New York State Energy Research and Development Authority

Environmental, Energy Market, and Health Characterization of Wood-Fired Hydronic Heater Technologies

Executive Summary

June 2012

No. 12-15

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Executive Summary
Prepared for the

New York State Energy Research and Development Authority

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NOTICE

ABSTRACT

This report describes a comprehensive emission, lifetime cost, energy market, and health characterization program on four wood-fired hydronic heaters (HHs) that span common to advanced technologies. The HHs were variously tested with two species of split logs, hardwood with refuse, and hardwood pellets for their performance in meeting the daily heat load requirements of a typical winter day in upstate New York. An extensive array of pollutants was sampled in batch and real time, including particulate matter (PM), carbon monoxide (CO), volatile organics, semivolatile organics, and greenhouse gases for determination of emission factors. Emissions were expressed in terms of energy input, energy output, and on a temporal basis as available. Significant differences were observed in energy and emission performance from the four units. Tests using a cone calorimeter showed that its emissions were predictive of the full scale units under fully ventilated and air starved conditions. Modeling regional residential space heating scenarios showed that the wood heat market share determined the total PM emissions for the residential sector, and that relatively modest changes in the wood heat market can have substantial impacts on residential and total PM emissions. The rate of turnover and retirement of older, highly emitting units to more efficient, lower-emitting units is critical to avoiding what could be substantial increases in emissions related to residential wood heat over the next 5-10 years. In an assessment of lifetime costs of HHs, fuel costs were shown to have the potential to dominate purchase and installation costs; as a result, market competitiveness is driven by efficiency and access to low cost wood fuel. Emissions toxicity results from animal exposure experiments were inconclusive, as extreme dilution of the combustion gas was necessary to avoid immediate acute toxic effects from the CO that at times exceeded 10,000 parts per million (ppm).

KEY WORDS

Outdoor wood-fired HHs, outdoor wood boilers, pellet burners, heat storage, gasification burners, emissions, particulate matter, energy, levoglucosan, methoxyphenols, polycyclic aromatic hydrocarbons, cone calorimeter, biomass

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The authors acknowledge the testing assistance of Steve Terll, Bill Preston, Donnie Gillis, Charly King, John Nash, and Daniel Janek of ARCADIS U.S., Inc. EPA's Office of Air Quality Planning and Standards (OAQPS) provided two of the four units tested. Dr. Lukas Oudejans of EPA's National Homeland Security Research Center conducted the resonance enhanced multiphoton ionization/ time-of-flight mass spectrometry (REMPI-TOFMS) sampling. Representatives from all of the companies that supplied units assisted with the unit tie-ins and operation and their contributions are gratefully acknowledged.

We thank Elizabeth Boykin, Debora Andrews, Judy Richards, Jim Lehmann and Rick Jaskot for their technical assistance. The emissions, economic, and MARKet Allocation (MARKAL) chapters have been reviewed by the Quality Assurance (QA) officers of the National Risk Management Research Laboratory and approved for distribution. The planning documents, raw data and health chapter have been reviewed by QA officers of the National Health and Environmental Effects Research Laboratory, EPA, and approved for distribution. Approval does not signify that the contents necessarily reflect the views and policies of the Agency, nor does the mention of trade names or commercial products constitute endorsement or recommendation for use.

EXECUTIVE SUMMARY

Wood-fired hydronic heaters (HHs) have proliferated in Northern states during the last decade as oil prices have increased. Some of these units are inefficient and have resulted in numerous complaints to state air quality and health departments because of exceptionally high levels of smoke. Fine particles in wood smoke are primarily composed of organic carbon (OC) and contain numerous toxic compounds, including polycyclic aromatic hydrocarbons (PAHs). Recent reviews of the health literature indicate that wood smoke exposure likely leads to a range of adverse health effects including increases in respiratory symptoms, lung function decreases, increases in asthma symptoms, visits to emergency rooms, and hospitalizations (Naeher et al., 2007; Schreiber and Chinery, 2008). High-efficiency HH units are relatively common in Europe and now are being manufactured in the U.S. by a few companies. The combustion efficiency improvements are due in part to a two-stage combustion chamber design that results in gasification of the fuel and more complete combustion in the second chamber. Despite the high level of environmental concern due to emissions from the older units and the more promising performance of the newer units, little data has been collected to understand emissions and potential human health risks associated with HHs.

A joint project between the U.S. Environmental Protection Agency (EPA) Office for Research and Development (ORD) and the New York State Energy Research and Development Authority (NYSERDA) addressed this data gap by testing four current and emerging technology HHs, which are also referred to as Outdoor HHs, or HHs, and Outdoor Wood-fired Boilers (OWBs). The emissions and energy-efficiency performance of four types of residential wood boiler technologies ranging from the common HH to a high-efficiency pellet heater to a unit with thermal storage were characterized. Measurements included emissions of particulate matter (PM), elemental carbon (EC), carbon monoxide (CO), PAHs, volatile organic compounds (VOCs), semi-volatile organic compounds (SVOCs), and polychlorinated dibenzodioxins/dibenzofurans (PCDDs/Fs). This work was complemented by an energy and market impacts analysis of HHs for the State of New York. Lastly, the health effects of HH emissions were evaluated with an exposure study for pulmonary and systemic biomarkers of injury and inflammation. The results of this study are anticipated to be of value to the State of New York in its efforts to develop a high-efficiency biomass heating market of technologies with acceptable emissions performance. It is also anticipated that these results will be of value to EPA as it sets New Source Performance Standards for biomass-fired HHs.

Wood Hydronic Heater Technologies Tested

This project provides a thorough scientific evaluation of the performance of a range of wood boiler technologies. The units tested included a commonly-used Conventional Single Stage HH, a newer Three Stage HH model, a European Two Stage Pellet Burner, and a U.S. Two Stage Downdraft Burner (see Table 1). Each unit was evaluated and tested on the same 24-hour wintertime daily “call for heat” load determined for a typical home (2500 ft^2) in Syracuse, New York.

Table 1. Outdoor Wood-Fired Hydronic Heaters (HHs) Used in this Study.

Unit Model	Conventional, Single Stage HH, Single Stage HH	Three Stage HH	European Two Stage Pellet Burner	U.S. Two Stage Downdraft Burner
Unit #	**1**	**2**	**3**	**4**
Technology	Combustion	Three-stage Combustion	Staged Combustion	Two-stage: Combustion and Gasification with Heat Storage
Fuel	Wood logs	Wood logs	Wood pellets	Wood logs
Heat Capacity, output Btu/hour (kW)	NA	160,000 (46.9)[2]	137,000 (40)[3]	150,000 (44)[4]
Water Capacity gal (liters)	196 (740)	450 (1700)	43 (160)	32 (120)

[1]Not available from the manufacturer

[2]Eight hour stick wood test

[3]Partial load output, based on manufacturer's specifications

[4]Heat rate based on manufacturer claim

The conventional, Single Stage HH uses a natural draft, updraft combustion single-stage combustion process that occurs in a rectangular firebox surrounded by a high capacity water jacket (Figure 1). The hot flue gases are vented through a stainless steel, insulated chimney connected to a rear exhaust outlet. Flue gas movement is by natural convection, assisted with a fan. Heat flow is regulated by the opening and closing of a combustion damper.

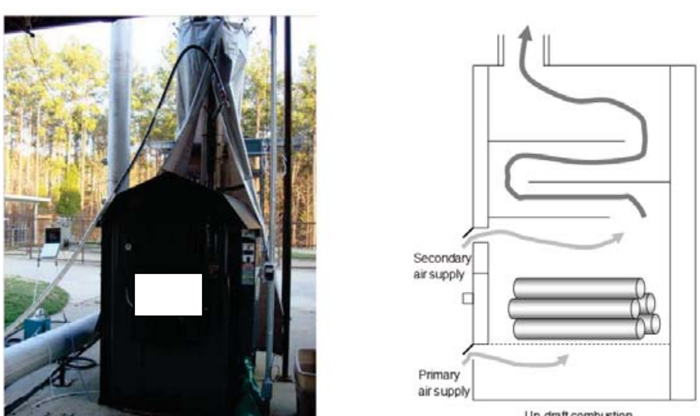

Figure 1. The Conventional, Single Stage HH and Illustration of an Up-Draft Combustion Unit.

The Three Stage HH (46.9 kW, 160,000 BTU/hour, Figure 2) uses a three-stage combustion process in which wood is gasified in the primary combustion firebox, the hot gases are forced downward and mixed with super-heated air starting the secondary combustion. Final combustion occurs in a third, high temperature reaction chamber. Like the conventional, Single Stage HH, the Three Stage HH is regulated by the opening and closing of an air damper.

Figure 2. The Three Stage HH Unit and Illustration of a Down-Draft Combustion Unit.

The European Pellet unit (Figure 3) is a commercially available, pellet burning HH rated at 40 kW (137,000 Btu/hour). Combustion occurs on a round burner plate where primary air is supplied. Secondary air is introduced through a ring above the burner plate. Fuel is automatically screw-conveyed from the bottom. Operation of the screw feeder was regulated by a thermostat. During normal operation, the fan modulates based on the measured oxygen level in the exhaust gas, maintaining 8-10% oxygen

The U.S. Two Stage Downdraft Burner (44 kW, 150,000 BTU/hour, Figure 4) is a two-stage heater with both gasification and combustion chambers. Air is added to the firebox continuously while the damper is open and is blown downwards through the wood logs. The gases are forced into a combustion chamber where additional super-heated air is added, resulting in a final combustion of the gases at temperatures higher than 980 °C (1800 °F).

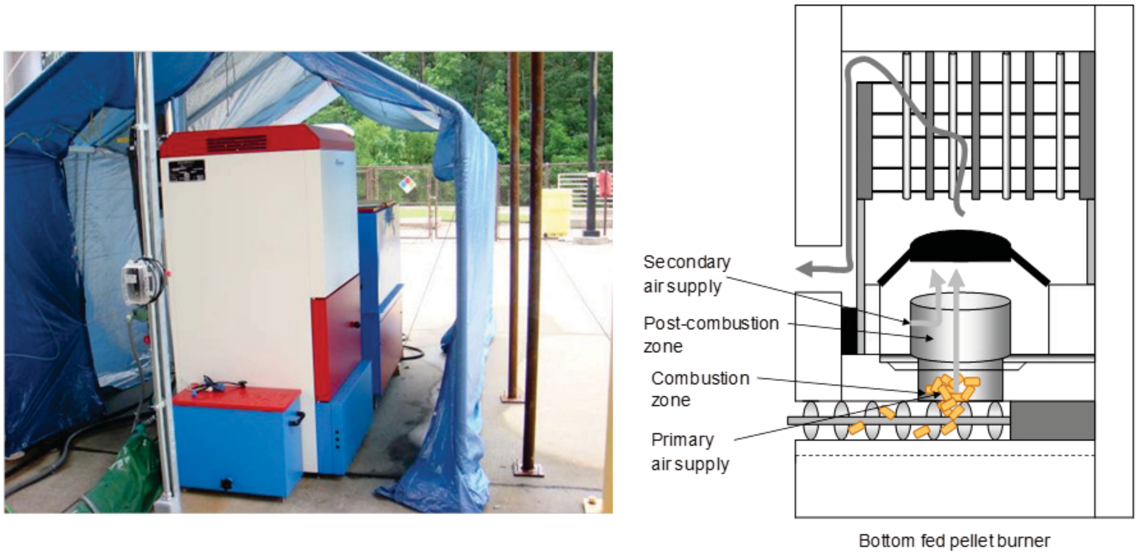

Figure 3. The European Two Stage Pellet Burner and Illustration of a Bottom-Fed Pellet Combustion Unit.

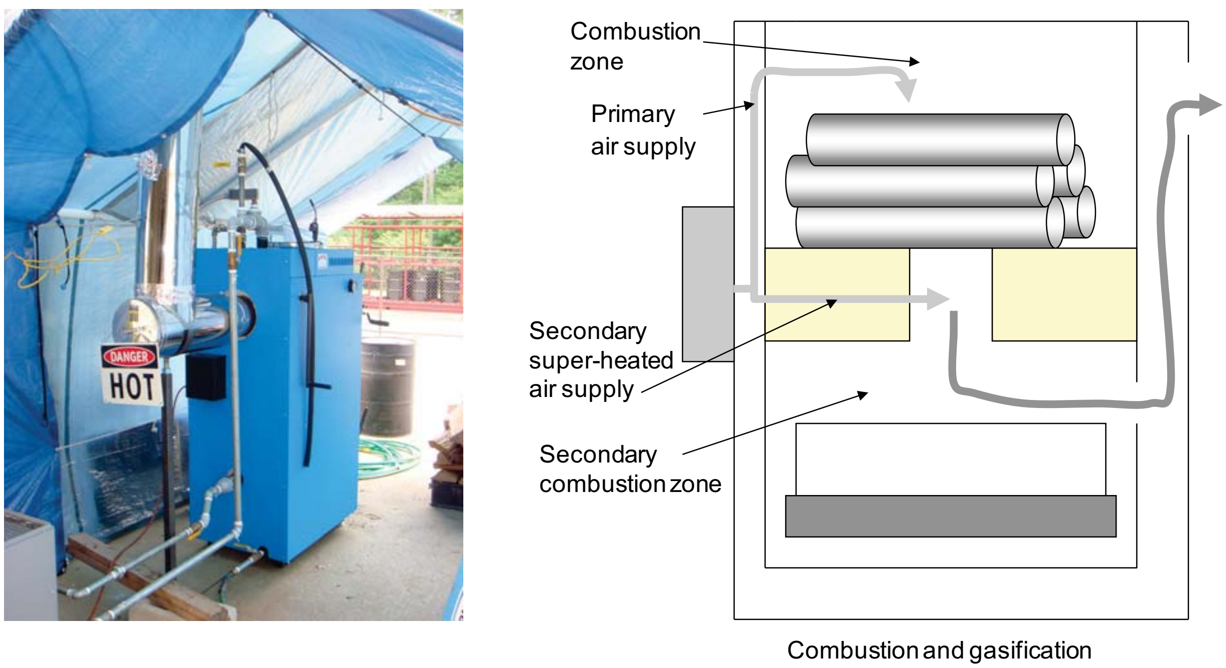

Figure 4. The U.S. Two-Stage, Down-draft Combustion and Gasification Unit Schematic.

FUEL LOADING AND CHARACTERIZATION

The fuel loading protocol was derived from the simulated heat-load demand profile and the type of unit and its capacity. The Conventional, Single Stage HH unit was used to compare emissions for three fuel types including seasoned red oak, unseasoned white pine, and red oak with 4.5% by weight supplementary refuse. The Three Stage HH was tested solely with seasoned red oak. A European Two Stage Pellet Burner and a split-log wood heater (U.S. Two Stage Downdraft Burner) with a simulated heat storage tank were tested under the same heat-load demand profile to characterize and compare their emission signatures. A common fuel type (red oak) was used across all units (hardwood pellets for the European unit) for comparability. The pellets are made out of sawdust from different wood processing industries and consisted of a blend of hardwood (no bark), mostly oak, with a diameter of 6 mm. The ultimate and proximate analyses of the fuels are reported in Table 2. Fuel moisture was determined using a wood moisture meter for three to four measurements on each of eight pieces of split wood chosen randomly from each charge.

Table 2. Fuel Ultimate/Proximate Analysis.

Properties	Fuel		
	Red Oak	**Pine**	**Pellets**
Ash	1.46%	0.44%	0.52%
Loss on Drying (LOD)	22.52%	9.68%	7.24%
Volatile Matter	84.23%	88.50%	84.27%
Fixed Carbon	14.31%	11.06%	14.11%
C :Carbon	48.70%	51.72%	50.10%
Cl: Chlorine	38 ppm	36 ppm	44 ppm
H: Hydrogen	5.96%	6.57%	5.86%
N: Nitrogen	<0.5%	<0.5%	<0.5%
S: Sulfur	<0.05%	<0.05%	<0.5%

“<” = below detection limit

HEATING PERFORMANCE

The heat load profile (Figure 5) that was used throughout the testing program is derived from a simulation program for heat demand (Energy-10^{TM}, National Renewable Energy Laboratory [http://www.nrel.gov/buildings/energy10.html?print]) for a 232 m^2 (2500 ft^2) home in Syracuse, New York, using an averaged hour-per-hour heat load for the first two weeks of January averaged over 25 years (Brookhaven National Laboratory). The average daily heat load for the first two weeks in January is about 827 MJ (784,000 BTU) with a maximum heat load of about 40,000 BTU/hr.

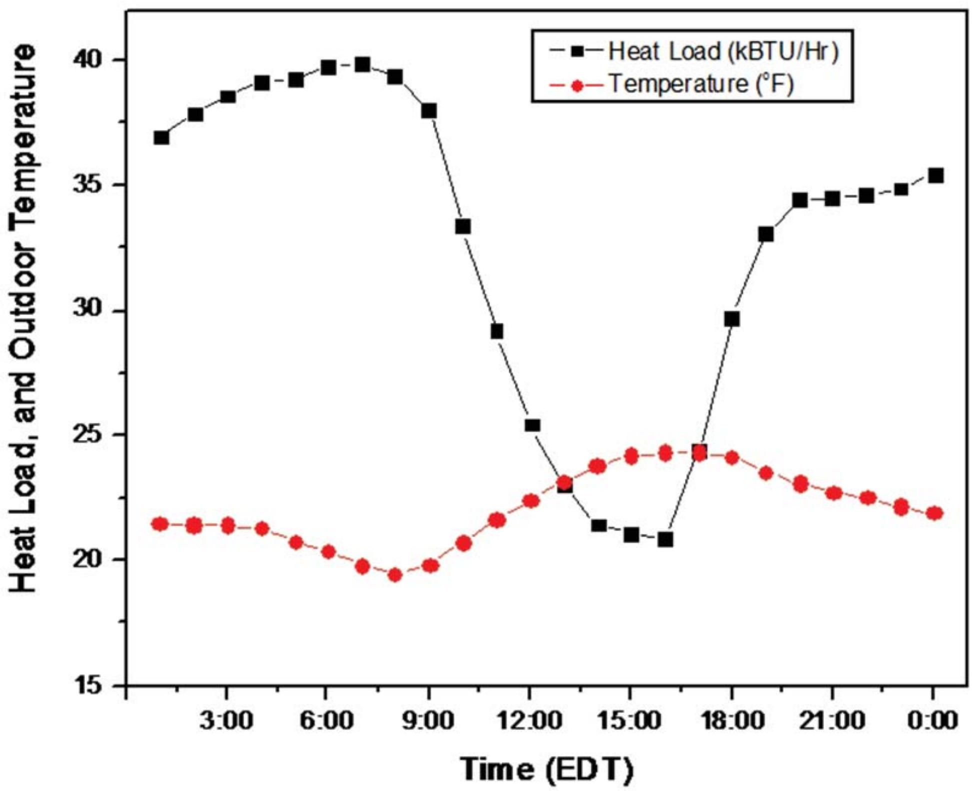

Figure 5. Syracuse, New York Area Heat Load Profile for the First Two Weeks of January.

The heat load demand was simulated by extracting the HH outlet heat with a water/water heat exchanger coupled to the building chilled water supply (Figure 6). The HH units were operated in a mode where hot water was continuously circulated through the water/water heat exchanger and the unit's water jacket. The pre-insulated piping system consists of two 25.4 mm (1 inch) oxygen barrier lines that are insulated with high density urethane insulation. The same piping system was used for all four units tested. The inlet and outlet temperatures of both the chilled water and recirculated hot water were monitored, as well as the chilled water flow rate. The heat load demand control system calculated the change between the chilled water outlet temperature and the chilled water inlet of the heat exchanger and controlled the heat removal by adjusting the chilled water flow rate through the use of a proportional valve.

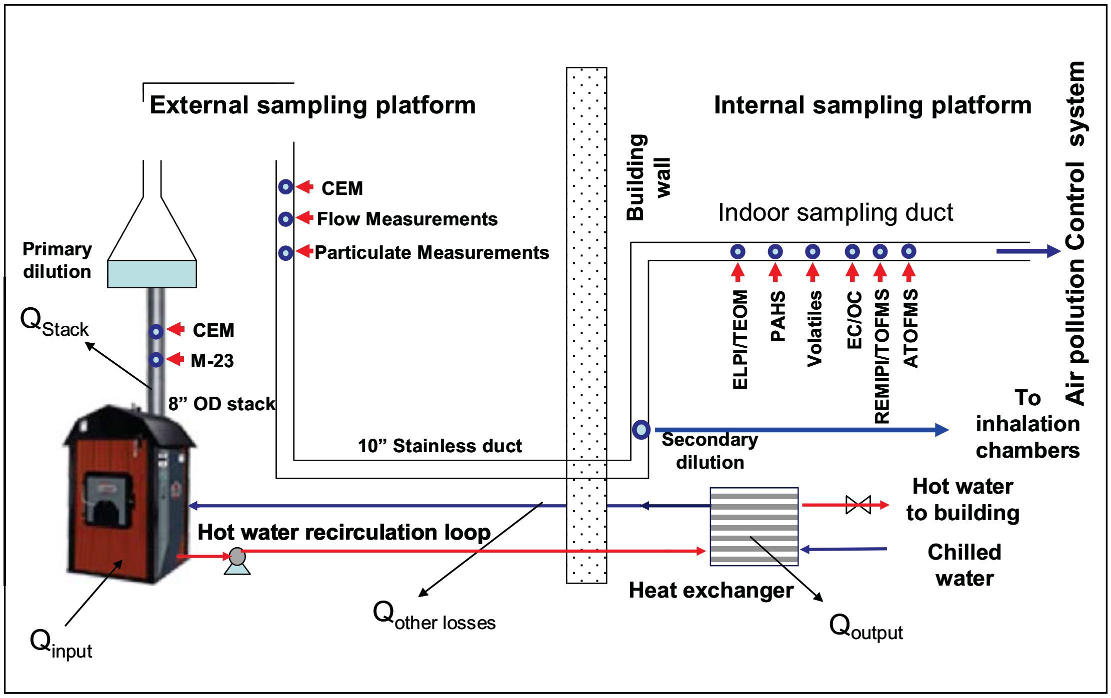

Figure 6. Test System for Wood-Fired Hydronic Heaters.

The units with cyclical damper operation to modulate their heat release resulted in considerable variation of heat transfer and concomitant emissions. When the dampers were closed, combustion became oxygen starved, resulting in incomplete combustion of the fuel and formation of pollutants. Upon damper opening and gas flow through the system, these pollutants are released, resulting in a cyclical increase in pollutant release. The modulating combustion also led to considerable nuisance odor (despite the emissions passing through the laboratory facility's additional air pollution control system (APCS) consisting of an afterburner and scrubber) and threatened to terminate the project.

A typical heat release rate for the Conventional, Single Stage HH unit is shown in Figure 7. The oscillating heat release reflects the cyclical damper opening and closing. Increased heat release is observed during all open damper periods when the fuel combustion rate is enhanced by the air supply. The frequency and duration of the damper openings is a function of the degree to which the unit is oversized for the heat load. The heat release rate is significantly higher than that required for the Syracuse winter load (about 40,000 BTU/hr). The European Pellet unit's moderate cyclical heat release (Figure 8) more closely matches the heat load demand. The U.S. Two Stage Burner unit burns continuously, storing its energy in a thermal storage tank (Figure 9).

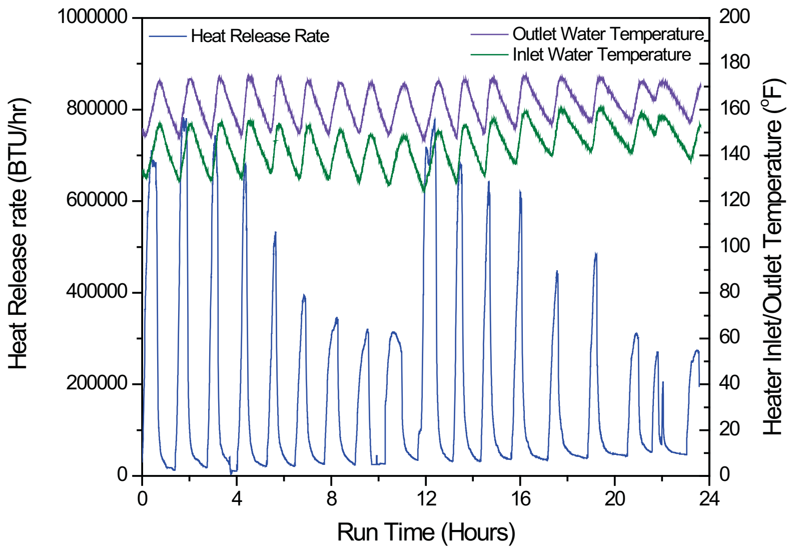

Figure 7. Heat Release Rate and System Water Temperatures for the Conventional, Single Stage HH Unit Firing Red Oak.

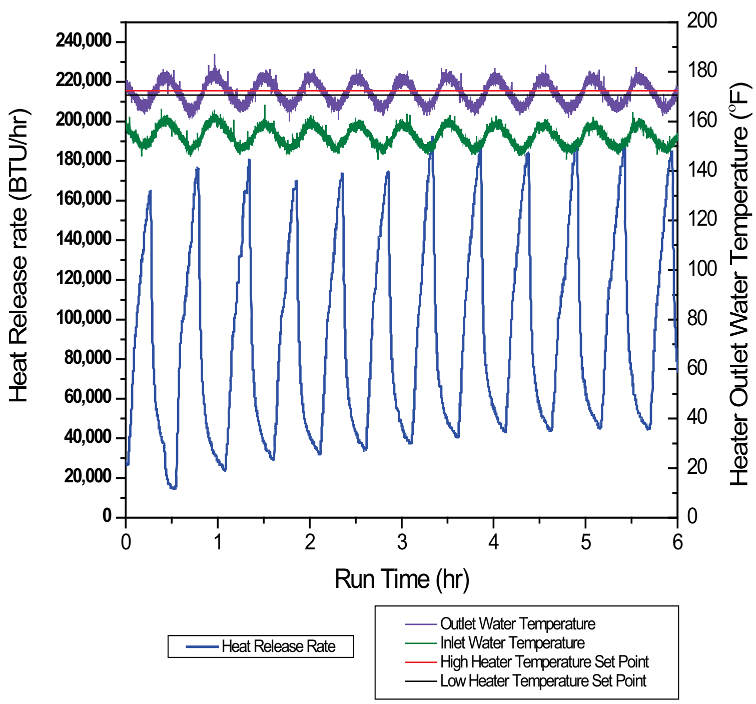

Figure 8. Heat Release Rate and System Water Temperatures for the European Two Stage Pellet Burner Unit.

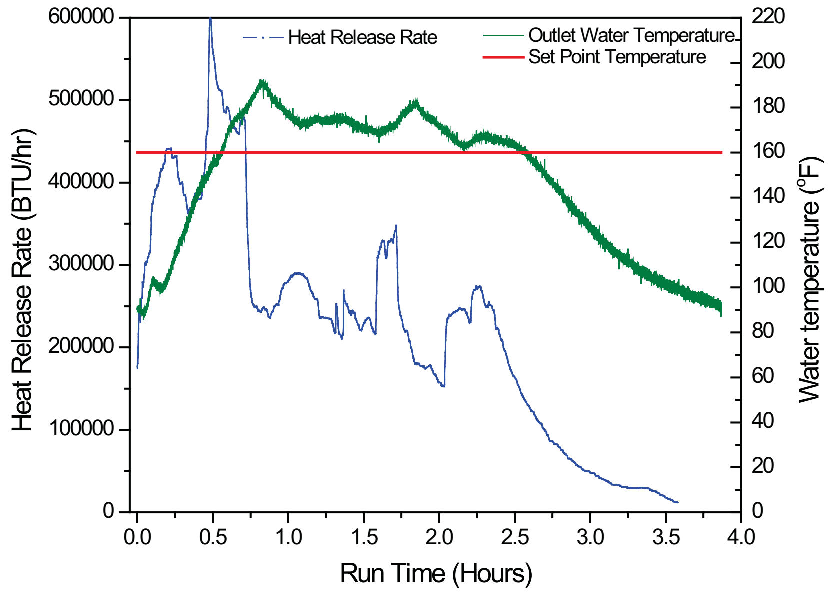

Figure 9. Heat Release Rate from the U.S. Two Stage Downdraft Burner Unit with Thermal Storage.

The performance of HH systems can be evaluated based on their ability to burn the fuel completely (combustion efficiency), the effectiveness of the heat exchanger to transfer the heat generated from the combustion process to the water (boiler efficiency), and the overall generation of useful heat through its transfer to meet the load demand (thermal efficiency). Table 3 summarizes all these efficiencies for all six unit/fuel combinations (boiler efficiency is not presented for cyclical units due to the difficulties inherent in quantifying dynamic measurements). No thermal efficiency can be calculated for the U.S. Two Stage Downdraft Burner unit because measurements of the thermal flows through the water/air heat exchanger were not recorded. The cyclical units had lower efficiencies than the pellet unit and the non-cyclical unit with heat storage. Efficiency improvements can be achieved by reducing the time spent at idle (closed damper) which can be accomplished by proper unit sizing and the use of thermal storage. As the HH's nominal output increases above that of the building's heat load, the amount of time spent at idle is increased (the damper remains closed for a longer time). The work reported here shows that in these closed damper periods energy and emissions performance decreases greatly. In the presence of an external thermal storage system, the low mass/volume ratio of the Two Stage Downdraft Boiler HH system allows it to run at maximum output under relatively steady-state conditions, improving performance. The thermal efficiencies, ranging from 22% to 44% for the conventional, three stage, and pellet systems, compare poorly with oil and natural gas fired residential systems with thermal efficiencies ranging from 86% to 92% and 79% to 90%, respectively (McDonald, 2009).

Table 3. Hydronic Heater Efficiencies.

Units	Thermal Efficiency (%)		Boiler	Combustion
Conventional HH RO	Average	22	NC	74
	STDV	5		3.0
Conventional HH RO + Ref	Average	31	NC	87
	STDV	2.2		3.4
Conventional HH WP	Average	29	NC	82
	STDV	1.8		3.2
Three Stage HH/RO	Average	30	NC	86
	STDV	3.2		1.8
European Pellet/pellets	Average	44	86	98
	STDV	4.1	3.5	0.16
U.S. Downdraft RO	Average	IM	83	90
	STDV		0.71	0.79

NC = Not calculated. IM = Insufficient measurements taken for this calculation

The unit efficiencies can also be viewed through the amount of fuel required to satisfy a given heat load. Figure 10 shows that amount of fuel mass required to supply the 24 hour Syracuse heat load. The European Pellet unit requires significantly less wood mass to meet this demand (the U.S. Two Stage Downdraft unit's wood mass could not be calculated because measurements of the thermal flows through the water/air heat exchanger were not recorded.

EMISSIONS

Carbon Monoxide

A full emissions characterization for each heater unit consisted of, at a minimum, PM (time integrated and real time), total hydrocarbons (THC), PAHs, organic marker compounds, organic carbon/elemental carbon (OC/EC), CO, CO_2, CH_4, N_2O, and PCDD/F. The results of this study are compared with those of EPA's Office of Air Quality Planning and Standards (OAQPS) ongoing validation tests of EPA Method 28 for HH PM and energy efficiency (http://www.vtwoodsmoke.org/pdf/Method28.pdf), particularly for the seasoned red oak fuel since this is the fuel specified in Method 23 OWHH.

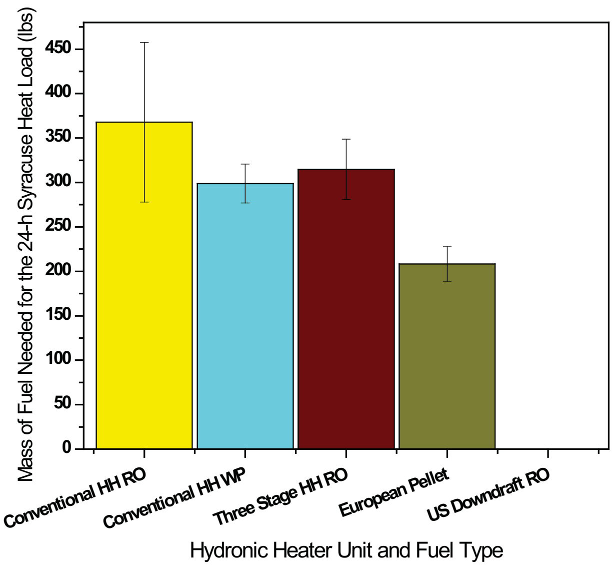

Figure 10. Mass of Fuel Needed for a 24 Hour Syracuse Heat Load. Data are missing for U.S. Downdraft RO.

Temporal emission profiles were more a function of the elapsed time from the last fuel charging than that of the heat load on the unit (Figure 11). The emissions of CH_4, THC, and CO (Figure 12) are consistent with the cyclic nature of the damper openings. These emissions are associated with the damper cycle creating alternately poor and good combustion conditions. Units that cycle the damper opening to regulate the heat production have much higher emissions than the pellet burner and the non-cycling U.S. Downdraft Unit unit. Predictably, lower CO emission factors result from those units that minimize pollutant formation.

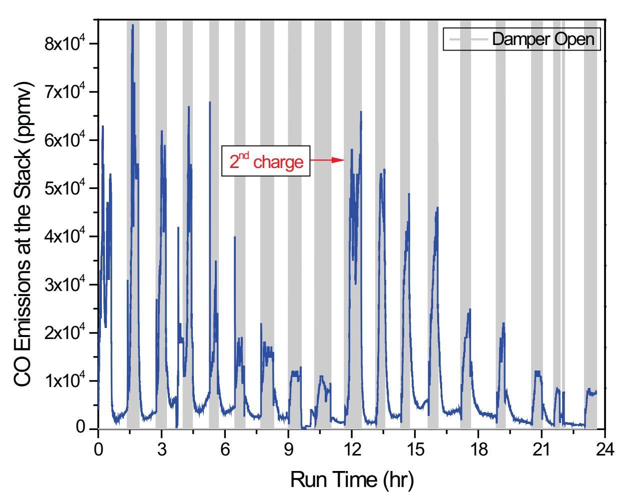

Figure 11. CO Stack Concentration as a Function of Damper Opening and Time of Fuel Charging, Conventional, Single Stage HH unit.

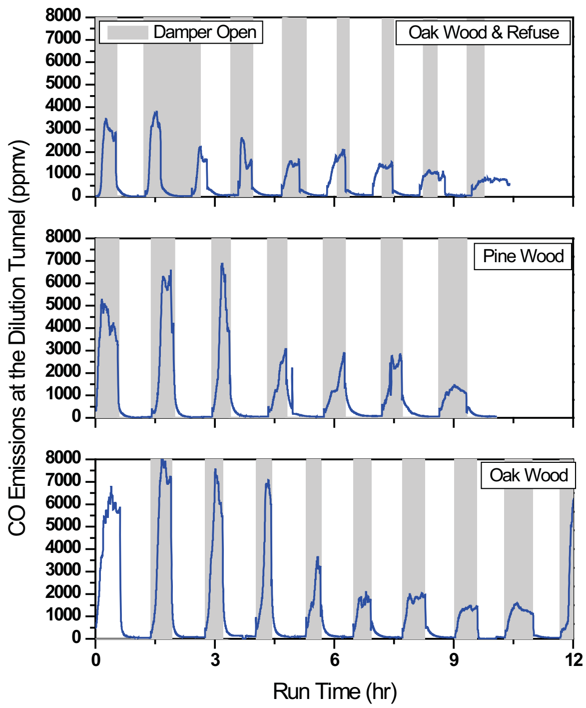

Figure 12. Typical CO Concentration Traces from the Dilution Tunnel for the Conventional, Single Stage HH Unit.

CO emission factors (Figure 13) are complementary to CO_2 emission factors (not shown). The European Pellet Boiler unit has the lowest value at 0.60 g/MJ (1.39 lb/MMBtu). A value of 7.2 g/MJ (16.6 lb/MMBtu) was obtained for the U.S. Downdraft Unit heater while the Conventional, Single Stage HH (average of the three fuels) had the highest value at about 8.9 g/MJ (21 lb/MMBtu) $_{input.}$ The European Pellet Burner unit is predictably lower in CO emissions as combustion is comparatively steady throughout its 6-hour burn, whereas the other units have variation in their combustion rate. These CO emission factors are orders of magnitude higher than are typically observed in conventional energy sources such as residential oil-fired heaters (< 0.1 lbs CO/MMBtu input, Krajewski et al., 1990).

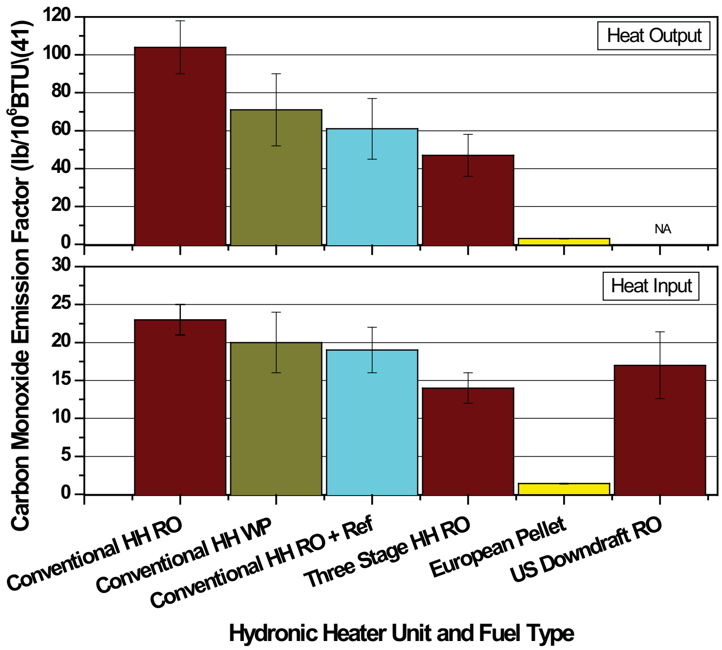

Figure 13. Carbon Monoxide Emission Factors. RO = red oak, WP = white pine, Ref = refuse.

Fine Particle Emissions

Testing showed a wide range of PM emissions depending on both unit and fuel types. Figure 14 compares average daily PM emissions from the four units and different fuels for a typical Syracuse, New York home on a January heating day. These data are analogous to the emissions based on thermal output as the different units attempt to match their thermal outputs to the Syracuse load demand. The Conventional, Single Stage HH burning white pine produced the highest total daily PM emissions [6.3 kg (14 lbs)] and the European Pellet Burner heater with red oak reported the lowest [0.036 kg (0.08 lb)]. Emissions for the Three Stage HH and U.S. Downdraft Unit units were comparable at 0.69 and 0.62 kg/day (1.51 and 1.37 lbs/day), respectively. Again, white pine combustion in the Conventional, Single Stage HH unit produced daily PM emissions that were 40% greater than red oak and 70% greater than red oak plus refuse.

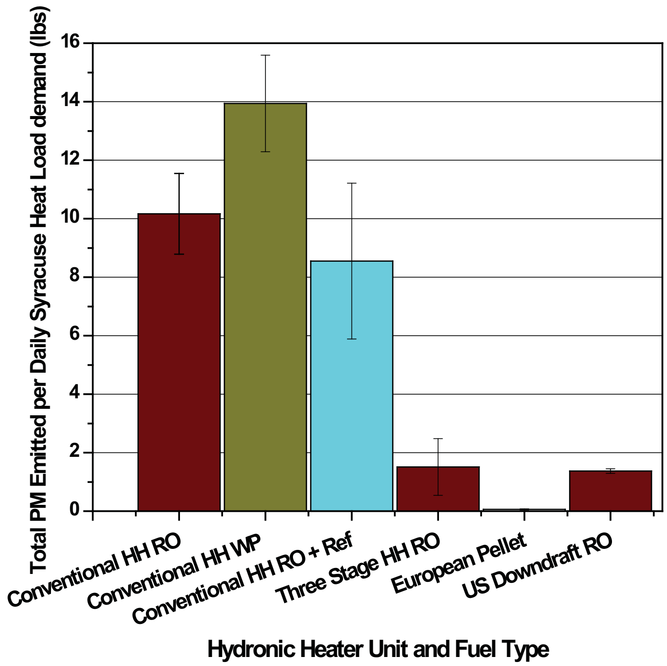

Figure 14. PM Generated per Syracuse Day for All Six Unit/Fuel Combinations. RO = red oak, WP = white pine, Ref = refuse.

For the Conventional, Single Stage HH, the PM emissions on a thermal input basis (see Figure 15) for the three fuels vary between approximately 2.9 and 5.1 lb/MMBTU with the emissions from the red oak and the red oak plus refuse being generally similar (2.9-3.0 lb/MMBTU). The PM emissions almost double, however, when white pine is burned in the same unit. Average emissions on a thermal energy input basis ranged from 0.54 lb/MMBTU for the Three Stage HH, 0.39 lb/MMBTU for the U.S. Downdraft Unit gasifier, and 0.037 lb/10^6 BTU for the European Pellet Burner. Lower PM emissions from these three units reflect the more advanced technologies and generally higher combustion efficiencies compared to the older Conventional, Single Stage HH unit. The Three Stage HH employs a secondary combustion chamber and larger thermal mass. The European Pellet Burner pellet unit uses a consistent uniform fuel and a more steady-state, but still cyclic, fuel feeding approach. The lower emissions from the U.S. Downdraft Unit are likely related to both its two-stage gasifier/combustor and its thermal storage design, where batches of fuel are burned during short, highly intensive, presumably more efficient periods and the extracted heat is stored for future demand. It should be noted, however, that due to our inability to properly measure the thermal flows through the heat storage, the thermal output for the U.S. Downdraft Unit was estimated using the heat loss method (boiler efficiency).

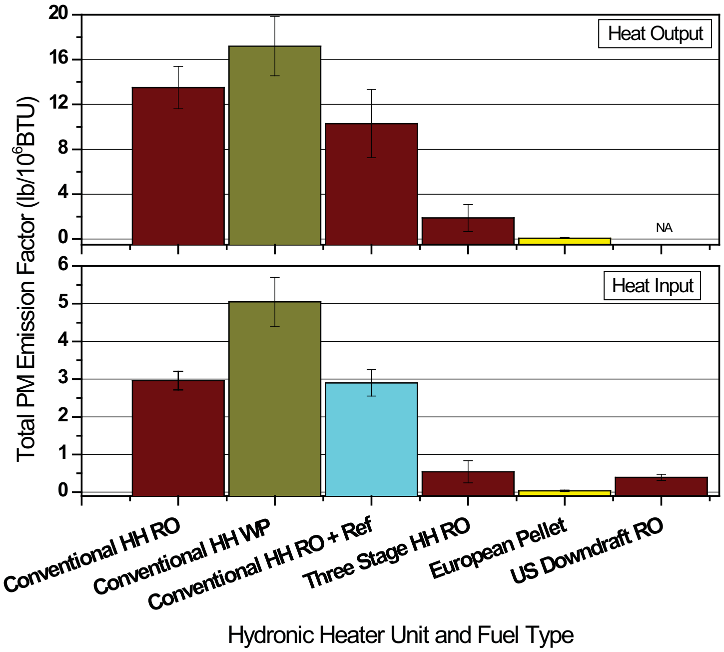

Figure 15. PM Emission Factors for all Six Unit/Fuel Combinations. RO = red oak, WP = white pine, Ref = refuse.

A comparison of PM emission factors determined from the current work with other published HH test data is shown in Figure 16. These data are taken from different studies (OMNI 2009; OMNI 2007, Intertek 2008), and were collected using EPA Method 28 OWHH. The percent rated load calculated from this testing is compared to the emission factor from the Method 28 OWHH report for the burn category that represents the same load. For the Conventional, Single Stage HH and 2300 this was Category II and for the U.S. Downdraft Unit it was Category IV. In the latter case, the maximum rated capacity was used. Also, the pellet emission factor is shown on the plot but there are no Method 28 OWHH data available for the pellet burner. The Other Conventional and Multi-Stage units are included only for comparison purposes. Data are presented in terms of mass of PM emitted per mass of wood burned and only the red oak and hardwood pellet data from this study are included. As shown, the EPA method tends to somewhat under-predict the emissions compared with the current work. This under-prediction is probably due to the differences between the EPA protocol method (e.g., use of cord wood in this project versus crib wood in Method 28 OWHH) and the use of a winter season heat load demand approach used here to characterize emissions. Finally, the PM emission rate for an oil-fired boiler is given for reference at 0.08 g/kg of fuel and cannot be shown on Figure 16.

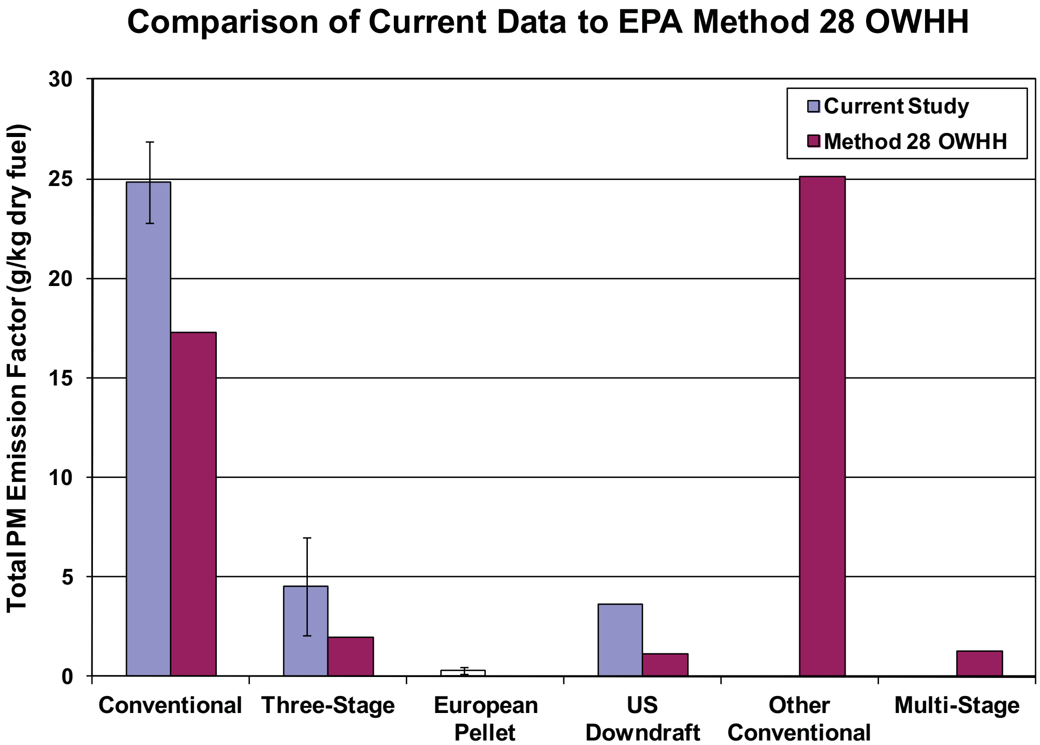

Figure 16. Comparisons of PM Emission Factors to other HH Test Data. Note that residential fuel oil = 0.08 g/kg fuel (Brookhaven National Laboratory).

Particle Composition

The ratio OC/EC was within the range of 20-30 for the Conventional and Three-Stage units regardless of fuel type (Figure 17). This ratio is typically greater than one for biomass combustion sources and less than one for fossil fuel sources. The OC/EC ratio for the European Pellet Burner pellet unit, on the other hand, was much lower indicative of higher combustion efficiency and lower emissions. The OC/EC ratio of the U.S. Downdraft unit, however, was only slightly lower than the Conventional and Three-Stage models indicating somewhat better combustion efficiency. Emission factors for black carbon in the particulate matter less than or equal to 2.5 micrometers in diameter ($PM_{2.5}$) were determined; these are believed to be the first such data for these unit types.

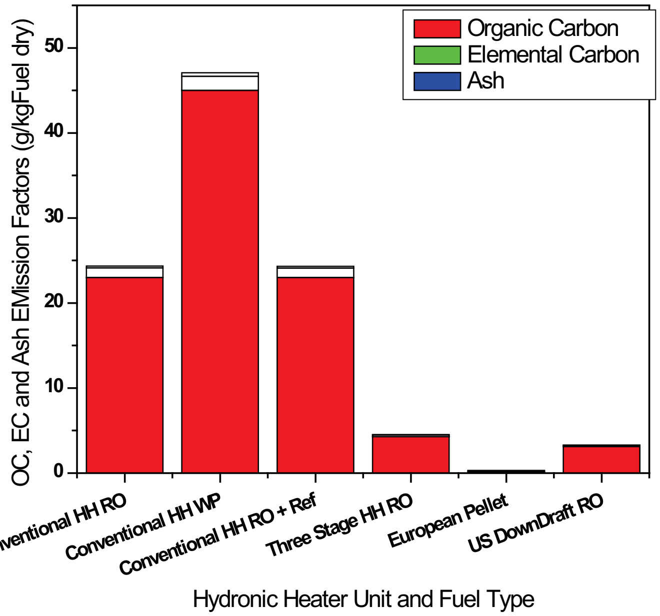

Figure 17. Average Organic Carbon, Elemental Carbon, and Ash for the Six Unit/Fuel Combinations.

Molecular Composition of the Organic Component of PM

Gas chromatography/mass spectrometry (GC/MS) techniques identified and quantified the PM bound semi-volatile organic compounds (SVOCs), which accounted for 9% w/w of the PM emitted from the HH boilers on average. The HH PM comprised 1-5% weight percent levoglucosan, an anhydro-sugar and important molecular marker of cellulose pyrolysis. The levoglucosan compound accounted for approximately 40% of the quantified species. Organic acids and methoxyphenol (lignin pyrolysis products) SVOCs were the compound/functional group classes with the highest average concentrations in the HH PM. These compounds are naturally abundant, also used as atmospheric tracers, and are important to understanding the global SVOC budget.

The PAHs explained between 0.1-4% w/w of the PM mass (Figure 18). All 16 of the original EPA priority PAHs were detected in the HH PM emissions. The older, Conventional, Single Stage HH unit technology emitted PM with higher PAH fractions. In general, the unit/technology type significantly influenced the SVOC emissions produced. Combustion of the white pine fuel using the older unit produced notably high SVOC emissions per unit energy and per unit mass of wood consumed; particle enrichment of SVOCs was also confirmed for this case. Addition of refuse to the seasoned red oak biomass generally resulted in a negligible increase in SVOC emissions per unit energy produced with the saturated hydrocarbons noted as an exception. Use of the pellet boiler generated the lowest SVOC emissions of the HH tested on a mass of fuel burned basis. Nevertheless, the U.S. Downdraft Unit gasifier unit showed the lowest SVOC emissions per unit energy produced. Results show that the phase of the burn cycle can influence the emissions on a compound class basis. These and similar differences are highlighted in the main body of the report.

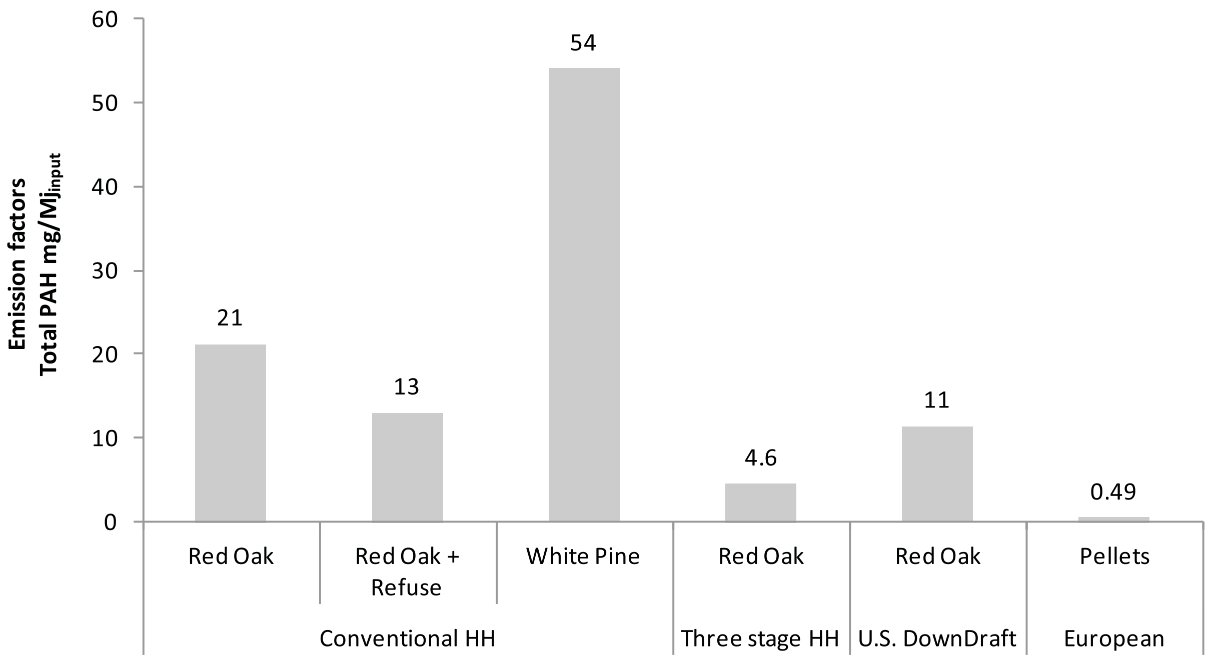

Figure 18. Total PAH Emission Factors.

PCDD/PCDF Emissions

Polychlorinated dibenzodioxin and dibenzofuran (PCDD/F) emissions were sampled and ranged from 0.07 to 2.1 ng toxic equivalents (TEQ)/kg dry fuel input, with the lowest value from the U.S. Downdraft unit and the highest from the Conventional, Single Stage HH with red oak + refuse (see Figure 19). The lowest value, from the U.S. Downdraft unit, may be due to the non-cyclical combustion resulting in consistent combustion and more complete burnout, but the limited data make this speculative. These values are consistent with biomass burn emission factors of 0.91 to 2.26 ng TEQ/kg) (Meyer et al. 2007), woodstove/fireplace values of 0.25 to 2.4 ng TEQ/kg (Gullett et al., 2003), pellet and wood boilers values of 1.8 to 3.5 ng TEQ/kg, and wood stoves and boilers of 0.3 to 45 ng TEQ/kg (Hübner et al, 2005).

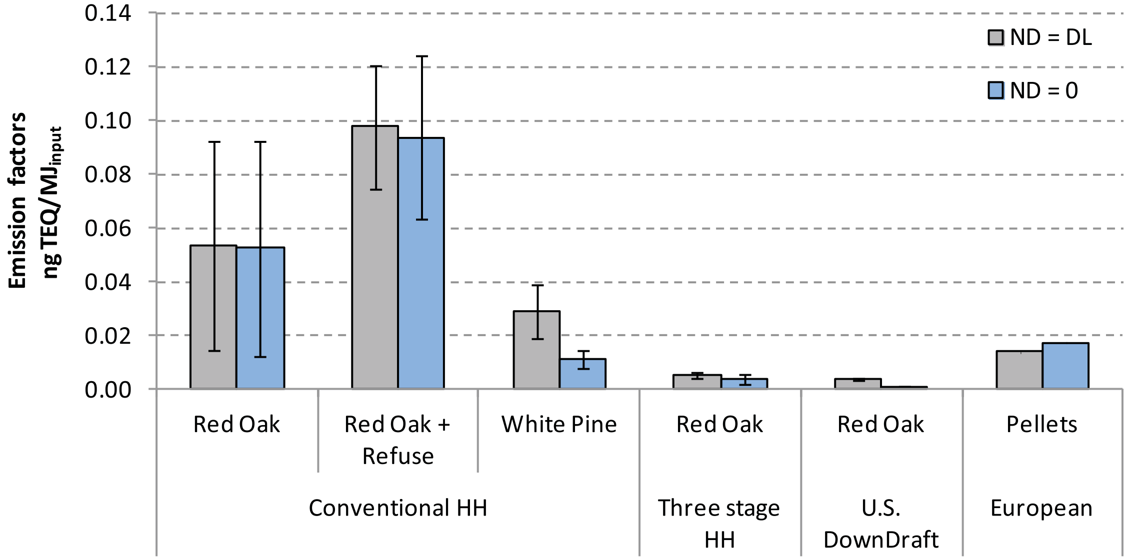

Figure 19. PCDD/PCDF Emissions with Non-Detects = Detection Limit and Zero.

ENERGY AND EMISSIONS IMPACTS OF WOOD HEATING TECHNOLOGIES IN THE HEATING MARKET

An energy systems model termed MARKAL (MARKet ALlocation), with the U.S. EPA's 9-Region database (Loughlin et al., 2011; Shay & Loughlin, 2008), was used to examine the broader energy and emissions impact of HHs. The goals of this analysis were to: (a) identify possible future scenarios for the penetration of HHs and other advanced wood heating systems, (b) place those scenarios in the context of total residential demand for space heating and total residential energy demand, and (c) determine the emissions implications of those scenarios between 2010 and 2030. Because of the unique nature of the market for wood heating devices and wood and pellet fuels, and the non-economic variables that often come into play, modeling this market in a pure cost optimization framework presents a challenge. We therefore used the model in a "what if" scenario framework, rather than in a predictive framework, asking a number of targeted questions, and running the model to assess the impact of certain assumptions regarding total wood heat market size, technology mix, rates of turnover, availability (or not) of advanced and high efficiency units, fuel price and availability, and emissions rates.

A baseline scenario and four alternative scenarios were examined. The baseline scenario models a modestly decreasing market share for wood heat in general, but greater penetration of outdoor HHs over the 2005 through 2015 time period, along with a changeover from existing wood stoves to cleaner wood stoves. The contribution of wood stoves and outdoor HHs to the full market for residential space heating is shown in Figure 20.

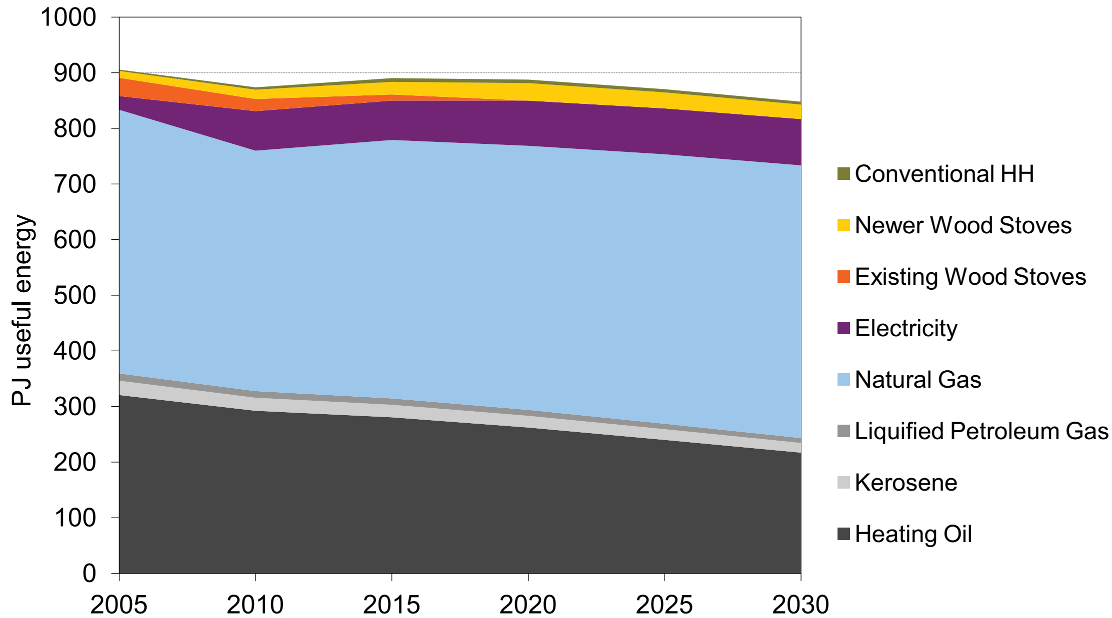

Figure 20. Market for Residential Space Heating for "Baseline" Scenario (PicoJoules of Usable Energy).

In terms of emissions, this scenario was pessimistic in the assumption that cleaner, more efficient outdoor HHs would not be available for the entire modeling horizon. Figure 21 shows the PM emissions trends over time for this scenario for all residential energy use (not just space heating). It becomes clear from this comparison that even though wood heat is a relatively small contributor to meeting total residential energy demand, it can dominate the emissions profile for the residential sector.

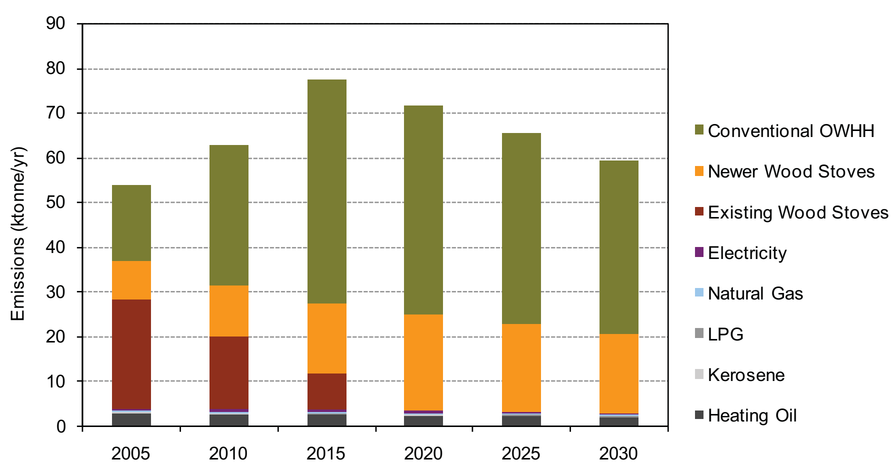

Figure 21. PM Emissions (ktonnes/year) for Total Residential Energy Use for "Baseline" Scenario.

The "baseline" represents only one possible scenario, and not necessarily the most likely. How the market for wood heat, and HH units in particular, will evolve over the next 5-15 years is highly uncertain, and is driven by consumer preferences and behavior that are difficult to capture in a quantitative framework. The role that policy measures will play in terms of the rate of technology turnover, efficiency of new units, and emissions, adds another layer of uncertainty. Figure 22 shows the range of potential emission outcomes for a number of scenarios.

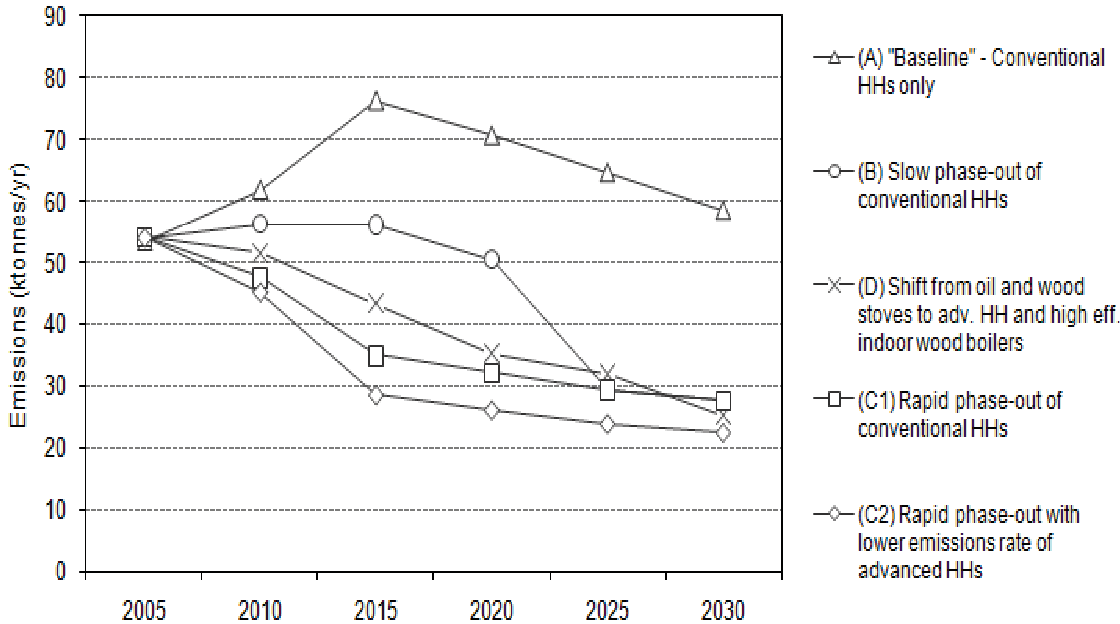

Figure 22. Total Residential PM Emissions "Baseline" and Four Alternative Scenarios (ktonnes/yr)

In contrast to the "baseline" scenario, the "slow phase-out of conventional HH" scenario assumes the same wood heat market share, but now allows for some introduction of advanced HHs. However, this scenario forces the conventional HH units to maintain part of the total HH market at least out to 2020. For 2015, the market for conventional outdoor HH and advanced HH (including higher efficiency outdoor HHs and indoor wood boilers) is split 50/50, but by 2025 there are no conventional outdoor HHs in the market. Two additional scenarios examine what happens under the same wood heat market share, when advanced HHs come into the market more rapidly. Under the scenario, "rapid phase-out of conventional HHs," new HHs start to enter the market in 2010. Another scenario "rapid phase-out of conventional HHs with lower emissions rate of advanced HHs" looks at the same market split over time, but with lower emissions for the advanced units coming in to the market. This is the most optimistic scenario from the PM standpoint. Finally, "shift from oil to wood heat" illustrates a different scenario both for wood heat in general and for the mix of technologies within the wood heat market. In contrast to the earlier scenarios, this scenario shows a growth in the wood heat market, with a large decline in heating oil, and major shift in the mix of wood heat technologies away from stoves. The key insights from this cross-scenario comparison are: (1) the extent to which wood space heating emissions dominate the total emissions from total residential energy usage, even out to 2030; and (2) the potential for wide variation in future emissions, depending upon the evolution of the technology mix within the market for wood heat, as seen in Figure 22.

Lifetime heating costs of wood boiler technologies in comparison to oil, natural gas, and electricity

Engineering economic techniques were used to compare estimated lifetime costs of alternative technologies, including HHs, automated pellet boilers, high efficiency wood boilers with thermal storage, natural gas and fuel oil boilers, and electric heat pumps. Assumptions for each technology and for fuel prices are listed in Table 4 and Table 5, respectively.

Table 4. Assumed Characteristics of Residential Heating Devices. For the wood devices, nameplate efficiencies are shown in parentheses alongside the observed operational efficiency.

Technology	Tested Efficiency (Rated Efficiency)	Output (BTU/hr)	Base Capital Cost	Scaled Capital Cost
Natural gas boiler	85%	100k	$3,821	$3,821
Fuel oil boiler	85%	100k	$3,821	$3,821
Electric heat pump	173%	36k	$5,164	$11,285
Conventional HH	22% (55%)	250k	$9,800	$9,800
Advanced HH	30% (75%)	160k	$12,500	$12,500
High efficiency wood boiler with thermal storage	80% (87%)	150k	$12,000*	$12,000*
Automated pellet boiler, no thermal storage	44% (87%)	100k	$9,750	$9,750

* The high-efficiency indoor wood boiler cost is assumed to include a supplemental hot water storage tank at a cost of $4,000.

Table 5. Assumed Fuel Prices for the State of New York. National Values are Provided in Parentheses.

Fuel	Price
Fuel wood	$225 / cord
Pellets	$280 / ton
Fuel oil #2	$2.83 / gal ($2.80 / gal)
Natural gas	$1.37 / therm ($1.00 / therm)
Electricity	$0.183 / kwh ($0.109 / kwh)

The engineering economic calculations used here are relatively simple, accounting for capital and fuel costs over the lifetime of the device, but ignoring other costs. Results of the Net Present Value (NPV) calculations are shown below in Table 6.

Table 6. Calculated annual fuel costs and net present value lifetime costs of various residential space heating technologies.

Technology	Annual Fuel Cost	NPV
Automated pellet boiler	$3,900	$64,000
High efficiency indoor wood boiler with hot water storage	$1,300	$30,000
Conventional HH	$4,700	$75,000
Advanced HH	$3,400	$62,000
Electric heat pump	$3,100	$55,000
Natural gas boiler	$1,600	$26,000
Fuel oil boiler	$2,400	$37,000

Under baseline assumptions, natural gas boilers were shown to have the lowest net present value of cost of all of the home heating options that were examined. Natural gas is not available in all parts of the State of New York, however, and many low-density, rural areas do not have access to natural gas distribution systems. It is in these rural areas that HHs are likely to compete with electricity and fuel oil for market share. Of these technologies, HHs were cost-competitive only with the pellet boilers under tested efficiencies and market prices for wood. These results do not imply that wood heat cannot be cost-effective, however. For example, the high efficiency indoor wood boiler with hot water storage had a lifetime cost that was less than all non-natural gas options that were examined.

Sensitivity analysis suggested that there may be situations where HHs *are* cost competitive. Major factors that can contribute to this result are wood price, HH efficiency, and the prices of competing fuels. The sensitivity analysis is summarized in Figure 23.

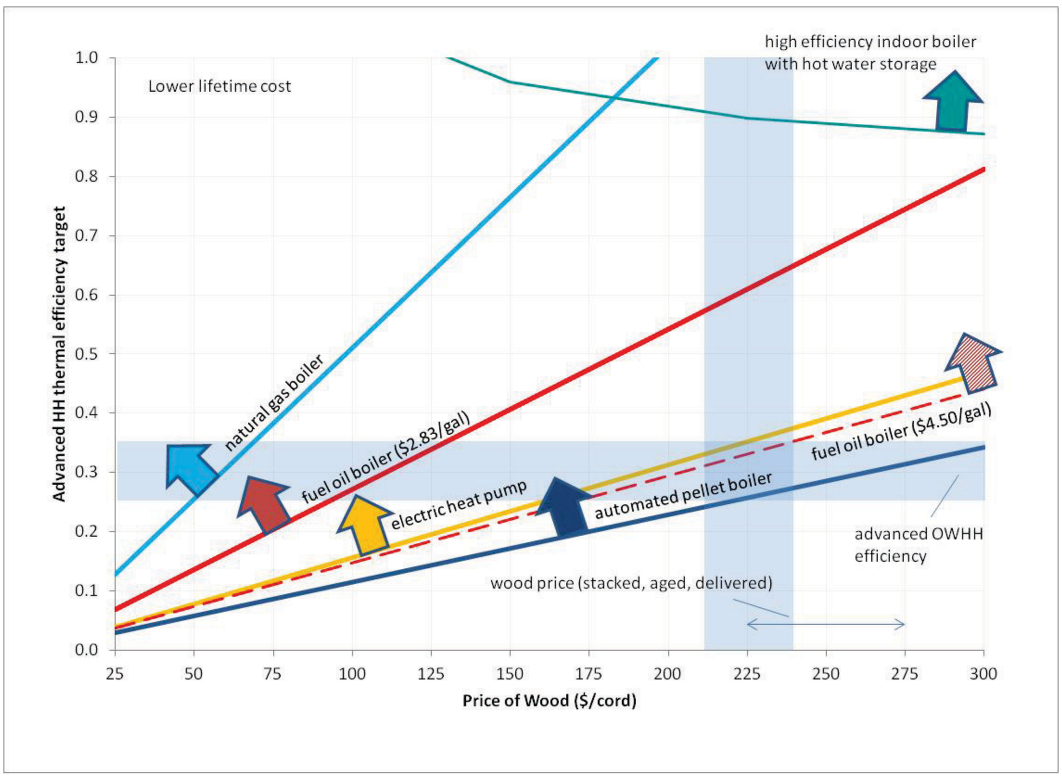

Figure 23. Comparative Technology Costs.

Figure 23 shows the combinations of wood price and thermal efficiency at which an advanced HH becomes cost competitive with other devices. A good starting point for interpreting the graph is the rectangular area created by the intersection of advanced HH efficiencies in the mid-20s to mid-30s and wood prices between $210 and $240, encompassing the baseline assumptions. The rectangle falls below all of the technology-specific lines on the graph except for the automated pellet boiler, indicating that the advanced HH is more costly than those technologies from a Net Present Value (NPV) perspective. Increasing efficiency or lowering the price of wood can result in the advanced HH becoming competitive, however. For example, increasing efficiency to above 35% results in the HH having a lower NPV cost than the electric heat pump (at a wood price of $225). Similarly, a wood price of below approximately $55 per cord is necessary for the NPV cost of the HH to equal that of the natural gas boiler (at an advanced HH efficiency of 30%). It is important to note that decreasing the wood price also has the effect of lowering the NPV cost of the high efficiency indoor wood boiler with storage, and the HH must achieve even higher efficiencies to be cost competitive. The solid and hashed red lines on the graphic indicate that competitiveness with oil is highly dependent on oil price. At a price of $4.50 per gallon, the advanced HH needs only achieve an efficiency of approximately 33% to rival the oil boiler. In contrast, at a fuel oil price of $2.83 per gallon, the HH unit must achieve a thermal efficiency greater than 60%.

As indicated by the figure, a major factor in the engineering economic assessment of HHs is the price for wood fuel. Many rural households have their own wood supply, which they may perceive to be low cost or free, even if the labor costs associated with carrying and splitting the wood are factored in, these homeowners may still perceive HHs as the most cost-effective option. This hints at the importance of difficult-to-quantify factors. Most homeowners may not undertake the analysis carried out here. They also may not go through an explicit process to evaluate the value of their time. They may not be aware of the correlation between wood and oil prices in many markets. Instead, it is likely that those who have chosen to install HHs have been motivated by qualitative perceptions of the technology's cost, perceived environmental benefits, and ability to hedge against increases in fuel prices. Tax credits may also be a highly motivating factor, even if they are far less important than device efficiency and fuel cost in determining lifetime heating costs. These factors cannot easily be quantified within an engineering economic assessment and yet may be the dominant factors in decision-making.

There are additional unmodeled factors that both work for and against the competitiveness of HHs. For example, it is likely that the thermal efficiencies used in this analysis are higher than would be experienced in practice since the units would likely be used during the fall and spring months when loads and efficiencies would be lower. Further, the high emission rates associated with HHs have resulted in some counties and communities to pass ordinances that ban or limit HH use. Space considerations also come into play. Households must have room to store delivered wood fuel, and many residents may find it inconvenient to have to go outside to load wood into the boiler. The high efficiency indoor wood boiler also requires firewood storage. It does, however, address efficiency concerns by storing heat in a large water tank, allowing the unit to operate without cycling. The increased efficiency associated with this configuration is dramatic, and the unit is able to compete well in NPV cost with even the natural gas boiler. Combining hot-water storage with an HH is also an option that may improve thermal efficiency. The high BTU output of many HH units would require a very large storage tank, however, and this option was not examined in our study.

HEALTH CHARACTERIZATION

A health assessment of emissions from three different HHs was conducted to determine if one unit or operating condition was better or worse than another. Adult CD-1 mice were exposed to filtered air, filtered wood smoke or unfiltered wood smoke for four hours per day for one or three consecutive days, then pulmonary and systemic biomarkers of injury and inflammation were assessed. Three days of exposure to either the filtered or whole wood smoke caused statistically significant increases in tumor necrosis factor in lung fluid and creatine kinase in serum. In the second study the only notable change was increased ferritin in the lung after a three-day exposure to whole or filtered wood smoke and smaller increases in creatine kinase in the filtered only group. The third study utilizing the pellet heater resulted in higher numbers of macrophages in the lung 24 hours after a one- and three-day exposure. The results show that none of the exposures caused acute lung injury but were associated with inconsistent increases in inflammatory signaling pathways. Still, the overall emission toxicity results from animal exposure experiments were inconclusive, as extreme dilution of the combustion gas was necessary to avoid immediate acute toxic effects from the carbon monoxide that at times exceeded 10,000 ppm.

CONCLUSIONS:

Comparison testing of four HH units, ranging from common to newer technologies, with different fuel types showed large differences in energy and emission performance. HH units that operated with cyclical damper openings and closings to regulate the supply of heat generally resulted in poorer efficiencies and higher levels of pollutants. The Pellet-fired unit and Two Stage Downdraft unit with heat storage showed greater combustion performance and lower emissions. Use of thermal storage allowed the Two Stage Downdraft HH to run at maximum output under relatively steady-state conditions, improving efficiency performance. For cyclical units, efficiency improvements can likely be achieved by reducing the time spent at idle (closed damper) through proper unit sizing. The thermal efficiencies, ranged from 22% to 44% for the conventional Single Stage HH, Three Stage HH, and European Pellet Burner. These values compare poorly with oil and natural gas fired residential systems with thermal efficiencies ranging from 86% to 92% and 79% to 90%, respectively (McDonald, 2009).

Testing showed a wide range of emissions depending on both unit and fuel types. The Conventional, Single Stage HH burning white pine produced the highest total daily PM emissions [6.3 kg (14 lbs)] and the European Pellet Burner with red oak reported the lowest [0.036 kg (0.08 lb)]. Emissions for the Three Stage HH and U.S. Downdraft Unit units were comparable at 0.69 and 0.62 kg/day (1.51 and 1.37 lbs/day), respectively. CO emissions showed a similar unit to unit trend, with the lowest value from the European Pellet Burner at 0.60 g/MJ (1.39 lb/MMBtu). This value was about 15 times lower than that of the Conventional, Single Stage HH (average of the three fuels). These CO emission factors are orders of magnitude higher than are typically observed in conventional energy sources such as residential oil-fired heaters (< 0.1 lbs CO/MMBtu input, Krajewski et al., 1990).

Market and energy modeling show that while wood heat is a relatively small contributor to meeting total residential energy demand, it is the largest contributor to emissions from the residential energy sector. While different regulatory and technology scenarios for the future can have a significant impact on emissions, pollution from residential wood space heating is likely to dominate the total emissions from total residential energy usage, even out to 2030. Economic calculations for residential heating options, accounting for capital and fuel costs over the lifetime of the device, show that natural gas systems have the lowest net present value cost of all examined home heating options, including HHs. However, natural gas is not available in all parts of the State of New York. In the predominantly rural areas where it is unavailable, HHs are likely to compete with electricity and fuel oil for market share, especially when thermal storage is incorporated. The rate of turnover and retirement of older, highly emitting units to more efficient, lower emitting units is critical to avoid what could be substantial increases in emissions related to residential wood heat over the next 5-10 years.

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