Getting There

High-Efficiency and Low-Emissions Wood Heating

by Nathan Russell
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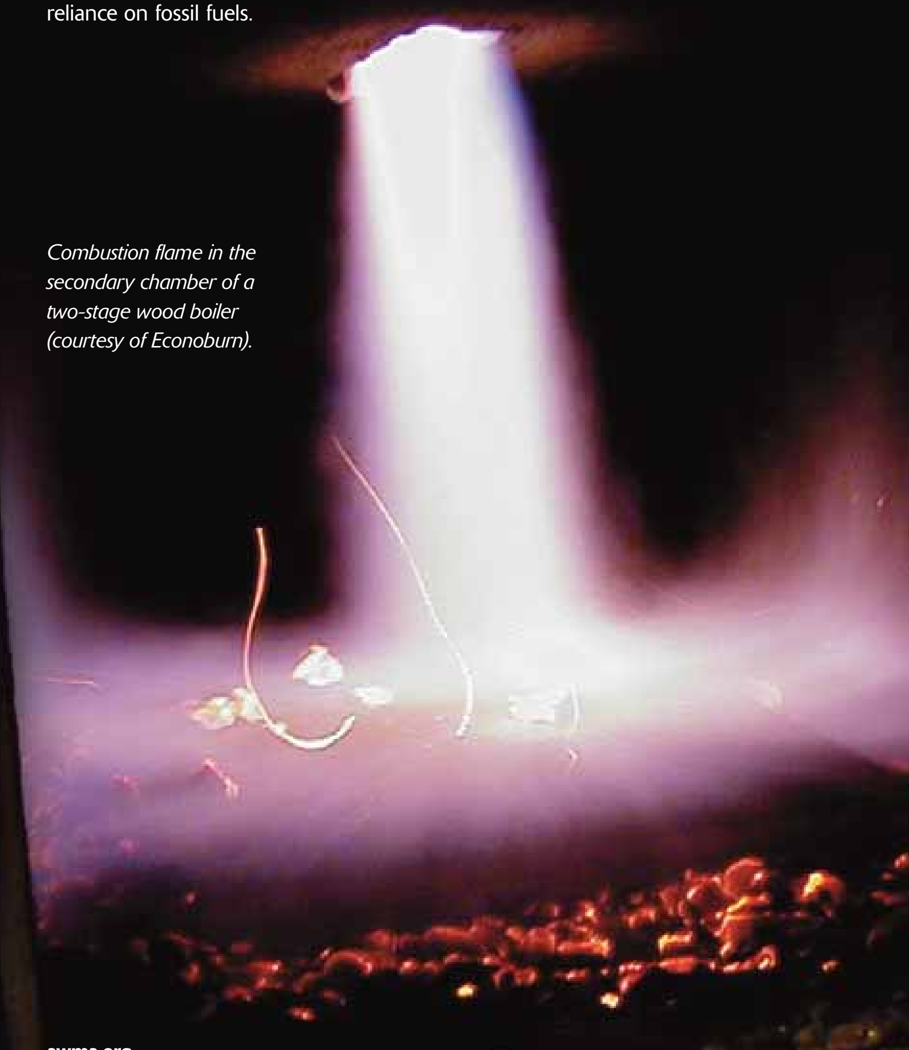
NYSERDA offers objective information and analysis, innovative programs, technical expertise, and funding to help New Yorkers increase energy efficiency, save money, use renewable energy, and reduce their reliance on fossil fuels.

For thirty years, the New York State Energy Research and Development Authority (NYSERDA) has maintained a heating research and development (R&D) program to help manufacturers develop more efficient technologies.

Traditionally, this program focused on advancing oil- and gas-fired heating systems and evaluating low-sulfur and biofuels. NYSERDA also has an environmental R&D program that evaluates air quality and other environmental impacts from the production and use of energy. In an effort to develop a high-efficiency biomass (e.g., solid wood and nonwood fuels, such as grasses and agriculture products) heating market in New York State, NYSERDA's environmental and buildings R&D programs are supporting 20 projects[1] to:

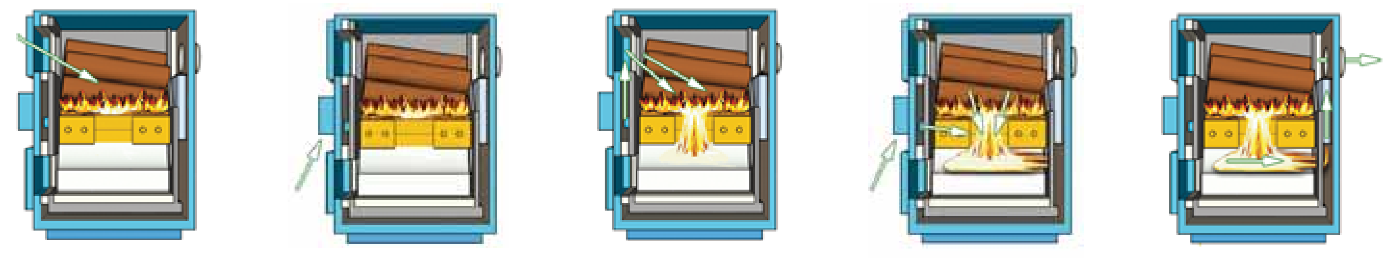
- Evaluate the energy-efficiency and emissions performance of conventional and advanced biomass-fired heating technologies;
- Develop advanced boiler technologies by supporting R&D and commercialization efforts with New York State manufacturers;
- Demonstrate advanced technologies in representative applications;
- Evaluate biomass fuel feedstocks;
- Improve monitoring and modeling of ambient wood smoke; and
- Provide objective scientific information for the development of high-efficiency and low-emissions biomass heating initiatives in New York State.



Combustion flame in the secondary chamber of a two-stage wood boiler (courtesy of Econoburn).

Wood Combustion

In the near term, wood primarily seeks to displace heating oil and as such, wood-fired systems must have competitive energy and emissions performance. Typical oil-fired boilers have efficiencies of 80–87%, although ultra-low-sulfur heating oil allows for 95%+, which is comparable to the best gas-fired systems. An oil-fired appliance is fully automated and requires little attention and the actual startup and shutdown operation minimally impact performance. Optimizing combustion performance for smaller-scale systems requires a fairly simple, annual adjustment to the air/fuel ratio. One of the roots of the simplicity of the systems is the fuel: it is fairly uniform and virtually completely combusted instantly. Conversely, biomass is a solid, nonuniform fuel regardless of whether it is chip, pellet, or split-wood that does not burn instantly, making it much more challenging to control and achieve high performance. Efficiencies of these systems range widely from 43–87%.[2,3]



1. Wood fuel is conventionally ignited in the upper combustion chamber.

2. Upper boiler door is closed. Draft fan begins drawing in fresh air.

3. Fresh air is forced downwards through the logs and coals intensifying the initial combustion.

4. Additional super-heated air is forced into the lower chamber producing intense heat & nearly complete combustion.

5. Remaining gases pass through the back of the lower chamber, up through the turbulators for final heat transfer and exhaust.

Figure 1. *Example of staged combustion (courtesy of Econoburn).*

Two-Stage, Gasification Combustion

Improvements in combustion design of wood-heating technology in Europe over the past 20 years demonstrate that high efficiency is attainable with impressive improvements in fine-particle emissions.[4] For wood-fired boilers to achieve high efficiencies, the static design of the boiler must separate the combustion process into two stages and design efforts must focus on time, turbulence, and temperature (i.e., the 3Ts) to maximize performance (see Figure 1).

In the first stage, the wood is combusted at relatively low temperatures under oxygen-starved conditions in order to off-gas (gasify) the volatile compounds. These gases are injected into a refractory lined secondary chamber under oxygen-rich conditions, where high temperatures, adequate residence time, and turbulent mixing yield nearly complete combustion. Note that features such as significant use of refractory and two distinct combustion chambers are more common for split-wood than pellet/chip systems, but optimization of the 3Ts is essential for high performance regardless of biomass type. Turbulators used in the exhaust tubes are also essential to maximize heat transfer. Incorporating a control system with these design fundamentals ensures the 3Ts are ideal and high performance is attainable.

Wood as a fuel is nonuniform, so a control system is necessary to continually optimize the air/fuel ratio. The best performing units often use a temperature and/or oxygen sensor. These sensors provide continuous feedback to the control system, which adjusts parameters, such as oxygen level and fuel feed rate, and also monitors the supply water temperature to determine when turndown is required. A basic algorithm will operate the boiler at high-fire until it meets the setpoint then drop down to low-fire, while an advanced scheme will gradually ramp down the output as the boiler nears the setpoint. Using the latter, the system avoids sudden changes in output, reduces complete shutdowns and low firing rates, and limits the use of heat dump loops to emergencies.

Single-Stage Combustion

Single-stage units have been the state-of-the-art wood boiler systems in the United States until recently. They are incapable of achieving high performance because they incorporate few of the design principles above. As they are only a single stage, gasification and combustion of these gases take place simultaneously with minimal control. This leads to incomplete combustion and the gases, which contain a substantial amount of energy, are exhausted through the stack instead of being consumed. The gases condense in ambient air and form copious amounts of organic particulate matter (PM). There is a rudimentary control system that

Examples of split-wood, wood chip, and pellet fuels. Wood chips are typically used in commercial applications. Photos courtesy of Dick Gibbs (split-wood) and ACT Bioenergy Systems (chips and pellets).

switches between high-fire and idle-fire, which is achieved through oxygen starvation, but there are no combustion sensors, which severely inhibits performance. These boilers can spend significant amounts of time in idle mode, as they typically have a very large firebox capable of holding a substantial charge of wood. Under actual operation, the efficiency is approximately half of the two-stage appliances.

Whole System Efficiency: Load Matching

Extensive time in idle-fire mode illustrates the importance of load matching. Ideally, the boiler's output should match the building's heating load, but in reality this never happens and boilers will respond to the load mismatch in different ways depending on the fuel and design. Upon meeting the heating load, the single-stage units will go into idle-fire mode. Fossil-fired systems respond rapidly after meeting the heat load and shut down and start up with a minimal impact on emissions and efficiency. There will be a performance penalty associated with cycling, but it will be relatively small compared to biomass-fired systems. The pellet system can respond fairly rapidly by reducing the fuel-feed rate and adjusting the air/fuel ratio. There will be some penalties associated with the transient loads. The two-stage split-wood systems do not have an idle mode and typically reduce to approximately 50% output with minimal impact on steady-state performance. If the output is pushed lower, performance will suffer and the boiler can overheat or shut down. Startup and shutdown of wood-fired systems carry severe impacts on performance. Currently, the best way to avoid frequent shutdowns, minimize operator attention, and handle load mismatches is through the use of hot water storage (HWS).

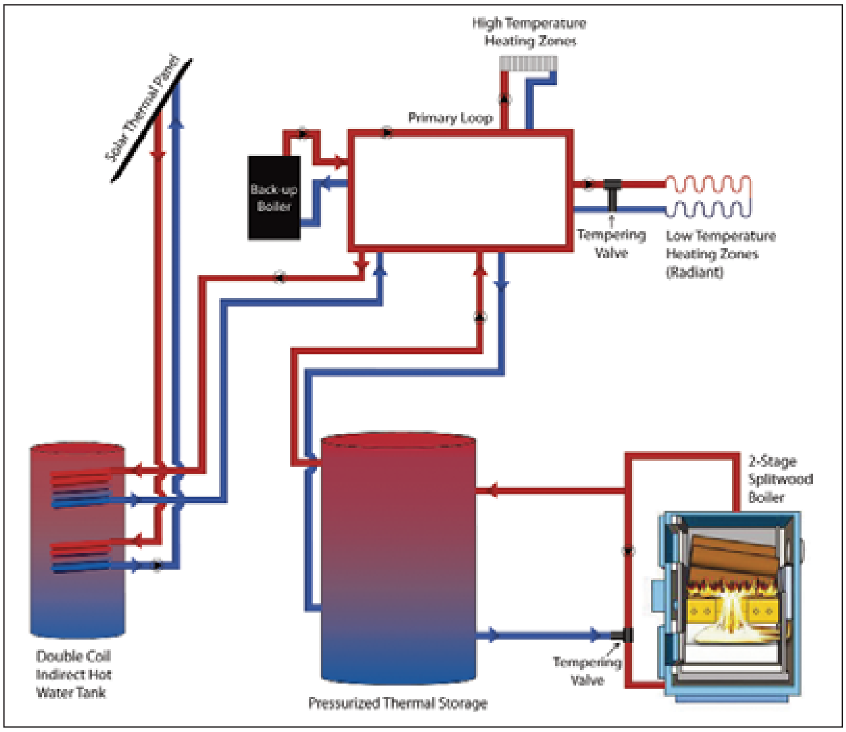
HWS is essentially a large, well-insulated tank that serves as a thermal battery (see Figure 2). It allows the boiler to fire in steady-state at any output, regardless of the building's heat load, as it will store any energy not immediately required for later use. Efficiency is maximized due to the nearly steady-state operation and drastic reduction in cycling. The benefits of HWS are most significant for split-wood, notable for pellet/chip, and minimal or even detrimental to fossil fuel-fired boilers. Marginal benefits are realized for single-stage units, as these systems would require a very large HWS volume. For a split-wood system to compete with oil it must be a two-stage combustion design and use HWS.

HWS also facilitates the addition of a solar thermal heating system (Figure 2). The solar-thermal system reduces the heating demand on the boiler. It is particularly beneficial in the summer and shoulder months, as it can meet the associated low and intermittent domestic hot water and heating loads, thereby preventing the boiler from firing.

Emissions

With staged combustion, not only are the particulate emissions greatly reduced, but the composition is largely inorganic.[5,6] Figure 3 shows the particulate emissions rate for residential fossil- and wood-fired boilers and includes a commercial, #6 oil boiler and the U.S. Environmental Protection Agency (EPA) White Tag limit for reference. It is important to note that the oil and gas boilers and the European wood boiler (HWS typically required) test are performed at high loads because this is where they operate in-use. The EPA Voluntary Outdoor Wood-fired Hydronic Heater Program[7] represents a >90% improvement over conventional outdoor wood boilers. (*Note:* Hydronic heaters are those that use hot water to heat the building.) EPA is revising a

Figure 2. *Simplified schematic of a biomass heating system that includes solar thermal (M. Nooney, M. Odell, and N. Russell).*



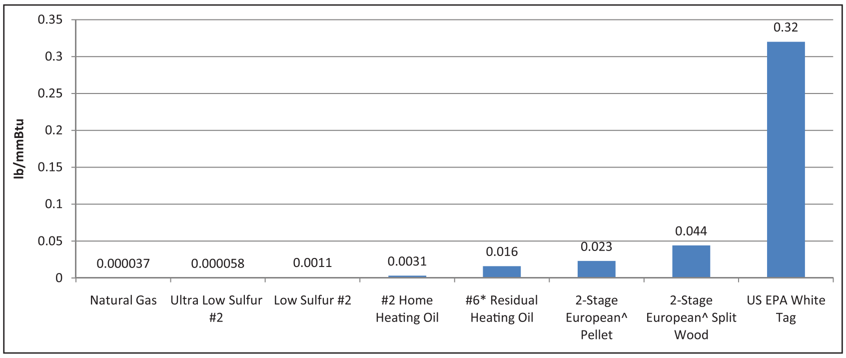


Figure 3. $PM_{2.5}$ emissions from residential heating fuels used in hydronic systems.

Notes: European performance is based on the use of hot water storage at 100% load, whereas the EPA White Tag limit evaluates performance over a range of loads [15%, 24%, 50%, and 100% and reported as a weighted average with 95% of the weighting for the lower loads]. The European test does not measure condensables, but does measure organic gases (OGC). Due to such complete combustion, if the OGC is condensed, it adds an average of only 8% to the particulate emissions of the top 25% performing units.[10-12]

New Source Performance Standard that will require further improvements in wood-fired boiler PM emissions.

Perhaps the projects that will assist policy-makers the most in the near-term with residential appliance performance are those being conducted by the EPA Office for Research and Development and Brookhaven National Laboratory (BNL). The EPA project will evaluate a range of wood combustion designs, including a single chamber OWB; two staged-combustion designs burning split-wood, one of which will utilize thermal storage; and a staged-combustion, fully automated pellet boiler from Austria. All four boilers will respond to a common call-for-heat modeled for a representative home in Syracuse, NY, during winter.[8] This will more closely represent an in-use test and remove differences in certification test methods. The BNL project will evaluate staged-combustion appliances and focus on performance evaluations benchmarked to oil-heat technology.

Whether wood smoke will continue to create elevated $PM_{2.5}$ concentrations as observed in New York's Adirondacks region[9] and elsewhere will depend on fully optimizing wood-fired heating systems. Removal of existing inefficient technologies through such voluntary programs as the Great American Wood Stove Changeout, managed by EPA, or removal upon sale of real estate, as required by some local jurisdictions, may also be necessary.

Future Steps

NYSERDA is supporting New York boiler manufacturers in their pursuit of advanced combustion designs to continue the development of a high-efficiency biomass heating market for residential and commercial applications. This will require further R&D involving boiler combustion- and thermal-efficiency improvements; development of best practices for boiler sizing; designing hydronic systems, including HWS; development of an annual-fuel-utilization-efficiency (AFUE) rating; possible development of post-combustion emission controls, such as electrostatic precipitators;[10] development of a pellet-fuel distribution infrastructure; development of appliances compatible with nonwood biomass; and continued outreach to regulatory and code officials, trade groups, manufacturers, and consumers. **em**

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