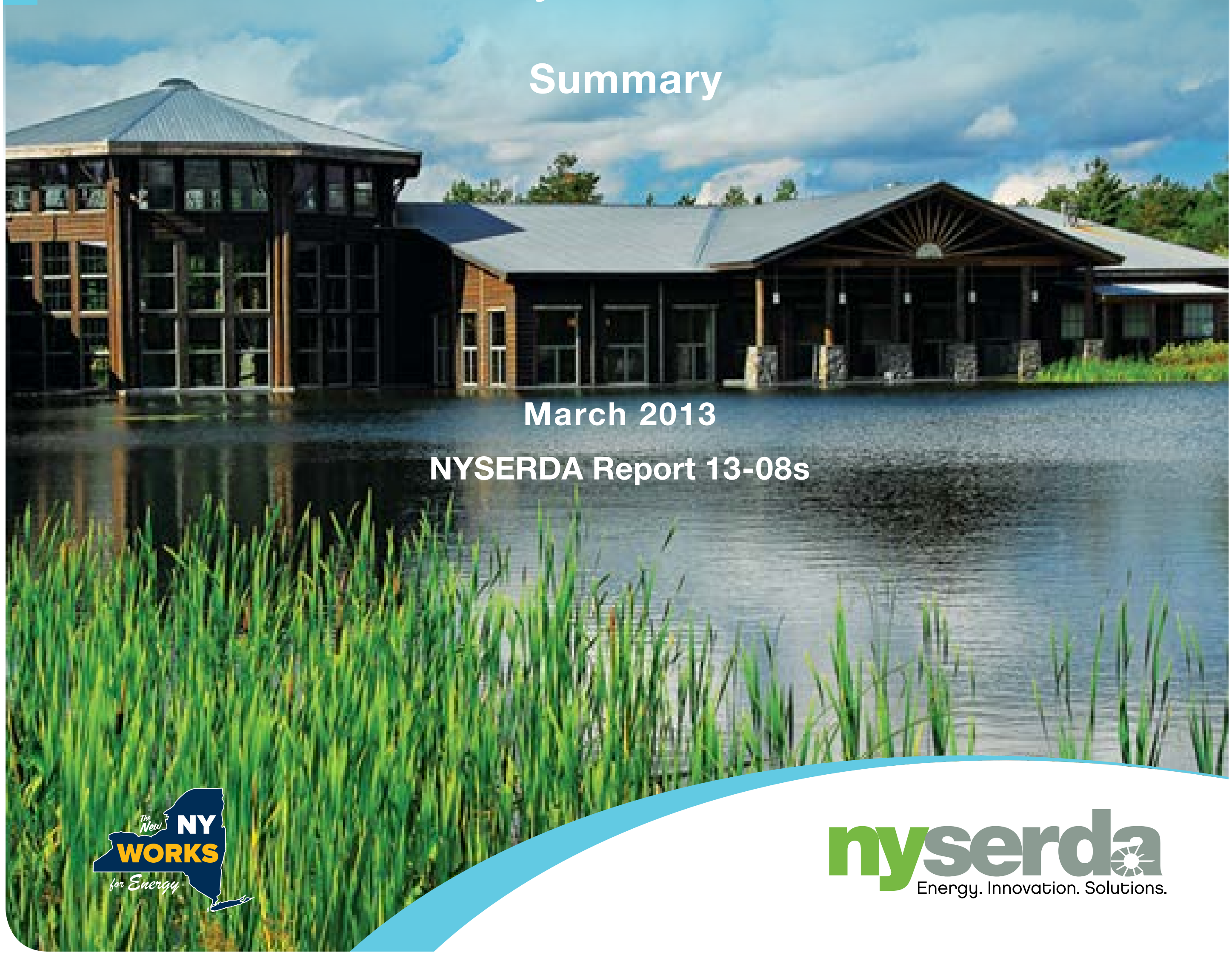
New York State Energy Research and Development Authority

The Wild Center Renewable Heating Demonstration:

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



Summary

March 2013

NYSERDA Report 13-08s

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Cover photo courtesy of Wild Center

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

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Notice

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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.

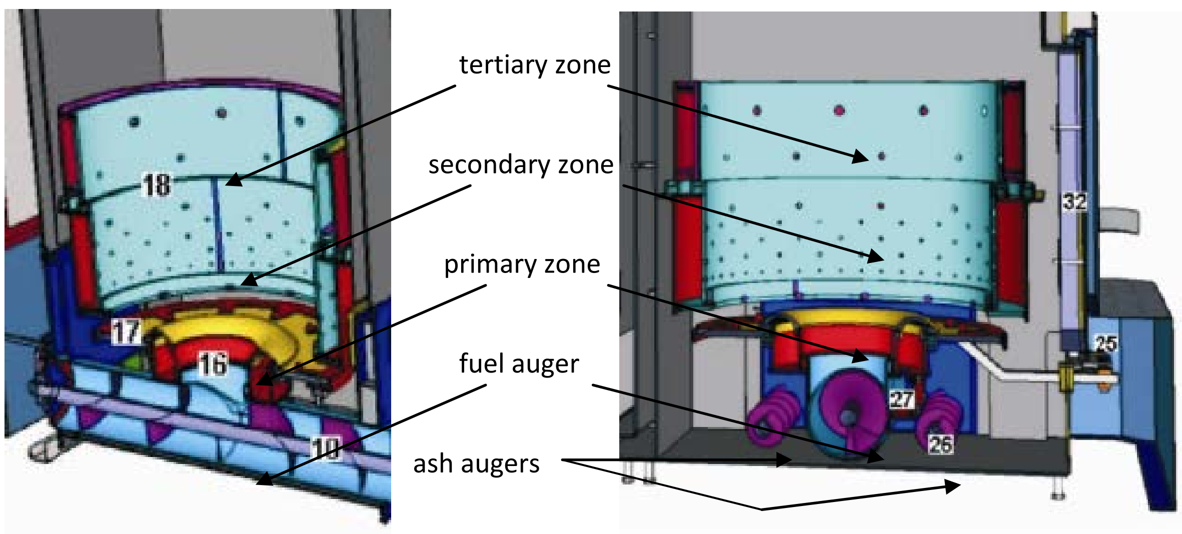
Figure S-2. The pellet boiler at the Wild Center was manufactured by Advanced Climate Technologies of Schenectady, NY.

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.

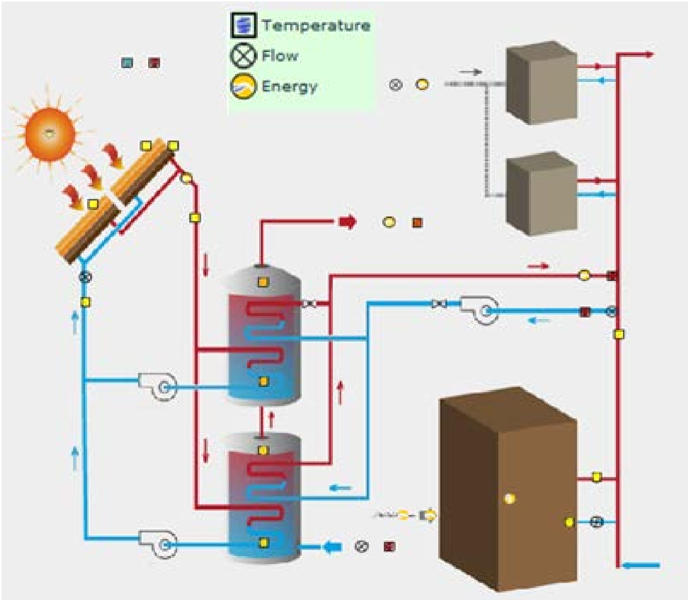


The Wild Center solar thermal system is an active indirect system as shown in Figure S-4. It consists of two types of solar collectors mounted on the south side of the wood-pellet container roof. Four flat plate collectors manufactured by Alternate Energy Technologies operate in parallel with 100 Viessman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



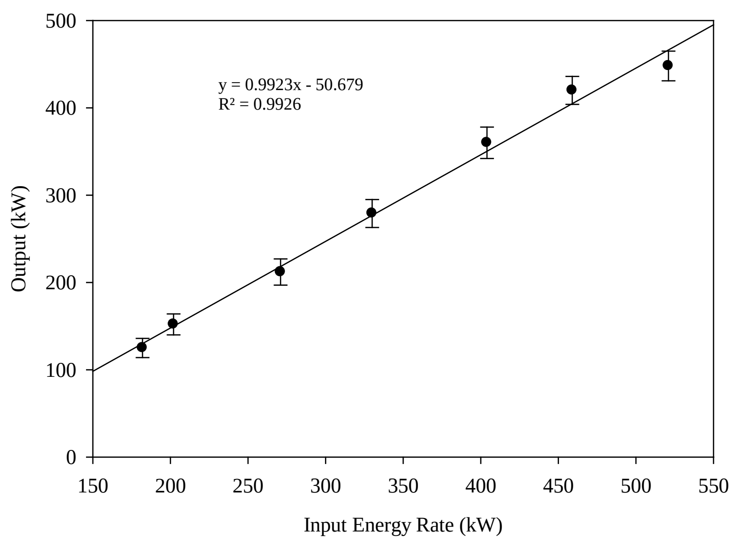
S.2 Efficiency Performance

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:

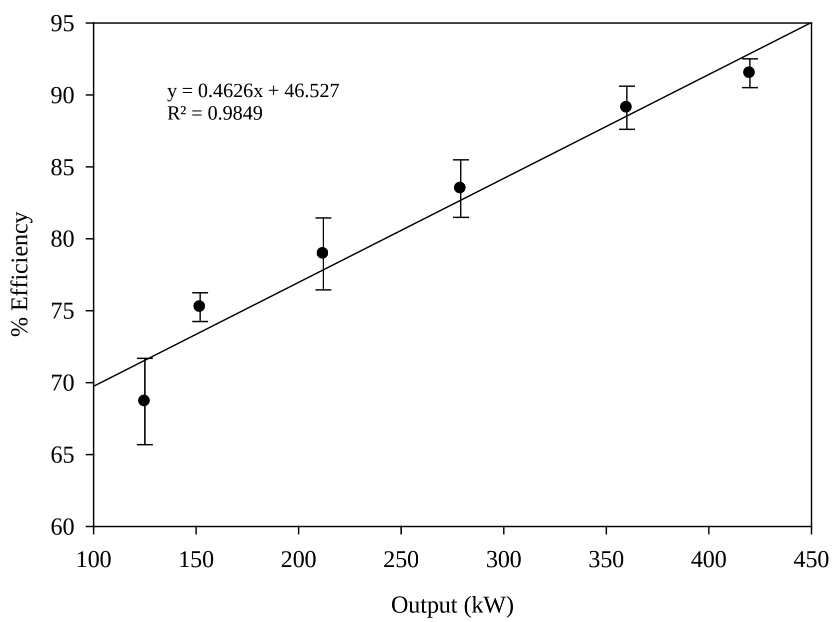
$$\%bd = \frac{(Tset - Tavg)}{T_{set}} * 100 \qquad \text{(Equation S-1)}$$

where

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

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.

	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 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 ºF 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 ºF while for May and June, the calculated temperature difference exceeded 75^{o}F. The temperature difference of 50 ºF 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 ^{o}Fand outlet water temperature ranging between 240 ºF and 260 ºF. 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.

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