar thermal system were reduced by $31,653 over the year prior.
- The pellet boiler heating system can be optimized further on a seasonal basis by adding more thermal storage. A 1,000 gallon tank is recommended to allow for quicker response during a call for heat, more operation of the boiler at high load, and less cycling of the boiler to meet low heating loads. It is anticipated that the system will have a payback of less than five years.
- The solar-thermal array was effective in providing domestic hot water and space heating during summer and shoulder seasons.
- Domestic hot water and space heating can be further enhanced by doubling the solar-thermal arrays. This additional thermal energy can be stored in the 1,000 gallon tank. The excess heat can be dumped in the heating loop that runs through the air handlers. This excess heat can be used to warm the moist air entering.

1 Introduction

The use of biomass fuel combustion for residential and commercial heating has gained attention due to the fluctuating price of fossil fuels and the desire to use renewable energy. However, conventional wood burning systems in the U.S. tend to have relatively low efficiency and high emissions of carbon monoxide (CO) and particulate matter (Gammie and Snook 2009). In Europe, a number of advanced combustion systems have been developed that are reported to provide substantially higher thermal efficiency and lower emissions than conventional U.S. systems. These advanced systems use staged combustion that provide high thermal efficiency above 85% and also greatly reduce emissions of pollutants from the stack when compared with conventional wood fired boilers. Thus, in 2008, the New York State Energy Research and Development Authority (NYSERDA) initiated a series of studies on these high-efficiency wood boiler systems. The stack testing and efficiency measurements were conducted on the Wild Center boiler (1.7 MMBtu/hr) system. The boiler was manufactured by Advanced Climate Technologies LLC (ACT) of Schenectady, NY integrated with a solar hot water system, and installed at the Wild Center in Tupper Lake, NY (44.33º N, 74.13º W). This is the very first demonstration of a Made-in-NY commercial pellet boiler with a high-efficiency design. Efficiency measurements were conducted during spring 2010 and the 2011 heating season. The wood boiler and the solar hot water system performance were monitored for the shoulder heating season.

2 Boiler Configuration

The ACT boiler (1.7 MMBtu/hr) utilizes a triple air staging process that promotes complete combustion of the fuel. Figure 1 shows an illustration of the fuel feed auger, ash auger, and combustion zones of the Hamont boiler.

Air staging is accomplished by injecting primary air into the fuel bed at a low air to fuel ratio (λ) to volatilize but not combust the fuel. Secondary and tertiary air streams are injected at higher λ values to burn the pyrolysis gases and achieve complete combustion. The optimum excess air delivery into the different combustion stages was ensured with an accurate process control system (CO/ λ control system) that varies the λ by measuring CO and λ using sensors in the combustion chamber. During the first stage, the fuel is heated to around 400 ºCelsius (ºC; 750 degrees Fahrenheit [°F]), and in the second and third stages, air is tangentially injected into the combustion zone to reach temperatures up to 1,100 ºC (2,000 ºF). Because of good mixing of combustion air with the pyrolysis gases, the boiler operates at low excess air levels enabling it to operate at high temperatures in the combustion zone with high combustion efficiency (Nussbaumer 2003).

2.1 Wild Center Boiler

The boiler installed at the Wild Center was an American Society of Mechanical Engineers-certified, 500 kW (1.7 MMBtu/hr) boiler manufactured in the U.S. based on the Hamont design and integrated with a solar hot water system. This system supplies much of the hot water required to heat the 54,000-square-foot facility. The boiler used wood pellets as fuel. Figures 2 and 3 are a photo and schematic drawing, respectively, of the pellet boiler with a solar thermal system at the Wild Center.

Figure 1. Detailed view of fuel feed auger, ash augers, and combustion zones of a Hamont Boiler.

Source: Hamont European Operating Manual for CATfire 150-1.7 MMBtu/hr Wood Boilers.

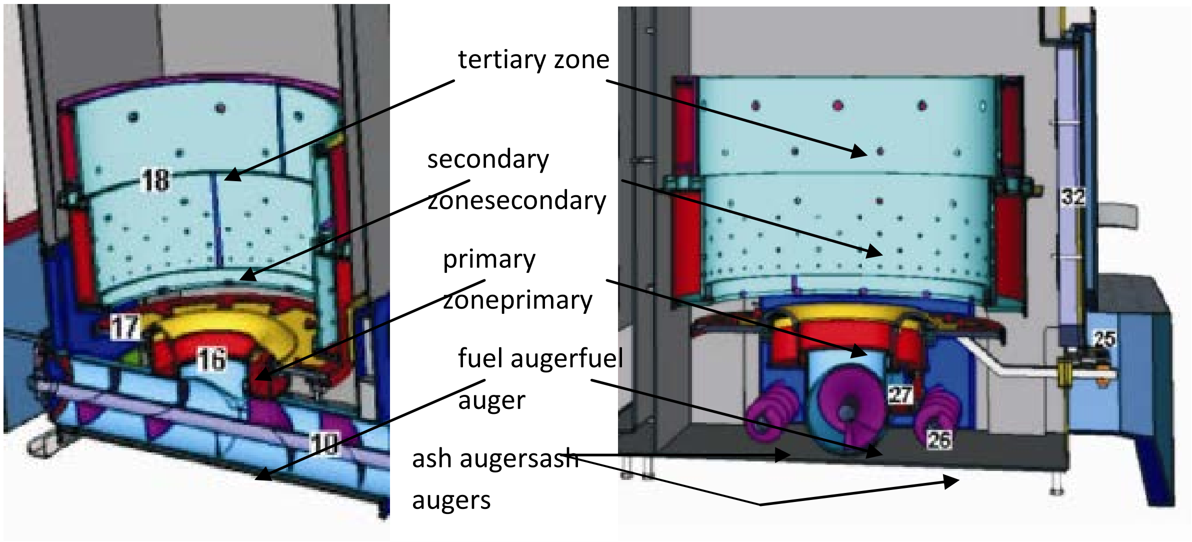
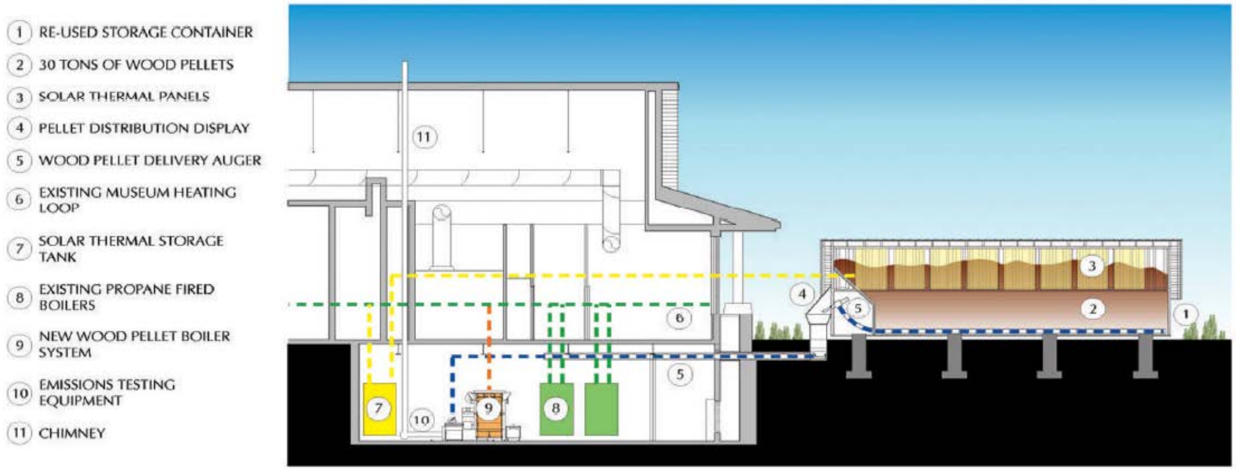


Figure 2. First Made-in-NY high-efficiency pellet boiler at the Wild Center (manufactured by Advanced Climate Technologies of Schenectady, NY).

Source: Wild Center

Figure 3. Schematics of commercial size pellet boiler with solar thermal system at the Wild Center.

Source:www.wildcenter.org.



The boiler was configured to operate with a CO/ λ control system to optimize combustion air flows. This control adjusts the combustion air fan speed based on measured CO and oxygen levels in the flue gas. The target oxygen level was 8%. The boiler was operated at 100% of the set fuel feed rate with the inlet and outlet water temperatures varying depending on the heat demand from the facility because most of the emission measurements were taken during late heating season of spring 2010. When the heat demand from the building was low, the boiler input and output water set temperatures and the feed rates were varied to artificially force the boiler load to 100% of the set fuel feed rate.

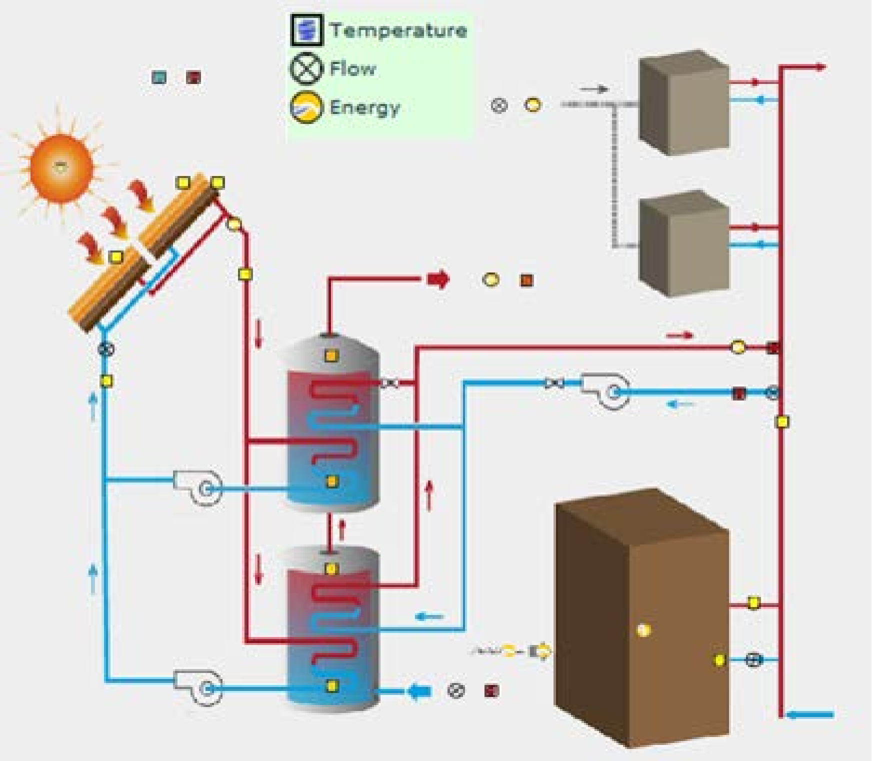
2.2 Wild Center Solar Hot Water System

The Wild Center solar thermal system is an active indirect system with 40% antifreeze in the solar loop. It consists of two types of solar collectors mounted on the south side of the wood-pellet container roof (Figure 4). Four flat plate collectors, manufactured by Alternate Energy Technologies were operated in parallel with 100 Viessman 200-T evacuated tubes.

Solar heated water was pumped and stored in two Steibel Eltron SBB 600 Plus storage / heat exchange vessels having a combined capacity of 320 gallons. Additionally, the Center’s existing well insulated hydronic piping loop provides an additional storage capacity of approximately 600 gallons (a part of building design) once the two Steibel tanks have reached pre-determined maximum temperature as shown in Figure 5. The collectors have the potential of harvesting up to 300,000 Btu per day for use in the Wild Center’s kitchen (domestic hot water) and space heat (hydronic loop). The pumped solar energy collection fluid was mixed with glycol to prevent freezing in the closed outdoor piping loop.

Figure 4. Solar-thermal plate collectors and evacuated tubes mounted on the roof of the pellet storage container at the Wild Center.

Figure 5. This schematic details the boiler and solar heating system at the Wild Center.



The system was designed to satisfy two main objectives. First, the harvested solar energy would satisfy most, if not all of the domestic hot water heating needs in the Waterside Café. Second, any excess harvested solar energy would be stored and released as necessary to the main hydronic loop in the Center basement to essentially pre-heat the water for space heating purposes. The benefit of this system was that the excess harvested solar energy released to the space heating loop would reduce the firing demand and cycling of the boilers particularly during shoulder heating seasons (fall and spring).

Controlled operation of the system pumps was maintained by 2 Steibel eltron model SOM 7 controllers operating on a delta T principle. The system pumps are turned ON/OFF at appropriate setpoint temperatures to maximize solar energy harvesting and provide for the domestic and space heating purposes.

3 Measurement Methods

3.1 Thermal Efficiency Measurement Methods

The efficiency measurements were conducted using American Society of Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) standard 155p, a new provisional protocol that provides a method to determine the full load, part load and seasonal efficiency. It examines a linear relationship between the input and output at full load and part load conditions. The standard is applied for space heating performance and is applicable to all boilers with energy input values ranging from 300,000 to 12,500,000 Btu/hr. It also includes methods for interpolating and extrapolating test data.

The test conditions and instruments were adjusted to the test conditions as required in ASHRAE standard 155p. The boiler was cleaned and serviced before firing for this heating season. The temperature of the water entering the boiler was around 150 °F and the hot water from the boiler is about 190 °F. Boiler efficiency was determined using the direct method of dividing the useful heat output of the boiler by the energy input of the fuel (Equation 1).

$$\eta = \frac{Q_w \rho c_p \Delta T}{C_v m_f} * 100 \qquad \text{(Equation 1)}$$

where:

- η is Boiler Thermal Efficiency.
- Q_w is Volumetric pipe flow rate (L/min).
- ρ is Density of water (kg/L).
- c_p is Specific heat capacity of water (MJ/kg *°C).
- ΔT is Water temperature difference (°C).
- C_v is Gross calorific value of fuel (MJ/kg).
- m_f is Fuel feed rate (kg/min).

Heat input was calculated from the gross calorific value (or higher heating value that takes into account the latent heat of vaporization of water) of the fuel and the fuel feed rate into the boiler. Gross calorific values were determined using an oxygen bomb calorimeter according to ASTM E711 (Parr Oxygen Bomb Calorimeter and Calorimetric Thermometer Models 1341 and 6772). The major components in wood are carbon (45-50%) and hydrogen (approximately 6%). Ash content was determined by ashing in a muffle furnace at 550°C for 2 hours (method ASTM D 1102–84) and moisture content was determined by drying at more than 103 ºC for 16 hours (method ASTM E871-82). The sulfur content was determined by the bomb-washing method in ASTM E775–87 and then measured using ion chromatography. The moisture in the fuel affects the heat content of the fuel and is inversely proportional to the Gross Calorific Value. During the combustion process, the hydrogen and oxygen in the fuel forms water that affects the efficiency. Table 1 summarizes the measured properties of fuel used in this work. The samples were taken during spring 2010 and spring 2011 measurements. Three replicates were prepared for each analysis.

Table 1. Measured fuel properties.

Fuel Property	**Wild Center – 1.7 MMBtu/hr**	
	Spring 2010	**Spring 2011**
Heat Content (Btu/lbs)	8060±3	8130±3
Moisture (%)	5.1±1.1	4.7±1.3
Ash (dry weight. %)	0.6±0.13	0.53±0.27
Carbon (d.w. %)	48.74±0.36	49.3±0.36
Nitrogen (d.w. %)	0.15±0.03	-
Sulfur (d.w. ppm)	67.1±0.027	69.6±0.019
Bulk Density (lb/gallons)	5.63	5.63

The Wild Center boiler had an automated reporting system from beta.solarwave.net. This is a green energy monitoring program that works with existing programs and hardware to allow for web-based monitoring and reporting. Figure 5 is the schematic diagram of the automated reporting for the wood boiler and solar water heating system. For the wood boiler, it reports the temperature of the inlet and outlet water, flow rate, energy input and energy output. Based on real time measurements and fuel feed rate settings on the boiler control system, the fuel feed rate of the Wild Center boiler was determined. The fuel feed rate was further monitored and verified by internal and precision augers.

For the solar hot water system, it reports collector production BTU, solar space heat BTU, and solar domestic hot water BTU utilizing a combination of temperature sensors (supply and return) and flow meters on the solar collection, space heat and domestic hot water loops, respectively.

3.1.1 CTM-39 Dilution Sampling System

Gaseous and $PM_{2.5}$ (particle matter less than 2.5 micrometers (µm)) concentrations were measured using a dilution tunnel sampling system obtained from Environmental Supply Co., Durham, NC and conform to U.S. Environmental Protection Agency's (EPA) conditional test method CTM-039. Stack gas was drawn isokinetically through an in-stack cyclone to remove particles larger than 2.5 µm and then into heated sample lines to prevent wall condensation.

The heated sample gas was then mixed under turbulent conditions with dehumidified and HEPA-filtered ambient air via a mixing cone. Dilution ratios of 20 to 60 were used. Sampling ports located at the end of the mixing chamber allowed for continuous measurements of CO, nitrogen oxides (NO_x), sulfur dioxide (SO_2), $PM_{2.5}$, and ultrafine particle number concentrations and size distributions.

Quartz filters, Teflon filters, and polyurethane foam plugs (PUFs) were collected for particle characterization and organic compound speciation. Continuous CO, NO_x and SO_2 measurements were taken using ambient gas monitors (Thermo Models 42i, 43i and 48i). Continuous $PM_{2.5}$ mass was determined using TEOM Filter Dynamics Measurement System (FDMS; R&P Model 8500b), and ultrafine particle number concentrations and size distributions in the range from 5.6 to 560 nm were measured using a Fast Mobility Particle Sizer Spectrometer (TSI Model 3091).

The 142 mm quartz filters were analyzed for organic and elemental carbon following the NIOSH 5040 method (Sunset Laboratories, Tigard, OR.), and anions and cations by ion chromatography. Organic artifacts from gas-phase adsorption onto quartz filters were corrected using a backup quartz filter. Teflon filters (47 mm) were analyzed for trace metals using inductively coupled plasma mass spectrometry.

Quartz filters (142 mm) in series with PUFs were collected and analyzed for organic molecular markers, polycyclic aromatic hydrocarbons and polychlorinated dibenzodioxin and dibenzofurans (PCDD/Fs) using gas chromatography-mass spectrometry.

All emission factors and concentrations in this report are average emissions at full load during steady-state operation at dry gas standard state conditions (temperature of 293.34 Kelvin and pressure of 101.31 kilopascals).

3.1.2 EPA Method 5 and OTM-28

At the Wild Center, additional measurements for particulate matter according to the EPA Method 5 and OTM-28 were conducted by CK Environmental under contract to Clarkson University. Briefly, particulate matter (PM) was withdrawn isokinetically from the stack gas, using a sampling apparatus obtained from Environmental Supply Company, Durham, NC. PM was collected on an out-of-stack glass fiber filter maintained at a constant temperature (248 ± 25 ºF) inside a heating box. The filter was heated to prevent condensation of moisture and gaseous compounds. The collected PM mass includes any material that condenses at or above the filtration temperature, and is determined gravimetrically. There are no specific load requirements for EPA Method 5 testing. Usually, the testing is done at loads between 90% and 100%, or the most probable boiler load.

After the particulate matter was removed from the stack gas using the sampling apparatus as described, the stack gas sample stream was passed through dry impingers for measurement of condensable particulate matter (organic and inorganic fraction). In this method (OTM-28), the stack sample gas passes through a water jacketed coil condenser, a dry short stem moisture dropout impinger, a dry regular impinger without a bubbler, and then through a Teflon® CPM filter. The sample gas is maintained at less than 85 ºF throughout this portion of the sampling system. Upon completion of sampling, the sampling train is purged with nitrogen for one hour and the components of the sampling train are rinsed with water and organic solvents. The organic and inorganic fractions are extracted in the lab, dried and weighed. The sum of these fractions is used to calculate the condensable PM mass concentration. The reported emission factors are at dry gas standard state conditions (temperature of 293.34 Kelvin and pressure of 101.31 kilopascals).

3.1.3 Measurement Results for the Wild Center Boiler

3.1.3.1 Thermal Efficiency

Thermal efficiency is defined as the ratio of energy output to the energy input. The efficiency determines how well an effort has been utilized for a given purpose. Table 2 shows the type of fuel used, energy input rate, energy output rate (by direct method calculation), boiler load capacity as percent of the input rate, and the calculated thermal efficiency for the boiler tested between spring 2010 and spring 2011. The results are plotted in Figures 6 to 9.

Table 2. Thermal efficiency of the Wild center boiler at different heat inputs.

Uncertainties indicated here are the 95% confidence intervals.

Testing Location	Testing Period	Fuel	Input rate (kW)	Output rate (kW)	$\eta_{thermal}$ (%)
Wild Center	Spring 2010	pellets	620	409	66[a] ± 2
Wild Center	Spring 2010	pellets	379	303	80[a,b] ± 2
Wild Center	Spring 2010	pellets	694	458	66[a] ± 1
Wild Center	Spring 2010	pellets	476	309	65[a] ± 6
Wild Center	Spring 2011	pellets	182	125	68 ± 4
Wild Center	Spring 2011	pellets	202	152	75 ± 4
Wild Center	Spring 2011	pellets	266	211	79 ± 3
Wild Center	Spring 2011	pellets	340	284	83 ± 2
Wild Center	Spring 2011	pellets	405	360	88 ± 3
Wild Center	Spring 2011	pellets	459	420	91 ± 1
Wild Center	Spring 2011	pellets	521	448	86 ± 2

[a] Boiler manipulated to run at 100% of selected feed rate.

[b] Boiler operated at steady state conditions.

A plot of thermal energy input and output for the Wild Center boiler is given in Figure 6. The plot shows a linear relationship between the boiler input and output but it is not 1:1. By examining this loss of efficiency, Figure 6 shows that the relationship between input and output is approximately linear. The efficiency decreases when the boiler is not running at maximum load. The boiler efficiency increased as the input rate increased (Figure 7).The amount of heat loss from the boiler is high at low loads. Hence, it is important to operate the boiler at maximum boiler capacity. In contrast, an oil-fired boiler will cycle on and off or sometimes modulate to a lower output if it is a multi-stage unit. In either case, essentially steady-state operation is rapidly achieved and high performance is realized. However, as with wood systems there will be emission and efficiency penalties associated with cycling although they will not be as large.

The demand in the buildings increased as the temperature dropped during colder days and nights. The maximum efficiency measured was 91% for The Wild Center boiler at a load of 98% and maximum outlet water temperature. The building demand is affected by a number of parameters. In addition to the outdoor temperature, the wind velocity, the solar gain, the presence of machines or equipment that radiate heat and the number of persons present in the building have to be considered. However, the most dominant factor of those above mentioned affecting the energy consumption is the outdoor temperature (Pilat detto Braïda 2010) that can be used to roughly estimate the building demand. In this analysis, the building demand was calculated using only the average outdoor temperature and the required building temperature (18 °C, which is a rough estimate) in Equation 2:

$$\%bd = \frac{(Tset - Tavg)}{T_{set}} * 100 \qquad \text{(Equation 2)}$$

where:

- bd is the building demand (%).
- T_{avg} is the average ambient temperature (°F).
- T_{set} is the set temperature in the building (usually 65 °F).

Figure 6. Thermal energy input rate and output rate of the Wild Center boiler.

Input rate calculated using the gross calorific value.

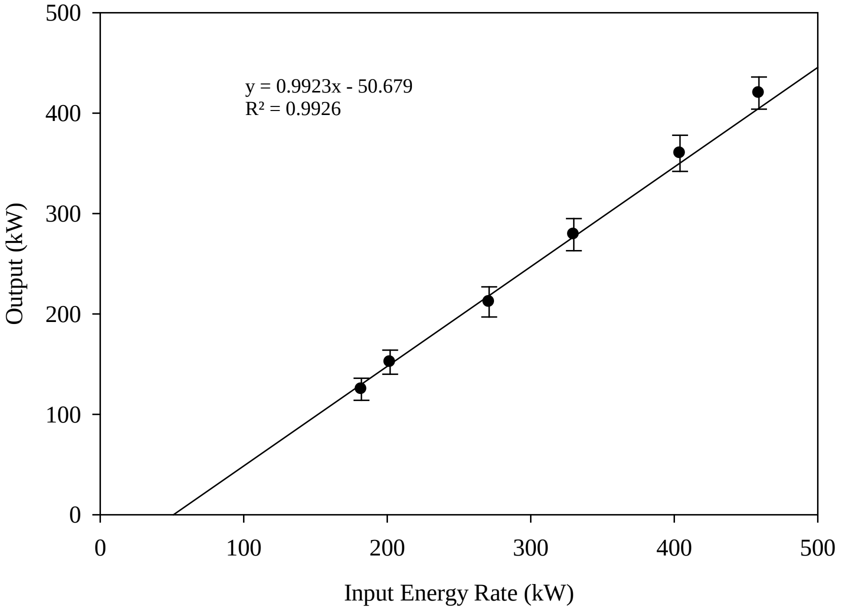


Figure 7. Thermal efficiency of Wild Center boiler for various boiler input using the gross calorific value with 95% confidence intervals.

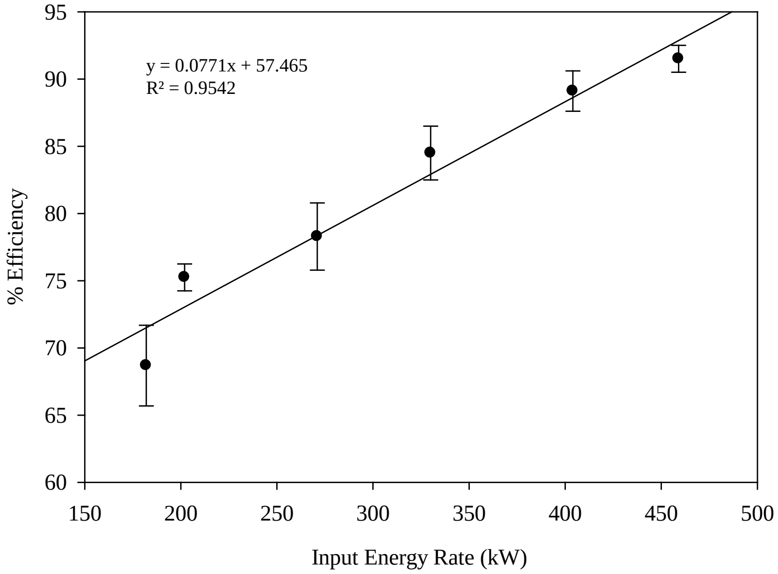
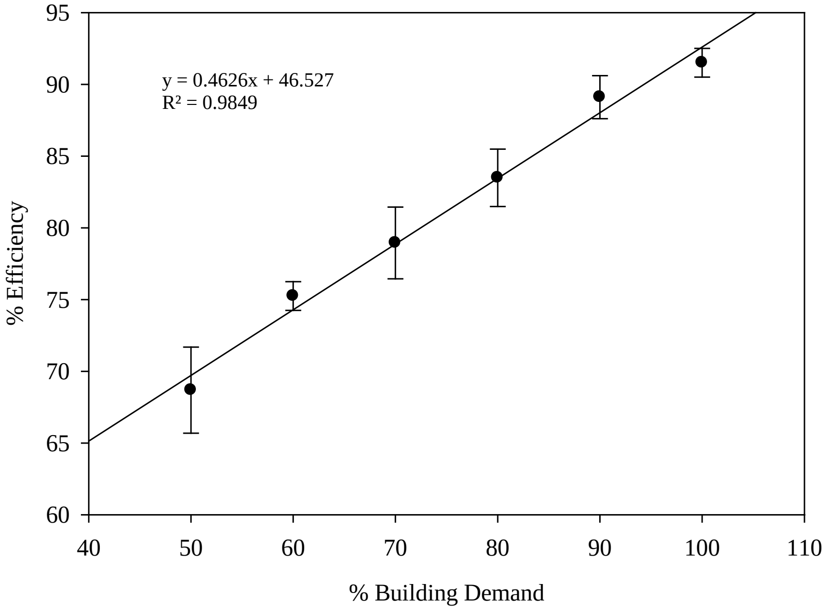


Figure 8 compares the efficiency of the boiler with respect to building demand. During the shoulder heating season when the demand in the building is low, the efficiency of the boiler drops due to increased cycling. This cycling increases the fuel consumption, thereby increasing the energy input. Thus it is important to operate the boiler at maximum load, without cycling to save the energy and operating cost.

Figure 8. Thermal efficiency of Wild Center boiler for various building heat demand using the gross calorific value with 95% confidence intervals.



Most of the 2010 spring Wild Center tests were run by manipulating the boiler since the measurements were made during the late heating season. However, this approach may have resulted in lower measured efficiencies than would be obtained when operating under actual steady-state conditions. The lowest efficiency of 65% was during this unsteady state operation at a load of 475kW (Figure 9). The one steady-state run did result in a higher thermal efficiency value. The highest efficiency measured was 91% (spring 2011) at steady state which is slightly higher than the value from the European measurements.

Figure 9. Thermal Efficiency of Wild Center boiler for various times in the heating season.

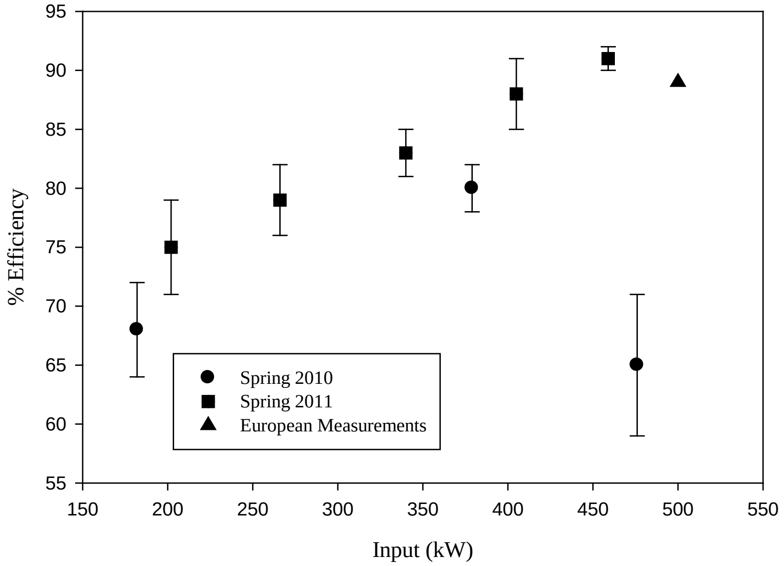


Figure 10. Frequency distribution of the average daily load (%) on the boiler from September 2010 to April 2011.

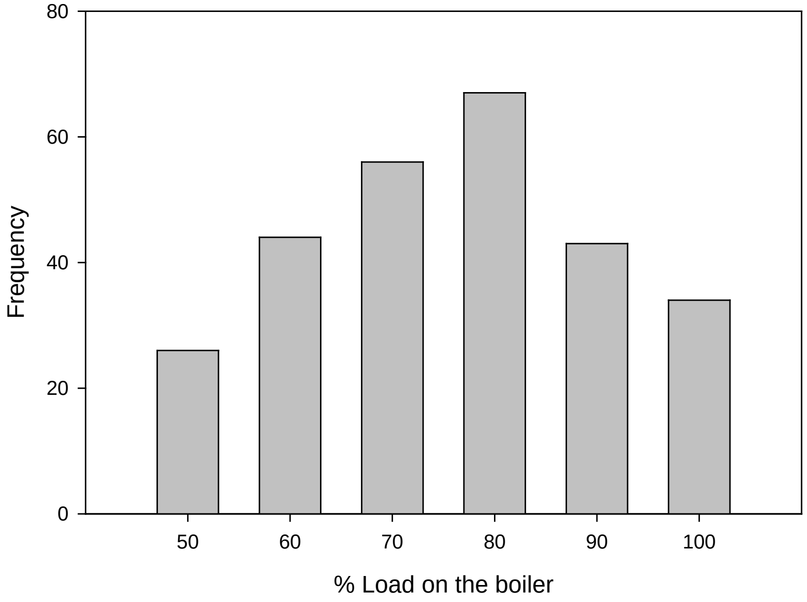
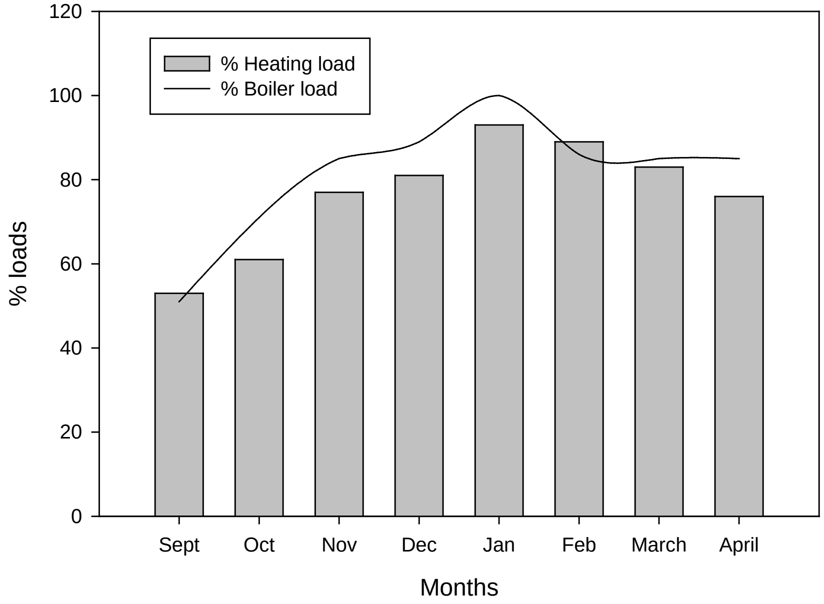


Figure 10 represents the frequency distribution of percent load on the pellet boiler in 10 % load increments over the heating period from September until April. The percent load was calculated based on the output capacity of the boiler. The data were averaged for the boiler operation in a day. From December until March, the boiler was operated continuously. The boiler operation for a day varied based on the heating demand in the building.

Figure 11. A plot of heating load (percent building demand) and boiler load over heating season.



Using Equation 2, the building demand was estimated at The Wild Center for each month during the heating season (Figure 11). The graph shows the building heat demands and the boiler performance cycling (boiler load) from September to April. The bars represent the building heating need (a rough estimate). The boiler load was estimated based on the operation and the amount of fuel consumed. Over the heating months, as the building demands increased the load on the boiler also increased. But, the wood boiler was sized to meet only 70% of heat demand in the building. Hence when the building heat demand was high, the boiler operation was also high. All the data used were averaged for the boiler operation for 24 hours.

From November through March, the boiler was cycling more than the building needed. One reason might be that the boiler cycles until it reaches an unsteady state operation or the desired temperature is achieved. The second reason might be an artefact in the percent building demand equation, which may need other heating gains such as passive solar and internal heat gains included. The third reason might be that the liquid propane gas LPG boiler was also supplying heat energy from December through March that was not taken into account because no data are available from the solarwave monitoring system. The percent boiler load is also given in Figure 11. During January, the average heating load (%bd) was 93% with a corresponding maximum boiler load (100%).

3.1.3.2 Emissions Measurements

Criteria pollutants were measured during operation at 100% load for the 1.7 MMBtu/hr ACT boiler burning wood pellets. Table 3 and Figures 12 and 13 give the full load average emission factors of the 1.7 MMBtu/hr boiler at the Wild Center. Table 4 compares the measurements conducted with EPA Method 5 using a glass fiber filter and Method CTM-039 using a dilution sampling system. A comparison was made of the PM measurements using these two methods. The results indicate that the EPA Method 5 measurements were about 11% higher than the CTM-039 dilution sampling measurements using Teflon filters.

Although loads of 25%, 50%, 75% and 100% were targeted, it was only possible to run the boiler at 100% by artificially manipulating the required temperature of the outlet water. Because of the very low heat demand during April 2010, it was necessary to force the system to operate under non-steady state conditions. Method 5 captures total particulate matter, while the CTM-039 sampled using an in-stack 2.5 µm cyclone. The calorific value of the fuel obtained from the measurements at Clarkson was 8060 Btu/lb. This value was used in the dilution method (CTM – 039) and EPA Method 5 calculations.

To quantify the mass of PM collected in the in-stack $PM_{2.5}$ cyclone during CTM-039 measurements, the particles were dissolved in hexane, dried and weighed. The estimate PM concentration collected in the cyclone for the first measurement on April 20, 2010 between 9:23 and 11:20 was 9.4 mg/m^3. Thus, the total PM collected during this measurement was 118.41 mg/m^3 from the Teflon filter measurement and 100.9 mg/m^3 from the TEOM FDMS measurement system. The difference in the result from Method 5 and CTM-039, therefore, is about 3.7 % and 17.9% from the Teflon filter and TEOM FDMS system, respectively.

During the second and the third measurements shown in Table 4, the boiler was mostly operating in an unsteady state. Because Method 5 is an aggregated filter measurement, the operator was unable to turn off Method 5 system during this unsteady boiler operation and, therefore, kept the measurement system running. The CTM-039 measurement system and the TEOM FDMS system were turned off temporarily to protect the instrument from these large fluctuations in the PM emissions. Therefore, the PM emissions during these fluctuations are not included in the reported values from the CTM-039 method, leading to the large discrepancy in the measured values.

Tables 5 and 6 compare emissions factors from England, 2004 for a No.6 oil-fired boiler and McDonald, 2009 for several pellet stoves with emissions from this study and previous testing of biomass boilers using woodchips and wood pellets (NYSERDA, 2012).

Table 3. Full load average emissions from the ACT 1.7 MMBtu/hr wood boiler at Wild Center using wood pellets as fuel.

Average emissions at steady state operation. Uncertainty indicated in this table represents the 95% confidence interval of the average value. Data in parenthesis indicate the range (minimum - maximum) measured during full load operation. Condensable PM was measured using EPA OTM-28.

Emission Species	mg/m^3	Lb/MMBtu
CO	1182 ± 64.11	1.21 ± 0.09
CO_2	96.74 ± 13.82	0.03 ± 0.00
NO_x	72.06 ± 0.79	0.07 ± 0.00
SO_2	0.92 ± 0.01	0.0007 ± 0.00
$PM_{2.5}$	55.50 ± 5.55	0.06 ± 0.01
Condensable PM	5.22 ± 0.46	0.004 ± 0.00
TOC[a]	2.27 ± 0.29	0.01 ± 0.00

[a] Data based on three aggregated 142-mm filter samples.

Table 4. Comparison of particulate matter concentration measurements by EPA Method 5 and Dilution Method CTM-039.

FPM – Filterable particulate matter, $PM_{2.5}$ – particulate matter with particles less than 2.5µm aerodynamic diameter.

Sampling Date/Time	FPM ($mg\ m^{-3}$) Method 5	$PM_{2.5}$ ($mg\ m^{-3}$) CTM-039		FPM ($lb\ MMBtu^{-1}$) Method 5	$PM_{2.5}$ ($lb\ MMBtu^{-1}$) CTM-039	
4/20/10 09:23 – 11:20	123.0	109.01[b]	91.50[c]	0.07	0.07[b]	0.06[c]
4/20/10 13:23 – 14:29	121.6a	57.29[b]	45.30[c]	0.11	0.06[b]	0.05[c]
4/21/10 8:52 – 11:12	93.8	38.34[b]	58.04[c]	0.10	0.06	0.08[c]

[a] Data were collected using an in-stack PM2.5 cyclone.

[b] Data collected using Teflon filter, averaging time was typically about 1 hour.

[c] Data collected using TEOM FDMS system.

Table 5. Comparison of emission from No. 6 Oil fired boiler and Wood boiler.

Emission Species	Site: Delta (Oil) (England, 2004)		Pellet Stove (average) (McDonald, 2009)		CAT 150 (Wood Chips)		CAT 150 (Pellets)		CAT 500 (Pellets)	
	lb/MMBTU	**mg/m^3**	**lb/MMBTU**	**ppm**	**lb/MMBTU**	**ppm**	**lb/MMBTU**	**ppm**	**lb/MMBTU**	**ppm**
$PM_{2.5}$	0.016	-	0.058	-	0.112	-	0.06	-	0.06	-
SO_2	0.033	-		2	0.004	0.7	0.001	0.3	0.001	0.3
NO_x	0.182	-		33	0.302	131	0.040	32	0.070	58
CO at7% oxygen		-		128		149		224		1015
Efficiency (%)		-	69		72		72		80	

Table 6. Comparison of emissions from residential wood stoves and commercial-size wood boilers.

	Appliance type	Scale	Over Feed	Drop down feed	Electric ignition	Gasification unit
			lb/MMBtu			
PM2.5 Emissions	Stoves I[a]	Residential	0.065	0.09	0.056	-
	Stoves J[a]		0.047	0.056	0.051	-
	Stoves K[a]		0.056	0.052	0.049	-
	CAT 500kW	Commercial				0.06

[a] McDonald 2009

Figure 12. Concentration of criteria pollutants (NO_x, SO_2 and $PM_{2.5}$) during steady state operation of 1.7 MMBtu/hr boiler (at full load).

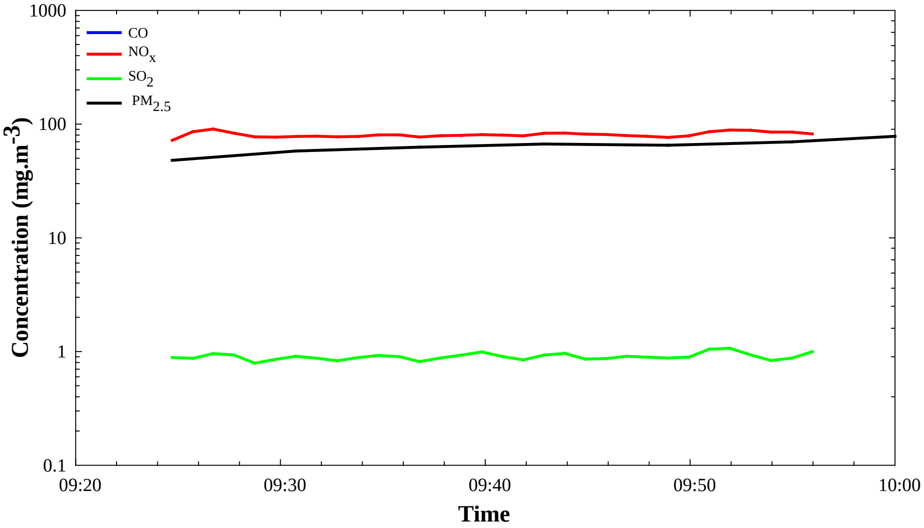
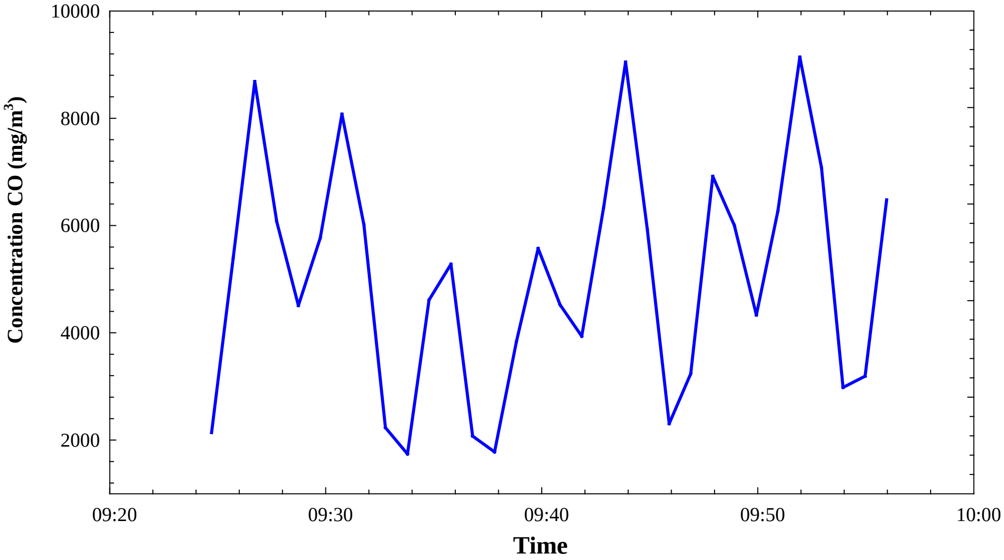


Figure 13. Concentration of CO (mg/m^3), during steady state operation of 1.7 MMBtu/hr boiler (at full load).



3.1.3.3 Particle Chemical Characterization

Elemental composition of wood pellets and trace metal recovery fractions are shown in Tables 7 and 8, respectively. The elemental composition is important as the emission depends on combustion appliance, operation condition and fuel composition. For example, in a study by Graham (NYSERDA 2010b) on residual oil composition, the sulfur content and other trace elements were determined. Ultra low sulfur diesel contains only 8 ppm of sulfur in the fuel, whereas the home-heating diesel and residual oil had sulfur at approximately 3,000 ppm. The recovery fractions are estimated by comparing the elemental concentrations in the fuel to the concentrations in $PM_{2.5}$. Despite low levels in the fuel, the portion of heavy metals released can have a substantial effect on public health. Cadmium, lead, thallium, rubidium and zinc were enriched in fine PM, with recoveries greater than 25%.

$PM_{2.5}$ chemical compositions are provided in Table 9. The majority of resolved fine PM mass was comprised of potassium (K^+) and sulfate (SO_4^{2-}) (79%). About 31% of K was recovered in fine PM, which is larger than that of most previous studies. Boman et al. (2004), Tissari et al. (2008) and Wiinikka et al. (2007) found recovery of K in fine PM to be in between 4 and 22% for residential scale wood combustion, whereas Sippula et al. (2009) found K recovery to be 35% and 5% for rotating grate and gasification district heating units, respectively. Because the boiler tested uses air staging, which has been found to decrease fine PM emissions through decreased temperatures in the fuel bed, recovery of K was expected to be lower.

It should be noted again that the fuel content of K is an estimate, and that this could be responsible for the calculated apparent high recovery. There were also minor amounts of sodium, magnesium, calcium, and zinc. The low amount of chloride relative to sulfate may be due to gas-phase sulfation reactions in which SO_2 reacts with alkali chlorides to form particle alkali sulfates and gaseous hydrochloric acid. The chemical analysis resolved 50% of total $PM_{2.5}$ mass. The unresolved portion could be oxygen, hydrogen and other elements not included in the analysis that are part of organic compounds, inorganic hydroxides and oxides, or carbonates. The unresolved fraction may also reflect analytical uncertainties.

Chemical analysis resolved 50% of the $PM_{2.5}$ mass. Tables 10 to 12 shows the average emission factors of some of the major aromatic compounds, linear alkanes and alkanoic acids at steady state operation. The concentration reported in Tables 4 to 6 are the total concentration of each species collected on a 142 mm quartz filter and a PUF plug. Although levoglucosan, a molecular marker of wood combustion, was a predominant compound found, the concentrations were relatively low at 82.3 μg/MJ. Total polycyclic aromatic hydrocarbon (PAH) emissions were relatively low (19.4-92.8 μg/MJ), which is comparable to previous studies of modern pellet stoves and boilers at steady state (7-320 μg/MJ).

Table 7. Elemental composition in wood ash.

nm means not measured.

Trace Elements	Pellets
elemental analysis [mg/kg dry fuel unless otherwise noted]	
C [% d.w.]	48.7
N	1424
S	63.6
Cl	nm
Al	12.5
As	0.01
Ba	6.04
Ca	638
Cd	0.001
Co	0.012
Cr	0.32
Cu	1.46
Fe	19
K	446
Mg	168
Mn	29.6
Na	10.4
Ni	0.095
Pb	0.15
Rb	1.17
Sb	0.013
Sn	nm
Sr	3.44
Tl	0
V	0.11
Zn	5

Table 8. Recovery fraction in $PM_{2.5.}$

Recovery fractions is the percentage of elements recovered from $PM_{2.5}$ calculated using emission factors.

Element Recovery	Wild Center (wt % PM 2.5)
Al	2.1
Ba	4.61
Ca	0.4
Cd	848
Cr	19.4
Cu	17.2
Fe	2.9
Mg	0.25
Mn	6.3
Pb	87.1
Rb	25.9
Sr	1.62
Tl	278
V	0.31
Zn	27.8
K	31.2

Table 9. Chemical composition of $PM_{2.5.}$

Species	**Wild Center**
Organic and Elemental Carbon (wt % of $PM_{2.5}$)	
OC	4.89
EC	1.95
Ionic Species (wt % of $PM_{2.5}$)	
Na^+	0.18
K^+	15.3
Mg^+	na
Ca^{2+}	na
SO_4^{2-}	24.4
Cl^-	1.68
Elemental Species (wt % of $PM_{2.5}$)	
Al	0.056
As	<DL
Ba	0.059
Ca	0.53
Cd	1.64×10^{-03}
Co	<DL
Cr	0.013
Cu	0.053
Fe	0.12
Mg	0.089
Mn	0.39
Ni	<DL
Pb	0.027
Rb	0.064

Table 9 continued

Species	**Wild Center**
Sb	<DL
Sn	2.70×10^{-03}
Sr	0.012
Tl	2.82×10^{-04}
V	6.97×10^{-05}
Zn	0.29

Table 10. Full load average emissions of selected aromatic compounds from a high-efficiency wood boiler using wood pellets as fuel.

Compounds	$\mu g/m^3$	ng/Btu	lb/MMBtu
Phenathrene	6.434	0.717	0.002
Anthracene	0.689	0.077	0.000
4-H-cyclopenta[def]phenanthrene	0.147	0.016	0.000
Fluoranthene	5.923	0.660	0.002
Pyrene	6.960	0.775	0.002
Benzo[a]anthracene	0.809	0.090	0.000
Chrysene+Triphenylene	1.492	0.166	0.000
1-Methylnaphthalene	2.355	0.262	0.001
2,6-Dimethylnaphthalene	0.278	0.031	0.000
2-Methylanthracene	0.025	0.003	0.000
1-Methylpyrene	0.277	0.031	0.000
3-Methylchrysene	0.009	0.001	0.000
Retene	0.078	0.009	0.000
Benzo[b]fluoranthene	1.623	0.181	0.000
Benzo[k]fluoranthene	0.575	0.064	0.000
Benzo[e]pyrene	0.668	0.074	0.000
Benzo[a]pyrene	0.562	0.063	0.000
Indeno[1,2,3-cd]fluoranthene	0.084	0.009	0.000
Indeno[1,2,3-cd]pyrene	4.366	0.486	0.001
dibenz[a,h]+[a,c]anthracene	0.492	0.055	0.000
Benzo[ghi]perylene	0.804	0.090	0.000
Coronene	0.823	0.092	0.000

* - Value reported here is the sum of species measured on the filter and the PUF plug. Data based on one PUF and one filter sample.

Table 11. Full load average emissions of linear alkanes from a high-efficiency wood boiler using wood pellets as fuel.

Compounds	µg/m^3	ng/Btu	lb/MMBtu
n-C11	1.174	0.229	0.00051
n-C12	0.925	0.180	0.00040
n-C13	0.802	0.156	0.00035
n-C14	1.467	0.286	0.00063
n-C15	3.196	0.623	0.00137
n-C16	4.537	0.885	0.00195
n-C17	5.971	1.164	0.00257
n-C18	4.647	0.906	0.00200
n-C19	2.100	0.410	0.00090
n-C20	1.146	0.224	0.00049
n-C21	0.889	0.173	0.00038
n-C22	1.037	0.202	0.00045
n-C23	1.412	0.275	0.00061
n-C24	0.770	0.150	0.00033
n-C25	0.747	0.146	0.00032
n-C26	0.824	0.161	0.00035
n-C27	0.867	0.169	0.00037
n-C28	0.634	0.124	0.00027
n-C29	0.618	0.120	0.00027
n-C30	6.731	1.313	0.00290
n-C31	5.590	1.090	0.00240
n-C32	2.083	0.406	0.00090
n-C33	0.146	0.028	0.00006
n-C34	-0.023	-0.005	-0.00001
n-C35	0.401	0.078	0.00017
n-C36	0.140	0.027	0.00006
n-C37	0.036	0.007	0.00002
n-C38	0.014	0.003	0.00001

* - Value reported here is the sum of species measured on the filter and the PUF plug. Data based on one PUF and one filter sample.

Table 12. Full load average emissions of alkanoic acids and other compounds from a high-efficiency wood boiler using wood pellets as fuel.

Compounds	µg/m^3	ng/Btu	lb/MMBtu
18α(H)22,29,30-Trisnorneohopane	0.000	0.000	0.00E+00
17α(H)-22,29,30-Trisnorhopane	0.340	0.066	1.46E-04
17α(H), 21β(H)-29-Norhopane	0.995	0.194	4.28E-04
18α(H)-29-Norneohopane	0.000	0.000	0.00E+00
17α(H)-21β(H)-Hopane	1.252	0.244	5.38E-04
22S,17α(H),21β(H)-30-Homohopane	0.000	0.000	0.00
22R,17α(H),21β(H)-30-Homohopane	0.000	0.000	0.00
22S,17α(H),21β(H)-30-Bishomohopane	0.000	0.000	0.00
22R,17α(H),21β(H)-30-Bishomohopane	0.000	0.000	0.00
20R, 5α(H),14β(H), 17β(H)-Cholestane	0.679	0.132	2.92E-04
20S, 5α(H),14β(H), 17β(H)-Cholestane	0.000	0.000	0.00
20R, 5α(H),14α(H), 17α(H)-Cholestane	0.000	0.000	0.00
αββ,20R,24S-methylcholestane	0.501	0.098	2.16E-04
αββ,20R,24R-Ethylcholestane	2.199	0.429	9.46E-04
ααα,20R,24R-Ethylcholestane	0.593	0.116	2.55E-04
n-Nonanoic acid	136.702	26.656	5.88E-02
n-Decanoic acid	8.894	1.734	3.82E-03
n-Undecanoic acid	3.085	0.602	1.33E-03
n-Dodecanoic acid	5.214	1.017	2.24E-03
n-Tridecanoic acid	-0.003	-0.001	-1.40E-06
n-Tetradecanoic acid	0.730	0.142	3.14E-04
n-Pentadecanoic acid	0.309	0.060	1.33E-04
n-Hexadecenoic acid	0.523	0.102	2.25E-04
n-Heptadecanoic acid	0.710	0.138	3.05E-04
n-Octadecanoic acid	3.159	0.616	1.36E-03
n-Octadecenoic acid	0.035	0.007	1.51E-05

Table 12. continued

Compounds	µg/m^3	ng/Btu	lb/MMBtu
n-Nonadecanoic acid	-0.265	-0.052	-1.10E-04
n-Eicosanoic acid	0.000	0.000	0.00E+00
n-Heneicosanoic acid	2.355	0.459	1.01E-03
n-Docosanoic acid	5.008	0.976	2.15E-03
n-Tricosanoic acid	1.074	0.209	4.62E-04
n-Tetracosanoic acid	0.462	0.090	1.99E-04
n-Pentacosanoic acid	0.712	0.139	3.06E-04
n-Hexacosanoic acid	0.031	0.006	1.35E-05
n-Heptacosanoic acid	0.173	0.034	7.43E-05
n-Octacosanoic acid	0.153	0.030	6.60E-05
n-Nonacosanoic acid	0.102	0.020	4.40E-05
n-Triacontanoic acid	0.000	0.000	0.00
2-Methylthreitol	0.000	0.000	0.00
2-Methylerythritol	0.000	0.000	0.00
Cholesterol	413.728	80.674	1.78E-01
Abietic acid	2.086	0.407	8.97E-04
cis-pinonic acid	3.493	0.681	1.50E-03
Vanillic acid	0.042	0.008	1.82E-05
malonic acid	0.570	0.111	2.45E-04
succinic acid	2.255	0.440	9.69E-04
methylsuccinic acid	0.036	0.007	1.55E-05
glutaric acid	1.575	0.307	6.77E-04
malic acid	22.674	4.421	9.75E-03
adipic acid	8.795	1.715	3.78E-03
suberic acid	8.519	1.661	3.66E-03
azelaic acid	5.900	1.150	2.54E-03
levoglucosan	141.085	27.511	6.07E-02
guaiacol	5.922	1.155	2.55E-03

Table 12. continued

Compounds	µg/m^3	ng/Btu	lb/MMBtu
eugenol	0.654	0.128	2.81E-04
vanillin	4.792	0.934	2.06E-03
homovanillic acid	0.026	0.005	1.10E-05
4-Hydroxyphenylacetic acid	0.000	0.000	0.00
campesterol	0.000	0.000	0.00
stigmasterol	0.317	0.062	1.36E-04
beta-sitosterol	1.713	0.334	7.37E-04
syringaldehyde	8.525	1.662	3.67E-03
4-Hydroxy-3-methoxy cinnamaldehyde	0.000	0.000	0.00

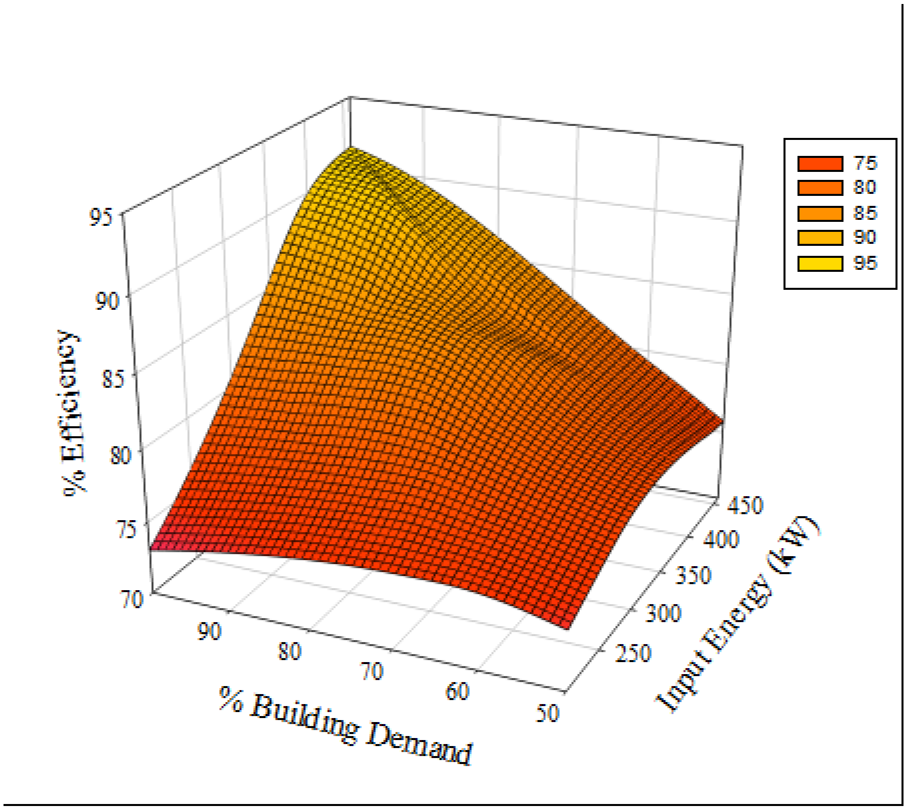
* Value reported here is the sum of species measured on the filter and the PUF plug. Data based on one PUF and one filter sample.

4 Optimization

To achieve maximum efficiency and also to save operating and fuel costs, it is important to operate the boiler under optimized conditions. Figure 14 shows the optimization plot of the Wild Center boiler based on the real time data obtained from the solarwave.net from October to May 2011. The plot represents efficiency variation as a function of the operating parameters such as fuel feed rate, building heat demands, and the outlet water temperature range between 150 ºF and 190 ºF for inlet and outlet, respectively. The efficiency was about 75% at lower building demands and at low fuel feed rates and about 91% at higher building demand and high feed rates. At low input rates of 250kW and low building demands (50%), the efficiency is around 75%. Even as the building demand increases, there is no substantial change in efficiency at low input rates. The efficiency increased as the input rate and building demand increased and is highest at an input rate (450kW) and at 90% -100% building demand. Plotting the sparse data led to distortions in the graphs, which were hard to interpret. The 182kW point was removed from the graph because it appeared anomalous. There were instances that the building heat demand was satisfied by the wood boiler and excess heat was absorbed by the space heat loop of the solar hot water storage tank resulting in slightly increased efficiency values. The boiler output plotted against the energy input does not allow the estimation of the potential for thermal storage to increase efficiency.

Thus, operating the boiler at highest fuel feed rate and outlet water temperature proved to be efficient at higher building demands. However, for the lower heat demands in the building, the boiler seems to be oversized with respect to the load demands.

Figure 14. Optimization of operating parameters in CAT 500 (Wild Center boiler).



4.1 Wild Center Solar System Performance

The performance of the solar hot water system during extreme weather condition is summarized in Table 13. The period from January until early March is considered winter, and late March until mid-May is considered to be the shoulder heating season. Each day is classified as clear day or a cloudy day based on the amount of sunshine received. T_i and T_a represent inflowing water temperature into the panel and surrounding ambient temperature of the panel, respectively. A more efficient use of solar energy was accomplished by using evacuated tube collectors to heat water. The round shape of the tubes exposed them to the sun at every angle during the day. The tubes performed well in cold weather conditions without much loss, whereas conventional flat plate collectors lose some collected heat on cold and cloudy days. Tupper Lake has latitude and longitude of 44.223N and74.464W, respectively, and an elevation of approximately 1,598 feet.

The observed energy output from the solar panel is close to the predicted value with efficiency about 95% except on a very cloudy day during winter. According to the data, it is quite clear that an indirect system with 40% antifreeze in the solar loop works well for the North Country.

Table 13. Solar System Performance.

	T_i-T_a	Expected output	Observed output	Efficiency
Weather Condition	**Degree F**	**kBtu/day**	**kBtu/day**	**%**
Sunny (Partly cloudy or clear) May 21	36	213.6	209.7	98
Sunny (very cloudy) June 2	90	134.6	127.2	94
Winter (partly cloudy/ clear) January 23	36	124.8	121.8	97
Winter (very cloudy) February 17	90	55.8	42.4	75

Figure 15 represents the Brookhaven National Laboratory heating energy model for the Wild Center from January 2010 to December 2010. The Minneapolis weather data was the available data to reflect the weather conditions of Tupper Lake, NY. Assumptions were made for lighting loads, occupancy periods and infiltration.

Figure 15. Brookhaven National Laboratory energy model for space heating requirements at the Wild Center from January 2010 through December 2010.

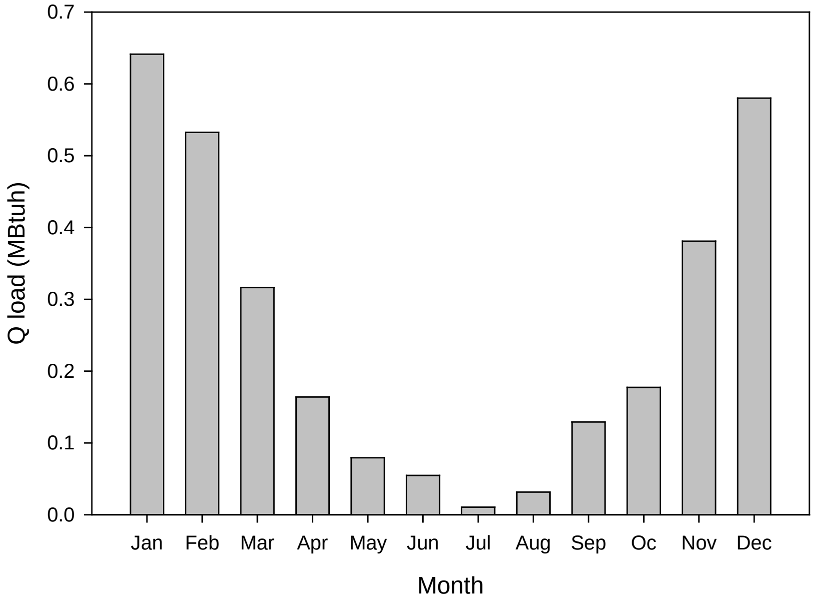
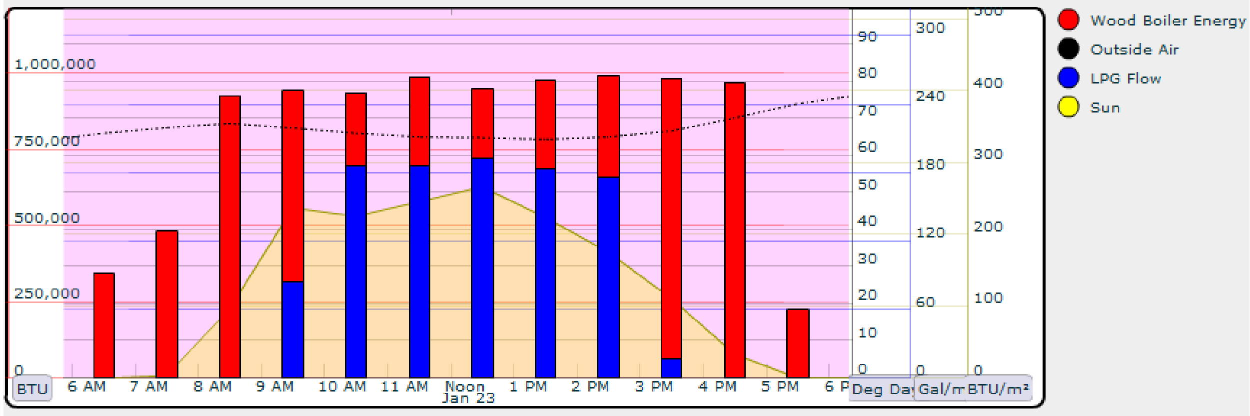
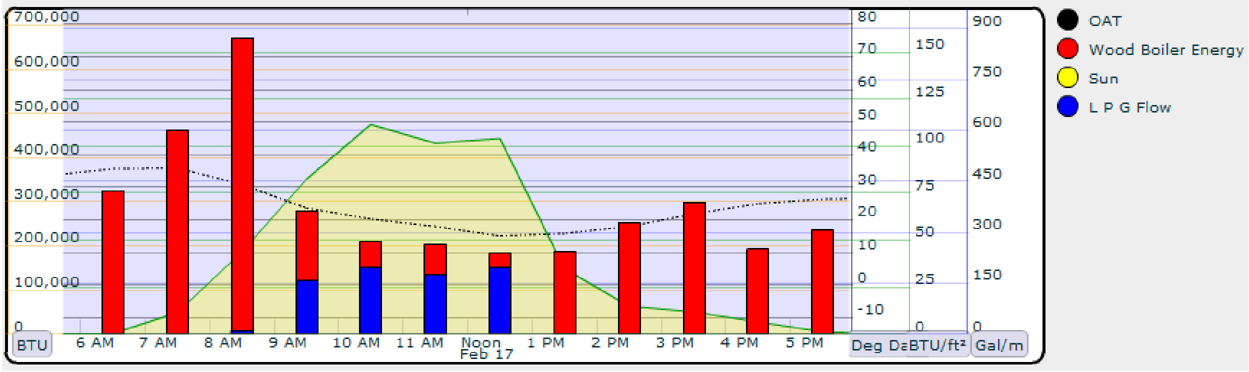


Figure 16. Heating performance at the Wild Center on January 23, 2011.



On January 23, the outside air temperature was approximately -9 ^{o}F (-22.7 ^{o}C) and it was a cloudy day. The wood-pellet boiler was installed to meet about 70% of the heating need in the building required for these conditions. The red bar in Figure 16 represents the wood boiler energy (Btu) and the blue bar represents the LPG flow in gallons. Pellet boiler energy is supplied only for the space heating energy demands, while the LPG contributes to cooking, cafe hot water needs and space heating (if the demand in the building is high). A majority of the space heating energy was supplied by the pellet boiler, contributing about 67% (the boiler was operated with an efficiency of 90% as the demand in the building was high) of the total. The rest of the heating demand was supported by the LPG flow and for the Waterside Café hot water needs indicated by blue bars (Figure 16). Hence, the LPG boiler makes a significant contribution in supplementing the heat demands during heating season. Although, there was some collection from the solar thermal system, the harvested energy (not clearly visible in the graph), the value is negligible when compared to the space heating needs (less than 15.8Btu/ft^2 averaged to the day). The harvested energy is calculated from the collector supply and return water temperature and from the flow meter on solar collection loop. However, the collected energy was sufficient during the midday for domestic hot water (DHW) (from the area under the curve given by yellow color).

Figure 17. Heating performance on February 17, 2011.

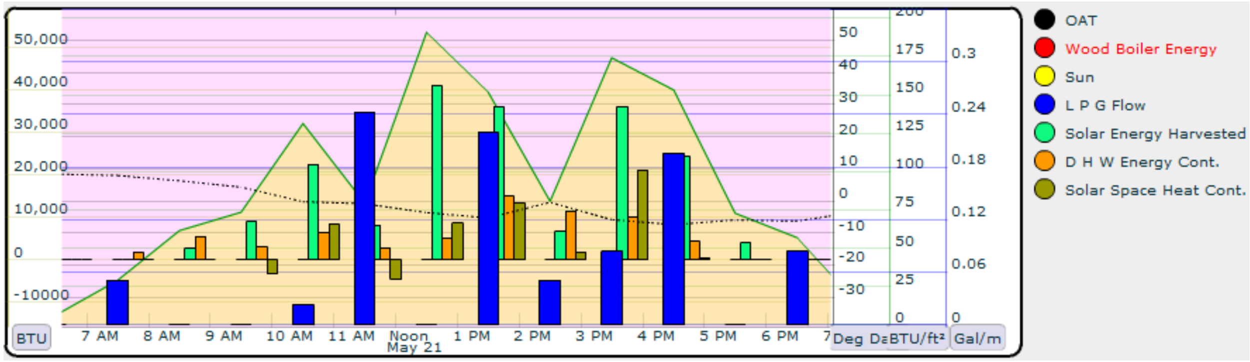


On February 17, 2011, the average outside air temperature was about 43 °F (6 °C). The LPG flow represented by the small blue bar was probably for the café hot water and for cooking. Much of the energy demand for the space heating was supplied by the pellet boiler (an estimate of 83%). The calculated demand in the building was about 80%. The rest of the heating was supplemented by the LPG boiler from 9:00 am until 1:00 pm. From the estimates of LPG energy supply, it can be noted that more energy was supplied by the propane boiler. Heat may be supplied to the air handlers to warm up the moist air. However, there is no way to quantify how and where the energy has been used. The solar energy harvested was about 101.47 Btu/ft^2 for about 2 hours from 10:30 am to 12:30 pm (when there was bright sun shine) represented by the area in yellow color. The harvested energy, calculated from the collector supply and return water (indicated by green and blue lines) temperature and from the flow meter on solar collection loop, was sufficient for DHW water supply and some for space heating, during midday since the solar tank temperature exceeded the set point temperature and the solar space heating valve opened to supply hot water to the space heating loop. This is seen from the drop in the energy supplied by the pellet boiler decreasing the boiler operation however not significantly.

Figure 18. Heating performance for June 2, 2011.

On June 2, 2011, the outside temperature was 53 °F (11.6 °C) and it was a clear day. The harvested solar energy was about 95.1Btu/ft^2 area covered by yellow fill for about 4.5 hours from 10:00 a.m. to 4:00 p.m. when there was bright sunshine. The harvested energy was sufficient for DHW water supply and some for space heating calculated from the energy balance (Solar space heating is equal to the solar energy harvested minus the DHW energy contribution, as the flow is split for two intended purposes mentioned before). Much of the space heating and DHW water were supplied by the solar hot water system supplemented by LPG boiler during late afternoon. The wood boiler was not operated as there was not much heating load required by the building. Some negative spikes were seen in solar space heat contribution towards the end of the day (Figure 18) the dry green grass color bars. This negative value indicates that the energy from the space heating loop has been sent into the storage tanks. The possible reason for this might the storage tanks might have lost the minimum heat required. The minimum heat is the set point temperature of the upper storage tanks (usually 130 °F). As temperature of the storage tanks falls below this set point temperature, the heat is taken from the space heating loop.

Figure 19. Heating performance of May 21, 2011.



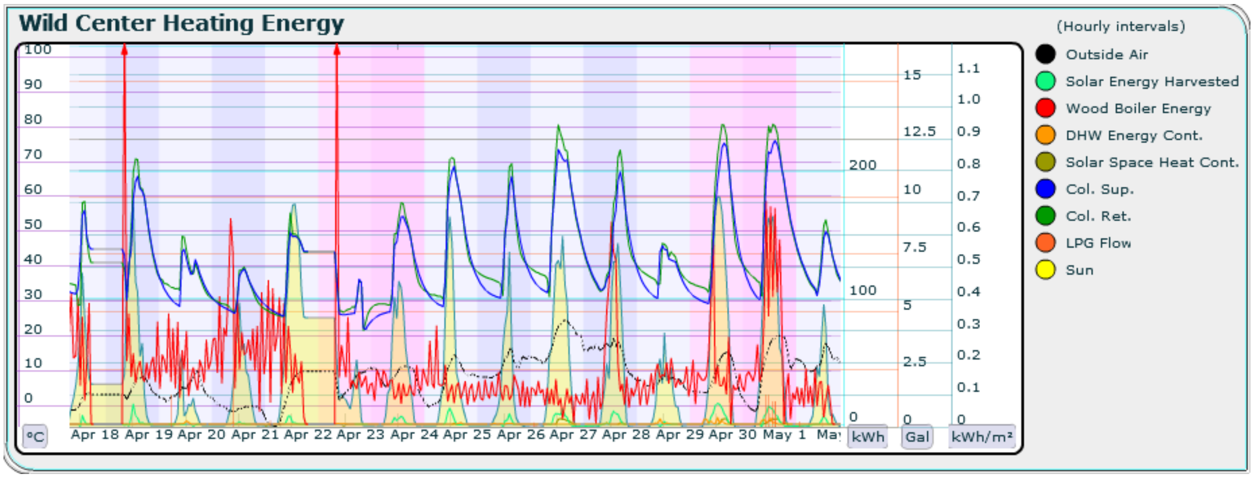
On May 21, 2011, the outside temperature was 62^{o}F (16.6^{o}C), and it was a clear sunny day. During the summer, the warm air moist is brought into the heating loop to dry out the air in air handlers thus reducing the LPG boiler firing that is used to maintain the temperature in tanks and heating loop, if the solar arrays cannot maintain the required temperature.The LPG boiler provided energy for the Waterside Café's hot water and for warming the moist air supplementing the solar-thermal system. Most of the energy supplied by the solar-thermal system was for space heating. Solar energy harvested was about 158.5 Btu/ft^2 for about 5 hours (from 10:00 am to 3:00 pm when there was bright sun shine represented by the area covered by yellow fill). The harvested energy was maximum (shown in Table 13) and was sufficient for DHW water supply. Because the storage tanks had enough energy stored (200,000 Btu), the harvested energy and some energy from the LPG boiler was used for space heating during the night. The LPG boiler was operated due to quick response time in the morning when compared to the Wood-Pellet Boiler. This significantly reduced the Wood-Pellet Boiler cycling at low building loads. Here also we see some negative solar space heat during the early hours (Figure 19 represented by dark green bars).

There were some negative values noted for harvested Solar Energy during the beginning of the day however, it is negligible as viewed in the graph. This was mostly observed during January and February. One explanation may be due to large negative spikes in the data at the beginning of the day. When the pumps had been turned off for a long time such as overnight, the temperature inside the pipes tends to settle to close to ambient. Then once the pumps were turned back on it took some time for the temperature of the fluid inside the pipe to get back up to temperature. This happened most of the time that the negative values were observed. On some very cloudy or cold days this negative value can exceed the amount of total daily energy harvested.

There is also a function on the Stiebel Eltron SOM 7 controllers that protects the fluid in the collectors from freezing. If the temperature at the collector falls below a certain temperature, the pump runs for a period such that the hot transfer fluid from the tanks will run through the collector preventing it from freezing. This function is reported as negative energy because the tank is losing heat through the collectors to keep them from freezing and will contribute negatively to the overall daily energy value.

In addition, a negative Btu value may be observed because of a phenomenon called thermosiphoning. This process might occur when there is a large enough temperature differential between two points. Although a check valve could minimize this phenomenon, there might be a possibility that thermo siphoning contributed to the negative values noted for harvested solar energy. Due to temperature gradient, the fluid moves from areas of high temp to low and may actually cause flow in the loop without the pump being turned on.

Figure 20. Energy profiles from April 18 to May 2.

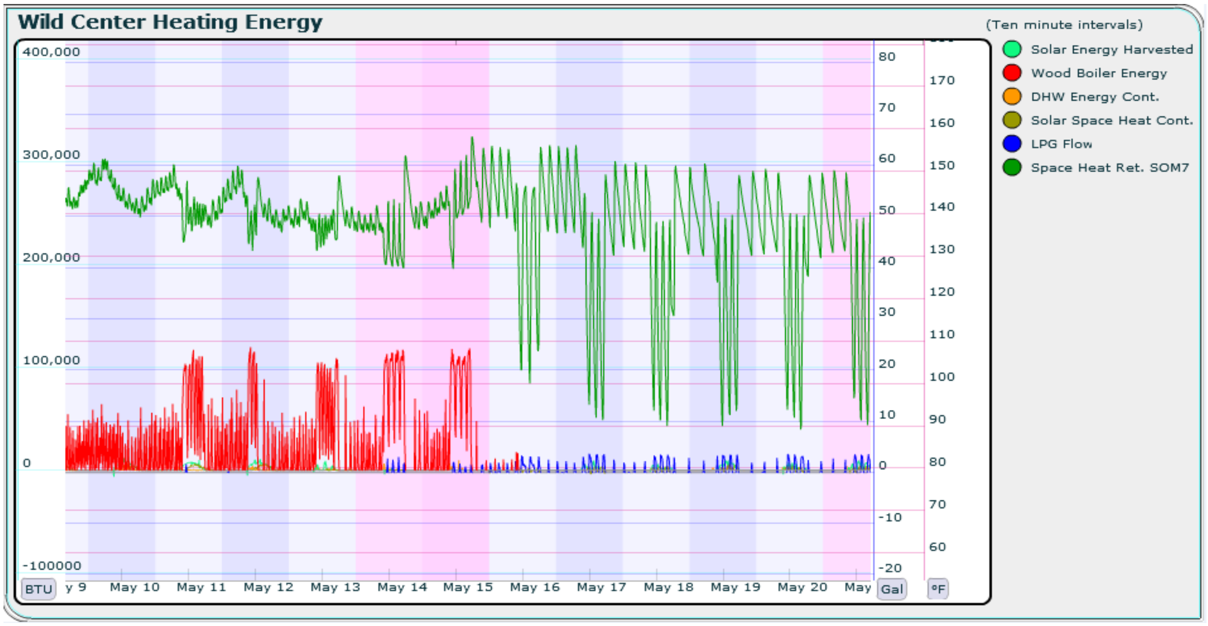


During shoulder heating season, most of the energy needs were satisfied by the solar energy during day times and decreased the boiler operation at lower efficiency (Figure 20). However, there was no energy transfer in the system during night times. The solarwave monitoring unit only reported energy when there was flow. Since there was no flow, no energy value was reported. Thus, during night times when there was no requirement to draw heat from the storage tanks, there was no DHW energy calculated. The storage tanks were temperature-controlled and programmed to initiate space heating contributions only when the tank temperature exceeded the hydronic loop return temperature by at least 6 °F. Hence, when space heating was needed during the night in the shoulder heating season, the demand was satisfied by the pellet boiler. The boiler operated at lower efficiency (about 60-65%) because of the relatively low building demand (See Figure 8). There was a reduction in boiler operation, but it was not significant in reducing fuel consumption.

As for the solar space heating, there was no DHW draw during the night hours, and no energy either entering or leaving the collectors. The insulated tanks retained their temperatures fairly well with some standby losses (about 1 ºF). Thus, there was no need for the hot water storage tanks to be heated by the Wild Center heating loop.

The LPG propane boiler also contributed to the Wild Center’s heating loop (Figure 21). According to the data, during this period (May 15 until May 22), the pellet boiler was intentionally shut off to avoid cycling, and the LPG boiler supplied the energy that the hydronic loop required. The gas range was in the Waterside Café and the flow was not recorded. Some fraction of the propane was used for cooking, providing hot water in the café satisfied, partly heating demands, and to heat the moist air coming in through air handlers during summer. The LPG boilers were relatively quicker in responding to the building heat demand during early morning when compared to the pellet boiler. Addition of a thermal storage unit would reduce the use of LPG boiler as well as reduce the pellet boiler cycling. The use of the propane boiler to satisfy heat demands may be due to the fact that the pellet boiler is oversized for much lower demands. It is more practical to rely on solar thermal unit and the LPG boiler during early fall or late spring.

Figure 21. Contribution of LPG flow for space heating.



4.2 Process Economics and Scope for Improvement

The fuel consumption and cost are compared before and after installation of wood-pellet boiler at the Wild Center in Table 14. The LPG consumption was prior to wood boiler installation from April 2009 to March 2010. The wood boiler was fired April 2010. The LPG consumption after wood boiler installation was from April 2010 to March 2011.

Table 14. Comparison of fuel utilization with respect to cost.

Parameter	Prior to Wood boiler installation	After WoodBoiler installation
LP G flow (Gallons)	38,208	5,472
Total Cost of LPG	$65,702	$10,394
Pellets consumption	-	$23,655
Total Cost fuels	$65,702	$34,049
Savings after 1 year	-	$31,653
Degree days	-	7,863[a]

[a] From August 2010 until April 2011. Data were available only from August 2010.

The response time of the storage unit is expected to be quick when compared to the wood boiler. Operating the wood boiler at low building demands during the shoulder heating seasons not only resulted in low efficiency but increased operating costs. To reduce the boiler cycling and increase the efficiency, thermal storage with capacity of about 1,000 gallon could be installed to store excess energy and facilitate rapid heat demand response the following morning. Tapping stored hot water would significantly reduce the boiler cycling allowing it to operate mostly at high load, high-efficiency conditions regardless of the heat demand in the building. This approach would result in lower emissions. Table 15 compares the boiler operations at 65% and 85% efficiency, demonstrates a return on investment calculation, and suggests a simple payback period of less than five years.

Table 15. Economics of installing a thermal storage unit with existing pellet boiler-solar thermal system.

	Wood-Pellet Boiler	
Parameter	**Efficiency 85%**	**Efficiency 65%**
Fuel Heat content	16.3 MMBtu/ton	16.3 MMBtu/ton
Fuel consumed, when operated at 100% load per heating seasona	~ 98 tons (reduced cycling)	~127 tons
Fuel Cost	$185/ton	$185/ton
Annual Fuel cost (1st year)	$18,130	$23,495
Annual Fuel cost (2nd year) Fuel consumption 80 ton**b	$14,800	$14,800
Thermal storage unit costs (1,000 gallon)	$15,000	-
Total costs	$47,930	$38,295
Cost after 5 heating seasons	$87,320	$108,780
Savings After 5 heating seasons	$21,460	-
Simple Payback period (year)	<5	-

[a] Estimated based on efficiency

[b] The boiler was down late in January and February for three weeks for repairs, and the winter was a very mild.

Furthermore, the boiler operation can be minimized by doubling the size of the solar collector. The current solar collector capacity is 300,000 Btu/day and the capacity of the storage tanks is 200,000 Btu (for a temperature difference of 75 ºF between the inlet water [city water] and DHW). This amount of energy is equivalent to that in two gallons of fuel oil. For the shoulder heating season month (during April), the calculated temperature difference had an average value about 50 ºF. For May and June, the calculated temperature difference exceeded 75 ºF. The temperature difference 50 ºF contributed to 133,333 Btu (calculated from energy balance and interpolation) which is about 67% of tanks capacity. By doubling the collector size to 600,000 Btu/day, excess solar energy can be harvested and stored in the thermal storage units that can be utilized for space heating during night and early morning hours.

It is difficult to estimate the Waterside Café's hot water consumption because there are no data available. However, there is no need to cover the panels during summer because the Wild Center's existing well insulated hydronic piping loop provides an additional storage capacity of approximately 600 gallons (a part of building design initially). The heating loop runs through the air handlers. During summer when the building needs some heating overnight and early in the morning, warmer ambient air is brought in to preheat the large hydronic loop during the previous day and retain that heat energy overnight. The boiler would, in theory, cycle less in the morning. The museum always maintains a minimum temp of 150˚F in the loop, even in the summer, as it could have been needed for heating on any given morning since summer morning temperatures can be in the 40s, with daytime highs in the 70s. An additional collector system would add a cost of $15,000 to the thermal storage unit (Table 13). However, it would be economical on a long term basis reducing pellet and LPG consumption and related costs. There are very little operating and maintenance costs for the solar-thermal system. It requires the operation of two coolant pumps and one space heat injection pump that demand a total of about 3 amps (a capacity of three 100-watt bulbs) when they operate.

5 Results and Recommendations

The first Made-in-NY commercial wood-pellet boiler manufactured by Advanced Climate Technologies, LLC of Schenectady, NY was installed at the Wild Center in April 2010 and integrated with a solar-thermal hot water system. The boiler was tested for efficiency and emissions performance by researchers at Clarkson University. The following describe results and recommendations:

- The thermal efficiency of the Wild Center boiler ranged from 61% to 80% during spring 2010 and from 65% to 91% during spring 2011 over a boiler thermal capacity of 50% to 100%.
- Efficiency performance was best when the boiler was operating at full load in steady-state.
- The PM emissions from the pellet boiler stack at full load were 0.06 and 0.07 lb/MMBtu by CTM-039 and EPA Method 5 respectively or 0.47 g/kg of wood pellets. In comparison a number 6 oil-fired boiler was measured in another study at 0.016 lb/MMBtu.
- CO from the pellet boiler measured 1.21 lb/MMBtu or 1015 ppm in contrast to CO emissions from No.2 oil-fired systems which are typically 0.026 lb/MMBtu or 33 ppm and the American National Standards Institute limit in flu gas of 400 ppm.
- SO_2 and NO_x were 0.001 and 0.07 lb/MMBtu and 0.005 and 0.42 g/kg respectively.
- Emissions of carbonaceous derived species (OC, EC, PAHs, and organic compounds) during high-load, steady-state operation were all relatively low because of the nearly complete combustion.
- The Wild Center heating costs following the installation of the ACT pellet-fired boiler and solar thermal system were reduced by $31,653 over the year prior.
- The pellet boiler heating system can be optimized further on a seasonal basis by adding more thermal storage. A 1,000 gallon tank is recommended to allow for quicker response during a call for heat, more operation of the boiler high load and less cycling of the boiler to meet low heating loads. It is anticipated that this will have a payback of less than five years.
- The solar-thermal array was effective in providing domestic hot water and space heating during summer and shoulder seasons.
- Domestic hot water and space heating can be further enhanced by doubling the solar-thermal arrays. This additional thermal energy can be stored in the 1000 gallon tank. The excess heat can be dumped in the heating loop that runs through the air handlers. This excess heat can be used to warm the moist air entering.

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New York State
Energy Research and
Development Authority

17 Columbia Circle
Albany, New York 12203-6399

toll free: 866 NYSERDA
local: 518-862-1090
fax: 518-862-1091

info@nyserda.ny.gov
nyserda.ny.gov

The Wild Center Renewable Heating Demonstration: High-Efficiency, Commercial-Scale, Wood-Pellet Boiler Integrated with a Solar Thermal System

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Andrew M. Cuomo, Governor

New York State Energy Research and Development Authority
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