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Wood Heater Design Challenge Workshop Report

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Ryan Fisher— *MF Fire*

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Ingo Hartmann– *Deutsches Biomasseforschungszentrum, gemeinnützige GmbH (DBFZ)*

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Abstract

To support the United States Department of Energy (DOE) Bioenergy Technologies Office's (BETO) goal of advancing residential wood heating technologies, Brookhaven National Laboratory (BNL), Lawrence Berkeley National Laboratory (LBNL), and the Alliance for Green Heat (AGH) hosted the fifth Wood Heater Design Challenge (WHDC). The Challenge consists of three virtual workshops and a Technology Slam aimed at inspiring and advancing the next generation of residential wood heaters. With an estimated 12.5 million homes in the United States using wood or pellets for space heating, this challenge stands to create a significant impact on the environmental footprint of domestic heating.

This report provides a summary of the activities and outcomes from the three virtual workshops held in January, March, and April of 2022. The goal of the workshops was to bring together stakeholders from across the world to discuss research and development (R&D) challenges and opportunities for advancing residential wood heaters in the United States. The workshops focused on three topics: 1. Advances in wood heater design and technology; 2. Advances in instrumentation used for wood heater testing and field data collection; and 3. Adoption of new wood heater technology and integration with other renewables. Each workshop had more than 100 participants each day which included wood heater manufacturers, researchers, academics, government agencies, and policy makers. Overall, a clear message was presented that collaborative input from experts at air quality agencies, industry, academic institutions, and non-profits is necessary to ensure that wood heating technology continues as a mainstream renewable energy option in our changing energy landscape and to facilitate innovative technology solutions. Participants also provided insights and recommendations that may help guide future R&D investments.

Executive Summary

Purpose

The use of biomass as a renewable fuel source has enabled the United States (US) to reduce fossil fuel dependence and continues to play a significant role in providing affordable heat for many middle-and low-income households. However, residential wood combustion can negatively impact air quality by increasing particulate matter emissions and other pollutants. To facilitate innovative wood heater technology solutions that reduce harmful pollutants, The Department of Energy's (DOE) Bioenergy Technologies Office (BETO) supported the 5th installment of the Wood Heater Design Challenge (WHDC). The WHDC consists of three virtual workshops and a Technology Slam aimed at encouraging entrepreneurs and academics to rapidly innovate, develop, and demonstrate novel wood heater inventions. This report summarizes the activities and outcomes from the three virtual workshops held in January, March, and April of 2022. The purpose of the workshops was to bring together stakeholders from across the world to discuss R&D challenges and opportunities for advancing residential wood heaters in the US.

Workshops Overview

Three virtual workshops were held using the vFairs platform that encouraged participation through poster sessions, booth exhibits, breakout sessions, and a lounge area specifically for networking. The workshops enabled participants to explore technology innovation, share experiences, and network with an international community of innovators, suppliers, students, manufacturers, and other experts in the residential wood heater community. The workshops were designed to identify challenges and needs, share knowledge, build relationships, promote collaboration and engagement, and address advancements in wood heater design, performance, and adoption. Each workshop had an overarching theme with related plenary sessions followed by more detailed breakout sessions targeting specific areas.

The three workshop themes were:

1) Advances in wood heater design and technology
2) Advances in instrumentation used for wood heater testing and field data collection
3) Adoption of new wood heater technology and integration with other renewables

Each breakout session had a short presentation followed by a question-and-answer discussion to disseminate knowledge and encourage participation. The workshops focused on identifying critical technology gaps, sharing resources and information, and providing research and development recommendations for significantly reducing emissions and improving efficiency of residential wood heaters. Breakout discussion topics included: wood heater designs, automation, catalyst development and other post combustion emission mitigation techniques, sensor technologies, performance testing methods and instrumentation.

Outcomes

Each workshop had more than 100 participants and included wood heater manufacturers, researchers, academics, government agencies, and policy makers. Participants expressed a need to collaborate with others, especially National Laboratories, to help with design iterations, detailed measurement capabilities for new wood heater technologies, and training students to foster the next generation of engineers and scientists focused on biomass combustion.

From the breakout sessions, participants identified modeling and the use or development of advanced controls to optimize burn periods as potential research areas. Participants also requested field testing to characterize how homeowners use their wood heaters, wood heater type, region, fuel use, and wood size. For field testing, they recognized the need for cost-effective and practical field-testing equipment, as nothing is currently available. Additionally, participants recommended future field studies include time-resolved particle measurements, black carbon, and ultrafine particles to better understand particle size and composition released from wood heaters.

Overall, participants agreed that improved combustion technologies, improved emission testing protocols, and improved regulatory policies are needed to advance wood heaters. Additionally, post-combustion strategies, such as catalysts or electrostatic precipitators, may be necessary to reduce wood heater emissions further. Participants also stated that hydronic wood heaters have strong synergies with solar thermal and heat pump-based systems and may help offset fossil fuel-based heating system; however, these systems must be properly sized.

Recommendations and Next Steps

To facilitate innovative wood-heater technology solutions that provide an affordable, competitive, and low emission heating option for U.S. households, we recommend the following activities and future R&D investments based on outcomes from the WHDC workshops:

- Collect more field data to better understand user behavior and its impact on wood heater performance so manufacturers can optimize heaters for real-world use.

- Integrate automation through sensors and controls to help optimize combustion, reduce combustion variability during transient periods, and minimize high emission events caused by the user.

- Develop computational modeling tools to help reduce R&D time by predicting the performance and emissions of various operating conditions and technologies (similar to engine research).

- Integrate post-combustion technologies such as electrostatic precipitators or catalysts to significantly reduce particle emissions and keep wood heaters reduce inorganic emissions further. It should be noted that the post-combustion technologies must also be capable of reducing start-up emissions and poor-user practices.

- Develop an affordable, portable, and accurate dilution system for conducting field emissions measurements that can be translated to laboratory dilution tunnel tests and accurately characterize particle emissions released into the atmosphere.

- Integrate time-resolved particulate measurement in the laboratory and field tests to identify high emission events and target innovative strategies for reducing wood heater emission.

- Quantify the role of wood heaters coupled with efficient and renewable technologies (e.g., heat pumps and solar) to support decarbonization efforts, especially in states with very cold climates or where electrification may be challenging. The study should also identify how wood heaters could be integrated with other systems, the energy and emissions impact, and how to ensure proper installation to achieve emissions reductions while increasing efficiency.

- Conduct a techno-economic analysis to quantify the impact of lower particulate regulations on air quality and health. This should also include exploring the impact of lowered particulate matter regulations on vulnerable populations (e.g., higher-cost heaters).

- Organize regularly scheduled opportunities for the wood heater community to come together and network, share ideas, and demonstrate novel technologies. Competitions like the WHDC have served as an impetus to innovate wood heater technologies, while rewarding and recognizing manufacturers for their novel technologies.

Next, we will host the Wood Heater Technology Slam competition, where applicants will present their novel wood-heater technologies. The top three teams will have their technologies evaluated at BNL and be eligible for prize money to support further development and commercialization.

Benefits to DOE's Bioenergy Technologies Office

The findings from this workshop series supports DOE's Bioenergy Technologies Office with addressing Congressional direction (S. Rept. 117-36) – to support development and testing of new domestic manufactured low-emission, high efficiency, residential wood heaters. Specifically, this series of workshops brought together wood heater manufacturers and regulatory agencies to identify opportunities for advancing wood heater technologies that meet local community needs. This work also supports energy and environmental justice through development of low-emission wood heater technologies that disproportionately affect marginalized and low-income communities.

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Nomenclature

AGH	Alliance for Green Heat
BETO	Bioenergy Technologies Office
BNL	Brookhaven National Laboratory
CFD	Computational Fluid Dynamics
CO	Carbon Monoxide
DOE	Department of Energy
EPA	Environmental Protection Agency
FY	Fiscal Year
GHG	Greenhouse Gas
LBNL	Lawrence Berkely National Laboratory
LCA	Life Cycle Analysis
NOx	Nitrogen Oxides
NSPS	New Source Performance Standard
O_2	Oxygen
PIs	Principle Investigators
PM	Particulate Matter
R&D	Research & Development
RWC	Residential Wood Combustion
T	Temperature
TEOM	Tapered Element Oscillating Microbalance
US	United States
VOCs	Volatile Organic Compounds
VTO	Vehicle Technologies Office
WHDC	Wood Heater Design Challenge

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Introduction

Residential wood heaters, such as wood stoves or wood-burning appliances, are used for heating homes and buildings using wood as a fuel source. There are an estimated 12.5 million homes in the United States (US) that use wood or pellets for space heating, according to the US Energy Information Agency.[1] As of 2018, the US Census said that 1.9% of homes use wood for primary heating, but noted that in many more rural counties more than 16% of homes use it as a primary heat source.[2] For 2.7 million homes, they serve as primary heaters, and for about 9 million, they serve as secondary heaters.

While these heaters are a popular and affordable option for many households, they also contribute to environmental pollution. Residential wood combustion (RWC) releases a range of air pollutants, including particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NOx), and volatile organic compounds (VOCs). These pollutants can have negative impacts on both the environment and human health, especially for those living in close proximity to wood-burning appliances. The use of old, inefficient wood heaters can worsen the problem of environmental pollution, as they release higher levels of pollutants than newer, more efficient models. To address this issue, many countries have introduced regulations to limit emissions from residential wood heaters, and promote the use of cleaner, more efficient appliances.

Many of the best wood heaters capable of primary home heating are made in the US. This is the result of decades of experience of stove manufacturers meeting stricter emission standards in third party labs that use federal testing protocols. Federal emission certification standards, dating back to 1988, preceded federal standards in almost all European countries, giving the US industry a head start in designing and deploying secondary air tubes and catalysts, which are still the primary tools for post-combustion emission reduction. In 2020, the US Environmental Protection Agency (EPA) finalized amendments to the 2015 New Source Performance Standards (NSPS) for New Residential Wood Heaters, New Hydronic Heaters and Forced-Air Furnaces as a continued commitment to ensure that RWC devices comply with Clean Air Act standards. The updates were based on improved wood heater technology and focused on strengthening the emissions standards for new woodstoves, while establishing the first-ever federal air standards for previously unregulated new wood heaters, including outdoor and indoor wood-fired boilers (also known as hydronic heaters), indoor wood-fired forced air furnaces, and single burn-rate woodstoves[3].

Increased engagement along with research and development (R&D) is needed in the US residential wood heater sector to help advance and design the next generation of domestic wood heaters. Specifically, there is a need to accelerate the design and deployment of clean and more efficient wood and pellet heaters in the US to ensure wood heating continues as a renewable energy option in our changing energy landscape coupled with changes in regulations. As a result, the US Department of Energy (DOE) has begun to provide R&D assistance to modernize the wood heating sector and help US made stoves be even cleaner and more efficient.

In the fiscal year (FY) 19, FY20 and FY21 Appropriations Bills, Bioenergy Technologies Office (BETO) was recommended to support the development of cleaner burning, higher efficiency residential wood heaters. BETO has since offered three separate Funding Opportunities in FY19 – FY21 (DE-FOA-0002029, 0002203, and 0002396) and has selected a total of eight projects for award to develop domestic manufactured residential wood heaters with lowered emissions and increased efficiency. BETO has also committed to supporting the 5th installment of a successful national wood heater competition. The 5th Wood Heater

[1] https://www.eia.gov/consumption/residential/data/2015/hc/php/hc1.2.php
[2] https://www.census.gov/library/stories/2018/02/who-knew-wood-burning-fuel.html
[3] https://www.epa.gov/residential-wood-heaters/compliance-requirements-residential-wood-heaters

Design Challenge (WHDC) complements BETO's competitive funding awards by encouraging entrepreneurs and academics to rapidly innovate, develop, and demonstrate novel wood heater inventions.

The 5th WHDC continues the tradition of the past four workshops focused on a healthy competition among manufacturers and universities to develop the cleanest and most innovative stoves on the market today. Based on feedback from the previous events, the 5th WHDC focuses on using more engagement tools to explore technology innovation, share experiences and perspectives, and reach a larger and more international community of innovators, suppliers, students, manufacturers, and other experts. Specifically, virtual workshops of invited experts and stakeholders, mainly from North America and Europe were planned, followed by a technology pitch event (similar to a 5-minute elevator pitch used in NSF I-Corps program or the Research Slam conducted at the National Labs) and ending with the core activity of R&D testing for the selected teams to design and build next generation stoves. This report summarizes the virtual workshop events and their key takeaways.

Workshop Purpose and Program

Brookhaven National Laboratory (BNL) in partnership with Lawrence Berkeley National Laboratory (LBNL) and the Alliance for Green Heat (AGH), with support from the DOE BETO, hosted a series of workshops as part of the 5th WHDC. The purpose of the workshops was to bring together national and international stakeholders to discuss R&D challenges and opportunities for advancing residential wood heaters in the US. The purpose of the workshops was to engage leaders and engineers of the wood heater industry along with academics, experts, and others by creating forums that they could have input to. To strategically identify challenges and needs, three workshops were organized to address advancements in wood heater design, performance, and adoption.

The workshop program was organized into three individual workshops, each with its own topic, spanning over two consecutive days. To keep participants focused and engaged, the vFairs platform was used and designed to enhance creative and effective discussions. The platform provided an interactive virtual conference environment, with an auditorium for plenary presentations, individual rooms for breakout sessions, poster presentations and exhibit booths, and a lounge area for networking. The workshops focused on the following: 1) Advances in wood heater design and technology; 2) Advances in instrumentation used for wood heater testing and field data collection; and 3) Adoption of new wood heater technology and integration with other renewables. Each workshop began with short plenary presentations related to the overall workshop theme and was followed by various breakout sessions to facilitate an open discussion focused on a targeted topic. In each breakout room, facilitators posed questions to encourage creative, in-depth discussions and promote networking. At the end of each breakout session, closing remarks were made with each session leader providing a short synthesis of the session's discussion and key takeaways.

The series of workshops sought to increase engagement in this community via collaborative input from experts at air quality agencies, industry, academic institutions, and non-profits to ensure that wood heating technology continues as a mainstream renewable energy option in our changing energy landscape. Overall, the workshop goals included identifying the needs, challenges and research opportunities related to advances in wood heater design and technology, instrumentation used for wood heater research—both in lab and in field, and the adoption and integration of wood heaters with other renewables.

Ancillary goals of the workshops included:

1. Engage and expand the wood heater community.
2. Facilitate collaborations between academia, industry, and other stakeholders to spur innovation to develop the most innovative wood heaters that are cleaner and more efficient.
3. Encourage and build strong teams to compete in the WHDC Slam.
4. Gain exposure for the wood heater industry with the potential to create new R&D opportunities and connections.

The following sections summarize the presentation highlights and discussions from the breakout sessions. Speaker bios and copies of their presentations can be found on the Workshop Proceedings webpage: https://www.bnl.gov/woodheater/workshops.php.

Summary of Workshop 1: Advances in wood heater design and technology

Overview

Workshop 1 was held on January 11th and 12th, 2022 using the virtual platform, vFairs. The goal of this workshop was to discuss advances in wood heater research and development. Advances in wood heater design and technology have led to the development of cleaner and more efficient wood heating technologies. Specifically, combustion science for wood heater R&D has developed significantly in the recent decade—therefore this workshop invited experts in various areas to discuss what the key metrics for improving wood heater designs are necessary to secure their role in the renewable heating sector. The advantages and disadvantages of different engineering strategies to reduce emissions and increase efficiency was also discussed. Plenary presentations focused on providing high level information about residential biomass combustion and disseminating knowledge regarding the use of sensors, automation, post emission controls and multiple types of secondary combustion to help ensure that wood heaters are not only clean in the lab, but also in the hands of consumers.

Day 1 breakout sessions focused on different strategies to improve solid wood combustion—through fuel type, control strategies, and combustion strategies, while Day 2 breakout sessions had a variety of topics focused on modeling, post combustion mitigation techniques, and advanced hydronic heater design concepts. A summary of the plenary presentations is provided in Table 1. The agenda, plenary presentation slides, and plenary recordings can be found on the 5th Wood Heater Design Challenge Workshop 1 website (https://www.bnl.gov/whdchallenge/events/index.php#w1). A summary of the breakout session topics is provided in the next section.

Table 1: Workshop 1 Plenary Presentations

Presentation Title	Presenter(s) and Affiliation	Summary
Basics of Biomass Combustion & Moving Forward	Rebecca Trojanowski *Brookhaven National Laboratory (BNL) & Columbia University*	Residential wood combustion plays a signification role in state and country renewable energy goals but suffers from high emission in comparison to other technologies. Designs of wood heaters must be reconsidered and incorporate techniques to reduce emissions and improve efficiency—with a focus on real life performance. Focusing on the state-of-the-art technologies and inviting big technical changes, to ask: what is the best we can do to ensure wood heat has a future?
Wood Combustion Agenda 2030— Development Pathways for Low Emission Future	Ingo Hartmann *Deutsches Biomasseforschungszentrum, gemeinnützige GmbH (DBFZ)*	Residential wood heaters can contribute to greenhouse gas (GHG) reduction goals, but first need to achieve near zero soot emissions under practical operating conditions. This can be achieved through system integration techniques which include automated controls, operator feedback, new chamber designs, catalysts, electrostatic precipitators, or water jackets. Stoves with a voluntary Blue Angel label recognize environmentally friendly stoves with low CO, VOCs and PM emissions—under realistic operating phases.
Incorrect Operation of Log Wood Stoves: Emission Impact and Potential Avoidance by Automatic Air Control	Hans Hartmann and Robert Mack *Technology and Support Center of Renewable Raw Materials (TFZ), Department of Solid Biofuels*	Advanced automatic air controls for log wood stoves offer a high potential for emission improvements during real life operation. A recent study focused on the emission impact from false operation of wood logs stoves. The results of the study then triggered an intensive national standardization activity concerning requirements for automated stove control.

Breakout Sessions

Workshop 1 included six breakout sessions, three on Day 1 and three on Day 2. Each of the six sessions focused on how to improve biomass combustion performance using various engineering strategies to improve the performance in terms of emissions and efficiency. A description of each breakout session, by day, and the major highlights are provided below in Table 2 and Table 3.

Table 2: Workshop 1, Day 1 Breakout Sessions (January 11, 2022)

Title	Participants	Description	Highlights
Session A Fuel of the future—keeping biomass relevant in the electrified heating sector	<u>Panelists:</u> Mark Knaebe (US Department of Agriculture Forest Service) Gillian Mittelstaedt (Tribal Healthy Homes Network) <u>Moderator & Note Taker:</u> Julien Caubel (Lawrence Berkeley National Laboratory)	Fuel is the foundation of any biomass energy system. However, with the push for electrification will there be a shift away from wood fuels? When considering biomass fuels for widespread adoption, it is crucial to understand and account for the fuel lifecycle: gathering the feedstock, processing, transportation, and final combustion in the target appliance. Each phase of the lifecycle contributes economic and environmental impacts that should be minimized. Perhaps the future is beyond and includes other fuels such as biochar as byproduct from other biofuel industries to reduce emissions. This session raised the question of pre-treating wood to decrease emissions. Additionally, how do changes in the fuel affect the design and flexibility of systems?	• Distribution and supply chains are highly varied by region. Therefore, establishing an economical and accessible supply chain is key to fuel adoption. However, not all geographical areas have the same fuel type (cordwood vs pellets) and species (hardwood vs softwood) available. Large anchor clients (schools, municipal governments, and industry) should be identified instead of focusing on the population density, and new fuels should leverage existing infrastructure to facilitate adoption. • Biomass fuel should complement other renewable energy streams. For example, in Canada there has been a strong push towards electrification in all energy sectors, including residential heating. However, this singular focus on electric infrastructure causes a surge of demand during cold snaps, which overloads the grid and can cause black outs. Biomass heaters can be used to meet some of this peak heating demand, reducing peak loads on the electric grid. • For residential heating, cordwood, pellets, and wood chips are likely to remain dominant as they are widely available at economical rates. Cordwood is often not a fuel of choice, but a fuel of convenience or necessity. Therefore, future efforts

			should concentrate on improving the heating performance from these fuels and developing sustainable supply chains.
Session B Advanced control strategies	Panelists: Jeff Hallowell (Biomass Controls) Philip Hopke (Clarkson University) Moderator & Note Taker: Jake Lindberg (Brookhaven National Laboratory)	Through the use of automation and various control strategies, combustion can be improved to minimize the emissions but also mitigate operator errors and provide a friendly user interface to educate users. This session focused on what has worked best so far and raised the question of what more we can do. More specifically, electronic control systems, including integrated sensors and microcontroller-based systems have improved the efficiency and reduced pollution within many combustion appliances including conventionally fueled heating appliances and automobiles. This session discussed, the ability of control systems to contribute to the development of low emission biomass combustion appliances, and the preferred pathway for integration of controls into these appliances.	• Temperature and Oxygen (Lambda) sensors seem to stand out above the others as important for wood combustion controls. Airflow rate and infrared (IR) cameras can be good for design purposes. Pollutant emission sensors are good for evaluation, but not for process optimization. • Different groups (Homeowners/Manufacturers/Regulators) want different data. More specifically, homeowners want actionable data (efficiency, output, fuel economy), manufacturers want indicator data (T, O_2, flow rates, etc.), and regulators want output metrics (usage, PM emission, etc.)
Session C Advanced combustion strategies	Panelists: Ingo Hartmann (Deutsches Biomasseforschungszentrum, gemeinnützige GmbH [DBFZ]) Elliott Levine (US Department of Energy, retd.) Moderator & Note Taker: Vi Rapp (Lawrence Berkeley National Laboratory)	Gasification and the use of combustion staging have shown improvements in emissions and efficiency. Direct air injection such as swirled air injection or swirled air direct injection are examples which have shown reductions in emissions and increases in efficiency. However, are there further improvements with novel airflow designs? What works and doesn't? This session also focused on using advanced control strategies to minimize emissions during startup and shutdown periods.	• The use of direct air injection to increase velocity and maintain low air volumes to reduce emissions and maintain thermal efficiency has proven effective. Additional considerations include preheating the secondary air. • To reduce emissions during startup or shutdown periods, the periods must be accelerated to optimize the combustion process. Participants suggested exploring other combustion strategies from engines, turbines, etc. and see how they can be adapted (e.g., oxygen sensors,

			cold-start control strategies, etc.). • The use of automated control strategies to optimize the combustion process is crucial. Specifically, any technology that can help address operator error and minimize operator interaction/intervention (e.g., fully automated). Further, recommendations included exploring advanced sensors to characterize wood combustion and integrate with control strategies to optimize operation (e.g., measure hydrogen/carbon ratio).

Table 3: Workshop 1, Day 2 Breakout Sessions (January 12, 2022)

Title	Participants	Description	Highlights
Session D Improving biomass combustion through modeling	Panelists: Dimitris Assanis (State University of New York Stony Brook University) Paul DesJardin (State University of New York at Buffalo) Moderator & Note Taker: Thomas Butcher (Brookhaven National Laboratory)	Preliminary modeling, including computational fluid dynamics (CFD), can help manufacturers explore new techniques and features to reduce emissions that could have a significant impact on air quality. However, CFD is rarely used in wood heater R&D. This session sought to understand why CFD is not more commonly used and the barriers. Questions such as 'are commonly available modeling techniques too rudimentary to provide sufficient resolution for design optimization?' were raised and discussions were held regarding the potential for modeling to contribute to further the R&D of low emission biomass combustion.	• Modeling has played a significant role in advancing technology and reducing emissions from engines. In comparison the modeling of biomass combustion and heating appliances is at a very early stage. • Uncertainty about user interaction can lead to significant differences between model results and field experience. In modeling, natural draft stoves boundary conditions and modeling transient draft conditions is an important challenge. • Modeling should focus on robust design – being able to predict performance under off-design conditions. This includes wet

			fuels, poor loading practices, bad draft for example. • The modeling of soot / incomplete combustion products is particularly difficult and can impose significant computational costs. The coal bed is also very difficult to handle from a modeling perspective and has a large impact on performance. • To reduce modeling time perhaps simpler, lower order modeling approaches should be considered. Sometimes it is seen as less time consuming to build and test rather than prepare and run a detailed model. • It is not always clear what the most important parameters are to focus on. Temperature is clearly important, but can we simplify other areas? • It would be valuable to document clear examples of the success of modeling in predicting the performance of a biomass combustion appliance.
Session E Catalysts and ESPs	Panelists: Nordica MacCarty (Oregon State University) Mirjam Müller (Deutsches Biomasseforschungszentrum, gemeinnützige GmbH [DBFZ])	Post control strategies such as catalysts and electrostatic precipitators (ESPs) can help mitigate emissions and recent trends in small scale ESPs and novel catalyst designs can help achieve lower emissions. What is the current state of the art, and how can we continue to advance this area?	• Electrostatic precipitators (ESPs) have proven effective and capable of reducing 99% of PM but are costly—some countries may see the requirement of ESPs in the future. • Catalysts are used to reduce emissions but are not efficient during start-up as it takes time for catalysts to reach temperature.

	<u>Moderator:</u> John Ackerly (Alliance for Green Heat) <u>Note Taker:</u> Caroline Solomon (Alliance for Green Heat)		• For wood heater technologies to remain competitive in the future of electrification, post-combustion controls will be needed to achieve near-zero PM emissions. • Optimization of post-control strategies must be optimized for all draft levels and address all poor user practices. • It is important to demonstrate technologies in real-world conditions to prove the performance is safe and impactful—otherwise, there is apprehension.
Session F Advanced hydronic heater design concepts	<u>Panelists:</u> Mark Caluwe (Caluwe, Inc.) Scott Nichols (Tarm USA, Inc.) <u>Moderator & Note Taker:</u> Rebecca Trojanowski (Brookhaven National Laboratory)	Wood-fired hydronic heating systems have evolved over the past decade significantly, shifting from traditional in-efficient, high polluting outdoor units with little advanced controls. With advances in test methods and US-European partnerships, advanced wood-fired hydronic heating systems have entered the US market boasting improved efficiency and lower emissions through advanced controls. For example, thermal storage and modulation have shown to have a positive effect in terms of emissions and efficiency performance, but their added cost continues to be a barrier. In this breakout session, the best practices, and advancements in technology of hydronic heating systems were discussed in addition to how can we move past some of the current hurdles.	• Manufacturers continue to think about Lambda sensors and other feedback controls. Currently, there are only two boilers on the market with a Lambda sensor. It's a proven, stable technology but they're expensive which drives the entire system cost up and continues to be a barrier to market. • New ideas of thermal storage are emerging. Specifically, the idea of using phase change materials. Past studies have shown the benefits of thermal storage with water, but ideas of new phase change materials raise the potential to reduce system footprint and overall cost. However, thermal storage must be installed correctly, otherwise performance is compromised. • The most common hydronic heaters installed are cordwood fired appliances as

			homeowners' biggest concerns are fuel cost savings and seek the fuel most readily available. Wood chips are the second most common, followed by pellets. Fuel moisture content of wood chips should always follow manufacturer recommendations for best performance. • Manufacturers continue to focus on safety and updraft gasifiers have a new market focus to reduce emissions.

Summary of Workshop 2: Advances in Instrumentation Used for Wood Heater Testing and Field Data Collection

Overview

It should be noted that the format of Workshops 2 and 3 were modified to include a panel discussion with polling questions. This modification was made to encourage more participant engagement during the breakout sessions and proved to be more effective for getting audience engagement.

Workshop 2 was held on March 28 and 29, 2022 using the vFairs platform. The goal of this workshop was to identify opportunities for improving laboratory and field (in-home) performance measurement practices and instrumentation. Performance methods and instrumentation are critical for providing innovation targets to wood heater manufacturers. These improvements also enable regulatory agencies to evaluate the impact of improved heaters. Improving standard test methods and making them accessible for field testing would ensure wood heaters consistently achieve environmental and health performance targets from laboratory to field operation.

Plenary presentations focused on disseminating knowledge of current and upcoming test methods and tools. Day 1 breakout sessions focused on laboratory test methods and instrumentation, while Day 2 breakout sessions focused on field test methods and instrumentation. During the plenary session, a general survey was presented to the audience asking participants the following question: "How much would the following DOE supported technical support areas help manufacturer development efforts?". Participants were then asked to rank the following choices from "Very Unimportant/No Interest" to "Very Important". The technical support areas are seen below in Table 4.

Table 4: Polling Question with Related Support Areas Presented to Participants

General Question: How much would the following DOE-supported technical support areas help manufacturer development efforts?	
Support Area 1	A place for iterative prototype testing with detailed measurement capabilities
Support Area 2	Prototype detailed modeling and support for iteration (new combustion geometries, designs)
Support Area 3	Design assistance under Non-Disclosure Agreements (NDA's)
Support Area 4	Preview testing against certification standards
Support Area 5	Other ideas for approaches under which DOE could support manufacturer development of much better performing stoves

A total of 32 participants responded to the poll, with the majority representing manufacturers of wood heaters and all other groups nearly equally represented as shown in Figure 1. Figure 2 below shows the results of the poll. Indicating, most found all categories of potential support areas very important.

However, the least favorable of support categories was design assistance under non-disclosure agreements (NDA's).

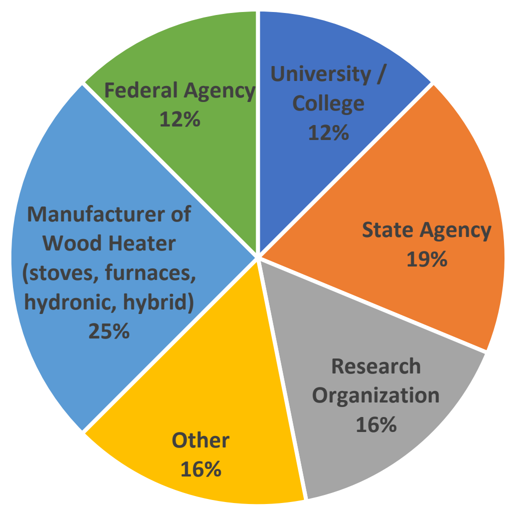


Figure 1: Affiliation of poll participants

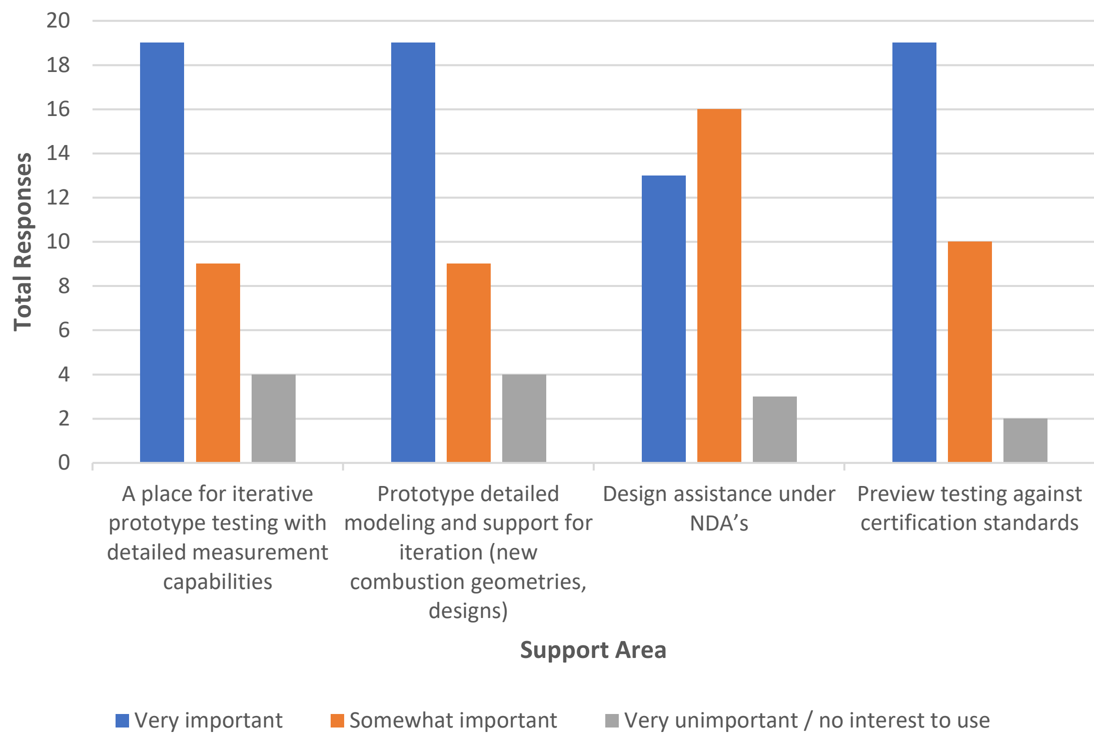


Figure 2: Responses to polling question: "How much would the following DOE-supported technical support areas help manufacturer development efforts?".

Other responses collected indicated respondents wanted to:

- Leverage the research expertise of principle investigators (PIs) at universities; they have extensive facilities, and a deep understanding of underlying fundamental physics phenomena that can be applied to accelerate R&D process. Universities and colleges train students which became part of the next generation of engineers and scientists with topical expertise that can really tackle biomass combustion future problems. Key partnerships with national laboratories can bring broader, longer-term industry background knowledge so that our fundamental knowledge can be successfully applied to improve wood heat design, improve combustion, and reduce emissions.
- Develop test methods that remove the variability of the biofuel and still represent the best probable case use in the field. Otherwise only automated stoves and boilers will exist on the market to remove glaring operator errors.
- Focus on field testing.
- Offer smaller, faster funding mechanisms to test out early-stage innovative ideas. Give many small grants to 'seed' the development of innovative concepts that can be further developed at the full 2.5M FOA stage.
- Help people match up with needed expertise.
- Product development support and guidance.
- DOE should be engaged when manufacturers and stakeholders discuss new revision of standards. There seems to be a disconnect between old EPA practices and modern good practices.
- Collect better data on how people use stoves: ideal appliance sizes by region, fuel use per year, fuel type usage etc.
- Develop inexpensive sensors to help users run existing stoves in the most efficient ways (can also be applied to new stoves).
- Better designs exist in Europe; therefore, the US should work with European manufacturers to share their research and help innovate.
- It is recommended that any future funded proposal include a manufacturer and a national laboratory - replicating the very successful model that Vehicle Technologies Office (VTO) has followed for many years - which has specifically led to improving efficiency and reducing emissions.

A summary of the plenary presentations is provided in Table 5. The agenda, plenary presentation slides, and plenary recordings can be found on the 5th Wood Heater Design Challenge Workshop website (https://www.bnl.gov/whdchallenge/events/). A summary of the breakout session topics is provided in the next section.

Table 5: Workshop 2 Plenary Presentations

Presentation Title	Presenter(s) and Affiliation	Summary
Biomass Heater Testing: Overview of Performance and Emissions Evaluation	Julien Caubel *Distributed Sensing Technologies*	Wood heater performance testing is commonly conducted to implement design improvements, characterize the impact on the environment, or to comply with regulations. Current methods for evaluating wood heater performance (thermal efficiency and emissions) are typically conducted in a laboratory setting and are not optimized for

		field (in-home) use. It is recommended that future performance test methods should be accessible, accurate, and representative of in-home operation.
Wood Heating PM Method Precision Testing: Evaluation of TEOM & IDC PM Measurement Precision	Steffan Johnson and Angelina Brashear *US Environmental Protection Agency, Measurement Technology Group*	The Northeast States for Coordinated Air Use Management (NESCAUM) has introduced the "Integrated Duty Cycle" test method for wood heater performance evaluation. The test method is designed to emulate in-home use and recommends a tapered element oscillating microbalances (TEOM) 1405D for particulate matter measurements instead of gravimetric-filter measurement methods. US EPA is currently evaluating methods for reproducibility and precision.
CleanAir2 Project – Citizen Science Investigating Real-Life Emissions from Firewood Stoves	Manuel Schwabl *Bioenergy Sustainable Technologies (BEST)*	Improving user-operation may result in significantly cleaner wood heaters. Many users disregard instructions from the manufacturer and instead rely on prior experience, advice from others, or anecdotal evidence. Most common mistakes occur during ignition and reloading. Integrating the user into the optimization process is essential for reducing emissions from wood heaters.

Breakout Sessions

Workshop 2 included six breakout sessions, three on Day 1 and three on Day 2. On Day 1, breakout session topics focused on laboratory test methods and instrumentation, including emissions sampling methods, thermal performance methods, and emission measurement instrumentation. Day 2 focused on field test methods and instrumentation and included discussions on emissions sampling (methods and instrumentation), performance evaluation methods, and impact (health and environment) evaluation methods. A description of each breakout session, by day, and the major highlights are provided below in Table 6 and Table 7.

Table 6: Workshop 2, Day 1 Breakout Sessions (March 28, 2022)

Title	Participants	Description	Highlights
Session A Emissions sampling: Dilution tunnel vs. flue	Panelists: George Allen (The Northeast States for Coordinated Air Use Management - NESCAUM) Henrik Persson (RISE Research Institutes of Sweden) John Steinert (PFS TECO Hearth Products Group) Moderator: Rebecca Trojanowski (BNL) Note Taker: Vi Rapp (Lawrence Berkeley National Laboratory)	Many countries have adopted national standards that limit pollution emissions from residential wood heaters, however these standards differ from country to country. This session focused on the common experimental objectives and major components of such standardized methods as well as how they differ. The session discussed the challenges and successes associated with different methods of testing– specifically focused on dilution sampling vs direct stack sampling. One question that remains at large; whether direct stack sampling can be correlated to dilution tunnel sampling– this session provided valuable insight into this question. Additionally, this session also discussed ways to help simplify and modernize methods.	● Stack and dilution tunnel PM emissions measurements serve different purposes. Stack PM measures combustion performance of the heater, while dilution tunnel measures condensable PM and its potential impact on health/air quality. ● The dilution tunnel method is the best approach for measuring the impact of PM on air quality and health. It is not recommended to use stack measurements (even heated) to quantify condensed PM. Trying to correlate stack and dilution tunnel measurements is not recommended. ● A standard dilution tunnel setup needs to be defined to help minimize variability between test facilities. Currently, dilution tunnel parameters are not well controlled by the test methods (i.e., every lab does not have the same dilution tunnel setup).
Session B Thermal performance: Direct and indirect methods	Panelist: Philip Hopke (Clarkson University) Sebastian Button (PFS TECO) Moderator: Thomas Butcher (Brookhaven National Laboratory)	Direct methods for determining energy output, burn rate, and thermal efficiency typically involve direct fuel input and direct heat output rate measurement. Indirect methods involve measurement of flue gas and (possibly) jacket losses. In this session measurement options and accuracy issues for the use of both of these measurements were discussed. Applications can strongly impact the selection of the method, and this includes stoves, hydronic heaters, warm air furnaces, and emerging hybrid systems.	● Measuring flue flowrate is a required portion of thermal performance calculation and is an exceedingly difficult measure. Flue flowrate measurements may be calculated using other stack measurements (e.g., emissions, temperature, and pressure), but these measurements are challenging to obtain giving the high temperatures, variable flow composition, and high concentrations of PM in the stack.

	Note Taker: John Ackerly (Alliance for Green Heat)		● Thermal performance and emissions performance are somewhat at odds as high temperatures generally produce more oxidized (less pollutant) products, but also result in high temperature flue gas and thus higher thermal losses. ● Current test methods incentivize low temperature combustion, by including charcoal/burnout phase in the method. The new Integrated Duty Cycle (IDC) test method may eliminate this test phase. However, consumers prefer "long burn times" between reloads for ease-of-use reasons. ● Direct thermal efficiency methods are accurate but expensive and complex. Indirect measurements are less accurate but more affordable and straightforward. Both are more accurate than the standard assumption of 75% thermal efficiency.
Session C Emission measurement instrumentation: PM and gaseous pollutants	Panelists: Amara Holder (US Environmental Protection Agency) Casey Quinn (Colorado State University) Jake Lindberg (Brookhaven National Laboratory) Moderator:	Traditionally, laboratory testing of biomass heaters has focused on measuring the mass of PM pollution emitted from the chimney using gravimetric filters. While gravimetric PM measurements are certainly an important indicator of air quality impacts and combustion performance, biomass appliances emit other harmful pollutants that merit monitoring, and instrumentation has advanced significantly in recent years. In this session, the particulate and gaseous pollutants that are key to characterizing the emissions performance of wood heaters, and new or novel methods for measuring these	● Time-resolved PM measurements (e.g., TEOMs, nephelometers, optical particle counters, etc.) are needed to drive heater development and impact assessment. ● Smoke opacity measurements are regulated emissions metrics in some regions, but measurement techniques are not commonly used in laboratory. They may be useful for evaluating combustion quality.

	Julien Caubel (Lawrence Berkeley National Laboratory) Note Taker: Amanda Sirna (Stony Brook University)	emissions in the lab were discussed. An accurate and expanded understanding of air pollution from wood heaters is critical to informing the development of improved combustion technologies, and effective public policy to protect human health and the environment.	● Additional air quality and health impact metrics such as ultrafine particles, black carbon, and carbon monoxide should be considered along with $PM_{2.5}$ emissions. ● Effective heaters must address both thermal performance and emissions reductions. Neither of these aspects can be treated alone. ● Meaningful heater testing can be conducted with a relatively limited set of instruments. ● More guidance is needed/desired on data analysis.

Table 7: Workshop 2, Day 2 Breakout Sessions (March 29, 2022)

Title	**Participants**	**Description**	**Highlights**
Session D Emissions sampling: Instrumentation and dilution	Panelists: Ryan Thompson (Mountain Air Engineering) George Allen (NorthEast States for Coordinated Air Use Management - NESCAUM) Woody Delp (Lawrence Berkeley National Laboratory) Moderator: Vi Rapp	This session discussed the logistics and challenges with measuring emissions in the field. This includes discussing emission measurement instrumentation and dilution methods. What emissions are critical and what me might be able to do without was also reviewed.	● Real-time PM may be most challenging to measure in the field followed by dilution. ● Audience seemed to benefit greatly from panelists knowledge about emissions sampling best practices. Many audience members did not seem to understand some fundamentals and panelists were able to shed light on many areas, especially around PM sampling. ● No ideal field-testing equipment suite exists and piecing ideal equipment together as a field-testing suite may not be cost effective.

	(Lawrence Berkeley National Laboratory) Note Taker: Jake Lindberg (Brookhaven National Laboratory)		• TEOM may provide real time PM measurements and be a good substitution for gravimetric measurements. However, the appropriateness of the TEOM for field measurements needs to be validated. Additionally, the TEOM may not be affordable for most. • Optical instruments may work if calibrated against gravimetric. • An affordable, portable, and accurate dilution system is needed.
Session E Performance evaluation: How do you measure performance in the field?	Panelists: Norbert Senf (Masonry Heater Association of North America) Rene Bindig (Deutsches Biomasseforschungszentrum) Tom Butcher (Brookhaven National Laboratory) Moderator: John Ackerly (Alliance for Green Heat) Note Taker: Jason Loprete (Stony Brook University)	Measuring the performance of wood heaters in the field is no simple task. For example, how to accurately measure the amount of fuel consumed to determine thermal efficiency remains a challenge in the field. Additionally, questions were raised to better understand what field measurements should focus on—an imposed duty cycle or how the heat is actually operated by the user. This session focused on what needs to be included in field measurements such as the user comfort evaluation and understanding what goes into a user's decision to purchase a heater. With this knowledge, could we ultimately design a better heater?	• PM Emission Factor (g/kg_{fuel}), Emission Index (g/kJ), and Emission Rate (g/kg_{fuel}) are important field metrics. Emission factor is easiest to measure but emission rates are used to score stove certifications. • Portable dilution tunnels may assist with diluting emissions samples during field measurements. • Optical particle sensors can be used to measure PM concentrations but are not as accurate as gravimetric methods as they miss small (< 300nm) particles. Optical sensors can also measure opacity, which is a quantity used for enforcement in some areas. • Drilling holes in the stack for sampling is challenging and may pose hazards to the occupant. Some use aluminum tape, others use a bolt to fill the hole. EPA has

			some requirements that limit flexibility. ● Unclear if sufficient studies exist that simultaneously measure stack and outdoor air emissions for wood burning appliances.
Session F Impact evaluation methods: Public health and the environment	Panelists: Brian Frank (New York State Department of Environmental Conservation -NYSDEC) Nicole Vitillo (New York State Department of Health - NYSDOH) Gillian Mittelstaedt (Tribal Healthy Homes Network) Moderator: Rebecca Trojanowski (Brookhaven National Laboratory) Note Taker: Julien Caubel (Lawrence Berkeley National Laboratory)	Traditionally, wood heater test methods have focused solely on particulate matter, on a mass basis. Recently, gaseous pollutants such as CO have been required to be reported during compliance tests. As residential wood combustion is often the highest source of PM emissions in states and held responsible for numerous health related issues, are there other measurements that should be considered beyond PM mass, such as speciation, number concentrations, and size? This session provided a forum that focuses on how to measure emissions related to health and environmental impacts.	● Gravimetric $PM_{2.5}$ provides a baseline. Ultrafine particles and particle composition are also important. However, not enough information is available to make definitive health statements or quantify health impact. ● Measuring additional pollutants (e.g., ultrafine particles, PAH, particle composition, etc.) in-field is challenging and may differ from lab measurements. Addressing these challenges is critical. ● Our current emissions monitoring network is not equipped for measuring ultrafine particles. ● Need to quantify and understand how black carbon plays a role in health impacts.

Summary of Workshop 3: Adoption of new wood heater technology and integration with other renewables

Overview

Workshop 3 was held on April 26 and 27, 2022 using vFairs. The goal of the third workshop was to discuss the adoption of new wood heater technology and integration of wood heaters with other renewable energy technologies. Within these topics, the barriers to wood heater adoption in the heating sector and how wood heaters could play a more long-term role as a renewable energy option was also discussed. Integrating wood heaters with other renewable energy sources can help reduce the environmental impact of wood heating and improve overall energy efficiency. More specifically discussed was the coupling of a wood heater with a heat pump system and emerging technologies to the European market. Additionally, the Integrated Duty Cycle (IDC) protocol was introduced.

Similar to the second workshop, a poll was presented to all participants during the plenary session to capture where participants felt the strongest need for innovation was. Results are shown in Figure 3 from 36 participants and indicate the majority of respondents felt there was a strong need for improving combustion technologies along with emission testing protocols and regulatory policies.

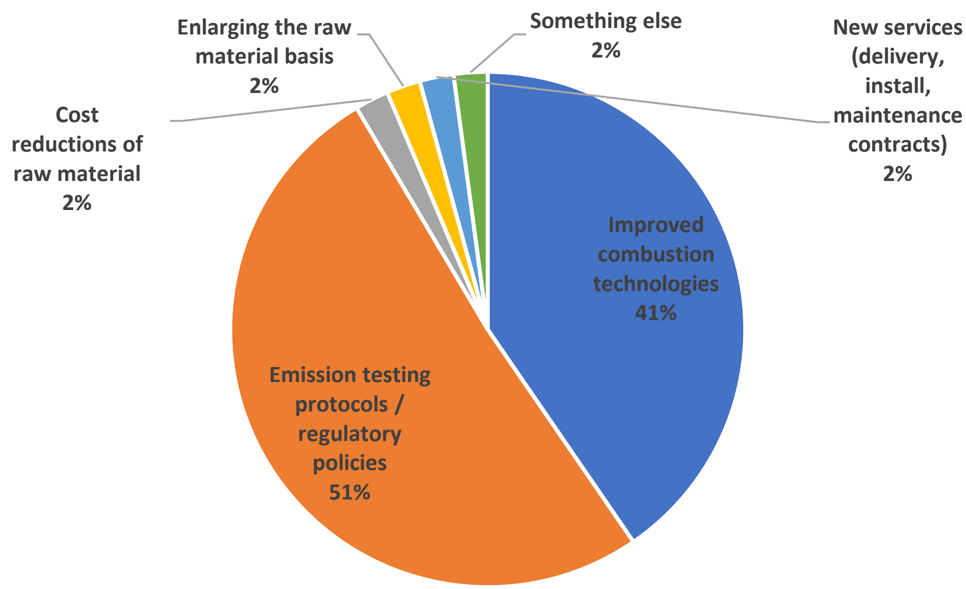


Figure 3: Responses to polling question: “Where do you see the strongest need for innovation in the wood heater sector?”

The plenary presentations for both days were broadly focused on integration. Specifically, the first day plenary topics were: integration of wood heater technology into the US market given current climate action goals and barriers to wood heater adoption due to pollution concerns. On the second day the plenary topics were: integration of European technology into the US market and possible ways to address pollution concerns. The breakout sessions on both days featured one talk focused on garnering attention for the upcoming WHDC Technology Slam and one technical session. A summary of the plenary presentations is provided in Table 8. The agenda, plenary presentation slides, and plenary recordings can be found on the 5th Wood Heater Design Challenge Workshop website https://www.bnl.gov/whdchallenge/events/). A summary of the breakout session topics is provided in the next section.

Table 8: Workshop 3 Plenary Presentations

Presentation Title	Presenter(s) and Affiliation	Summary
Advanced Wood Heat's Role in Renewable Energy and Clean Heating Policy	Adam Sherman *Vermont Energy Investment Corporation*	Decarbonizing the heating sector is a multi-solution problem, no single solution will work. Wood heaters and heat pumps synergize strongly to provide reliable, comfortable (on demand), green heating. Wood heat is desirable to compensate for poor heat pump performance in the dead of winter and to mitigate load spikes due to cold snaps.
Integrated Duty Cycle (IDC) Protocols	Lisa Rector *Northeast States for Coordinated Air Use Management - NESCAUM*	Real-world operation is highly variable. Day-to-day variability in operation occurs based on user input and heat demand is variable year-to-year. Current certification methods are steady-state test methods and typically use the same loading conditions for every test, burn fuel loads to 100%, resulting in a loss of particle mass, do not require replicate test runs, and allow for re-testing until a positive result is reached. New methods such as the beReal method in Europe and the Integrated Duty Cycle method in the US aim to address these concerns. These methods have multiple loads (testing fueling transients) and multiple output conditions (testing heat-output level effects) and use more modern, real-time, instrumentation.
Emerging technologies from abroad: A report from World Sustainable Energy Days 2022	Rebecca Trojanowski *Brookhaven National Laboratory & Columbia University*	The World Sustainable Energy Days is a biomass heating conference in Wels, Austria organized by OÖ Energiesparverband and serves as a hub event for clean energy technology in Europe. European technology development is focused on increasing innovation and the technology level of biomass heaters, apps to make operating a heater easier, and ensuring biomass sources are renewable and are used sensibly. This presentation provided a review of emerging technologies across the EU related to biomass.
A review of field testing	Tom Butcher *Brookhaven National Laboratory*	There are two main types of field tests: surveys and field studies. Surveys – aim to collect a broad range of data on appliance information and usage. Field Studies – aim to ground truth surveys, lab data, or modeling estimates, etc. Technical approaches for field studies are trending toward small dilution samplers feeding multiple instruments, real time PM measurements (mass-based with other supplemental) and adding more detailed characterization of pollutants.

Breakout Sessions

Workshop 3 had four breakout sessions with two on Day 1 and two on Day 2. The breakout sessions on both days featured one talk focused on garnering attention for the upcoming WHDC Technology Slam and one technical session. On Day 1 specifically, the first breakout session focused on major accomplishments made by DOE grant recipients in the wood heater area, the second session focused on an impact analysis of wood heater use intended to start a discussion about the sustainable use of wood. On Day 2, the first session was devoted to answering questions about the upcoming Wood Heater Technology Slam event, the second session focused on integration of wood heating technology with other renewable energy systems. A description of each breakout session, by day, and the major highlights are provided below in Table 9 and Table 10.

Table 9: Workshop 3, Day 1 Breakout Sessions (April 26, 2022)

Title	Participants	Description	Highlights
Session A - Adding automation to a wood heater Q&A (Past DOE FOA recipients)	Panelists: Guillaume Thibodeau-Fortin (Stove Builders International -SBI) Paul LaPorte (MF Fire) Ryan Fisher (MF Fire) Moderator: John Ackerly (Alliance for Green Heat) Note Taker: Jake Lindberg (Brookhaven National Laboratory)	The effort to begin "automating" wood stoves, usually refers to using sensors and computer chips to adjust airflow after the wood has been loaded by the operator. Automated stoves have the potential to enable the consumer to "load and leave," allowing the stove to maximize efficiency and emissions reductions on its own. Yet, even with low-cost sensors and extensive expertise in the field of combustion, automating the wood stove has proved challenging for multiple reasons. Making sense of data from sensors and responding correctly to that data is an engineering challenge. Additionally, there is also the issue of whether manufacturers have any significant incentives to automate, if automation does not help manufacturers pass EPA certification testing and consumers may be reluctant to purchase them. This was primarily a session for participants to share information, solutions, and problems.	● Automation can significantly improve combustion quality and thus generally reduce emissions. Further automation can make minor adjustments to account for issues invisible to the user: one wet log, covered air vents, ash buildup, etc. ● Automation features can also be used to coach the user into better operating habits. Poor user habits such as: using unseasoned wood, overloading a stove, poor ignition, poor airflow, etc., can cause massive emission peaks which make these features especially attractive. ● Automation features can provide data, which is an added benefit for users: as an optimization tool for fuel efficiency and evaluating their personal GHG/pollution impact, and policymakers as a usage survey. ● Automation features add some cost to the wood heater. ● Automation can complicate certification test methods and require manufacturers to request alternative methods, leading to delays in testing and getting to market. ● Automation features may not be aesthetically pleasing for users who desire a rustic look and automation requires electricity, which excludes an automated appliance from the market of users interested in an off-grid heating appliance.

Session B - Impact evaluation: Quantifying health, energy & climate impacts for biomass heat deployment	Panelist: Tami Bond (Colorado State University) Corinne Scown (Lawrence Berkeley National Lab) Stefan Unnasch (Life Cycle Associates) Oleksandra Tryboi (Scientific Engineering Center Biomass) Moderator: Julien Caubel & Vi Rapp (Lawrence Berkeley National Laboratory) Note Taker: Jason Loprete (Stony Brook University)	Residential biomass heaters have the potential to be key players in clean energy portfolios of the future, as they leverage renewable and economical energy stocks that may not be useful otherwise. However, the collection and distribution of biomass fuels has inherent impacts (ranging from habitat destruction to transportation), and biomass combustion emits air pollution that contributes to climate change and is harmful to human health. As biomass energy becomes more widespread, it is crucial that both the benefits and impacts be accurately quantified. In this session, key life cycle analysis (LCA) to inform responsible adoption of biomass heater technologies at the residential scale was discussed. This forum provided an opportunity for stakeholders to share information on state-of-the-art methods for determining net greenhouse gas emissions over the product life cycle, evaluating health impacts on surrounding populations, and integrating biomass into renewable energy economies. These considerations depend greatly on the deployment context, so a common toolbox of objective evaluation methods must be established to ensure that biomass heaters provide a net benefit to their local communities and environment.	● Accounting of particulate matter, carbon dioxide and ozone emissions often form the core of LCAs, but other key pollutants, such as black carbon are excluded. Analyzing an established set of metrics allows for widespread comparison to other studies. ● The scope and scale of the LCA must be appropriate for the technology or policy under consideration. For energy commodities like electricity and fossil fuels, LCAs are often conducted on a national or state level. However, biomass heater use and implementation varies widely across small regions, and so national or state level analyses may not be appropriate. ● LCA is a relative assessment of one solution versus another. The results of biomass heater LCAs must be compared against the energy alternatives that are available. Wood heat is often compared to electrification, but those meet two different needs: electricity may be used for a wide range of end uses, while wood is largely restricted to residential heating. Therefore, the comparison may not capture that electrification provides benefits that are outside of the LCA's scope and skew the insight that is generated.

Table 10: Workshop 3, Day 2 Breakout Sessions (April 27, 2022)

Title	Participants	Description	Highlights
Session C - DOE/National Laboratory Q&A Tech Slam, 5th	Panelists: Mark Shmorhun (US Department of Energy, Bioenergy Technology Office)	This breakout session was a more in-depth look into the DOE's strategy to promote R&D in the wood heater sector and to provide more details about the Technology Slam and stove competition. Included in the presentation was	● The notes from this session were adapted into a living Q&A page hosted on the Wood Heater Design Challenge webpage (https://www.bnl.gov/woodheater/). For a summary of the discussion from this session

Design Challenge, and Future Events	Thomas Butcher (Brookhaven National Laboratory) Vi Rapp (Lawrence Berkeley National Lab) John Ackerly (Alliance for Green Heat) Moderator: John Ackerly Note Taker: Rebecca Trojanowski	a mock slam, where two fabricated teams presented their fantasied heater designs and judges asked questions and identify their strengths and weaknesses.	please refer to the Q&A page (https://www.bnl.gov/woodheater/questions-answers.php). ● The DOE BETO is supporting the 5th Wood WHDC. This competition offers a total of $120,000 in prize funds and aims to inspire R&D in the wood heater sector and accelerate commercial development of wood heaters that consistently reduce particulate matter across the US. Competitors can win up to $15,000 as a prize in Phase 1 (the Technology Slam) and up to $40,000 in Phase 2 (the R&D Testing Competition). The WHDC provides competitors a pathway to advance their wood heater technology to a field-tested system that may provide affordable, renewable heat in homes. The goal of the WHDC is to aid in the development of innovations that address the largest challenges in the wood heater development community such as: inconsistent emissions, low heater efficiency, affordability, ease of use, and obtaining US EPA emission certification. To help overcome these challenges, we are offering teams a prize that includes laboratory performance testing to advance their heater designs and accelerate its path to market. ● The Wood Heater Technology Slam is an event where teams pitch innovative wood stove ideas to retailers, the public, and panels of expert judges. The expert judges will evaluate participant presentations and score the technologies based on innovation, consistent and low emissions with focus on a 20% reduction in PM emissions and 15%

			increase in efficiency from current EPA certification limits, and commercial potential. It is anticipated that the three (3) teams with the highest score will win a $15,000 prize and move forward to the R&D Testing Competition (Phase 2) of the 5th WHDC. ● The Slam will be held virtually on September 29th, 2022. During the Technology Slam, teams will have seven minutes to virtually pitch their wood heater technology to a panel of expert judges and an audience of wood heater stakeholders. Teams can use slides, short videos, or any other props they choose. Next, judges will have up to five minutes to ask questions regarding the team's technology and development plan. Teams will then be scored based on innovation, consistent performance, commercial potential, and expected performance.
Session D – Integrating wood heat with other residential energy systems	Panelists: Scott Nichols (Tarm Biomass) Richard (Dick) Gibbs (NYSDEC ret.) Moderator: Jake Lindberg (Brookhaven National Laboratory) Note Taker: Jake Lindberg	In order to combat climate change CO_2 emissions from the heating sector must be reduced through increased use of sustainable heating options at a large scale. These options include low-carbon heating options such as electrical heating, heat pumps, and biomass combustion. While there has been much debate as to the extent to which each of these heating options is sustainable, relatively less attention has been paid to combining these types of heating systems together to realize a sustainable and effective low-carbon heating solution. This session focused on how wood heaters can be integrated with other heating systems (heat pumps, warm air furnaces,	● There are no generalities in residential energy systems, each choice (integrated technology or feature) should be approached on a case-by-case basis. ● Wood hydronic heating has strong synergies with solar thermal and heat-pump based systems: Wood heating provides a strong heat source during the cold months when heat pumps and solar thermal are weakest. ● Thermal storage for the hydronic system is a sub-feature which is integral in this synergy large volume low-temperature thermal storage works for wood hydronic systems,

	(Brookhaven National Laboratory)	existing hydronic heating systems, etc.) and with other home energy systems (solar PV, batteries, etc.). This session showcased examples of wood as a primary and secondary heat source for homes and the successes integrating renewable wood heat and renewable electricity. Integrating wood heat into the residential heating sector at large including barriers to entry into the wood heater market and barriers limiting the adoption of wood heaters into the residential heating sector in the US was also discussed.	solar thermal, and air-to-water heat pumps alike. ● The audience believed "good insulation" i.e., a tight building envelope is the most important feature to achieve zero/low-carbon heating. ● Participants suggested investment in new and more integrated stove technologies, and regulatory changes, are the most important methods to facilitate adoption of wood heaters.

Conclusions and Next Steps

The Wood Heater Design Challenge successfully brought together experts from the wood heater community to identify R&D needs, challenges, and opportunities for advancing wood heater technologies in the US. Over 100 participants joined for each workshop representing experts and stakeholders from wood heater manufacturers, researchers, academics, government agencies, and policy makers. Summarized conclusions from each workshop are provided below.

Workshop 1 (Advances in wood heater design and technology) focused on identified current R&D on wood heater technologies and key metrics for improving wood heater. Participants discussed the advantages and disadvantages of various engineering designs to reduce emissions and increase efficiency—with a particular focus on field performance. Specifically, participants discussed the use of different solid biomass fuels, sensors, automation, secondary combustion techniques, modeling of combustion chamber geometries, overall system design, and post combustion emission mitigation strategies. Key takeaways from the breakout sessions are as follows:

- Cordwood is often not a fuel of choice, but a fuel of convenience or necessity. Pellets and wood chips offer the advantage of a more homogeneous fuel type in terms of moisture content and size, compared to cordwood which can vary significantly in moisture content and size, and lead to incomplete combustion and increased emissions. Additionally, pellet and woodchip fired systems are automatically fed which can further improve performance due to the reduction of manual interventions. However, it is recommended that efforts focus on the development of affordable and sustainable supply chains for pellets and wood chips to be competitive with cordwood and must also be widely available.

- Temperature and oxygen (lambda) sensors still remain the best sensors for combustion controls and feedback for hydronic heaters and boilers, whereas others such as air flowrates and particulate emission sensors are useful for evaluation but not optimization.

- Wood heater performance data is valued by everyone—the manufacturer, consumer, and regulator. Specifically, consumers desire fuel use and efficiency data, manufacturers desire certification and field performance data, and regulators desire usage patterns and emission data.

- Automated controls are necessary to maximize emissions reductions from wood heaters, especially when minimizing emissions from transient periods (start-up and burn-out) and addressing user errors. However, they can cause delays in compliance testing as current methods are challenged by automation.

- Modeling can help advance wood heater technology and reduce R&D times by predicting the performance of various conditions. However, developing comprehensive wood heater models is challenging and requires domain expertise that is not available to many manufacturers. Basic heat transfer modeling is used by many because combustion models are incomplete or too challenging.

- Post-combustion technologies such as ESPs or catalysts may be necessary to significantly reduce emissions from biomass combustion, meet future regulations, and keep wood heaters competitive in an electrified market. However, these technologies must also be capable of reducing start-up emissions and poor-user practices.

Workshop 2 (Advances in instrumentation used for wood heater testing and field data collection) focused on identifying opportunities for improving laboratory and in-field performance measurement practices and instrumentation. Plenary presentations focused on disseminating knowledge of current test methods, upcoming test methods, and field measurements made in Europe. Breakout sessions for Day 1 focused on laboratory test methods and instrumentation, while Day 2 focused on field (in-home) test methods and instrumentation. The breakout sessions demonstrated great value to the audience as many learned more about instrumentation and fundamentals of data collection. Key takeaways from the breakout sessions are as follows:

- A standard dilution tunnel setup needs to be further defined to help minimize variability between laboratory testing facilities. Furthermore, an affordable, portable, and accurate dilution system is needed for conducting field emissions measurements.

- Time-resolved particulate measurements are needed to drive heater development and impact. Specifically, the continuous data on the performance of wood heaters can allow researchers to track changes in emissions, combustion efficiency, and other parameters over time. This can help identify trends and potential issues in real-time and inform strategies for improving wood heater performance. Measurements should include $PM_{2.5}$ mass, ultrafine particles, and black carbon, and include metrics to quantify health impacts of the pollutants. Additional measurements of these pollutants from the field are necessary but challenging. It should be noted that the existing emissions monitoring network is not equipped to measure and monitor ultrafine particles.

- No ideal field-testing equipment suite exists and piecing together laboratory instrumentation may not be cost effective or practical. It is also unclear if sufficient studies exist that simultaneously measure stack and outdoor air emissions for wood burning appliances.

- Measuring thermal performance of a stove or furnace in the laboratory and the field poses several challenges. Direct thermal efficiency methods are accurate but expensive and complex (e.g., require a dedicated room or facility). Indirect measurements are less accurate but more affordable and straightforward. Both are more accurate than the standard assumption of 75% thermal efficiency. Measuring flue flowrate accurately is difficult and necessary for quantifying thermal performance. Measuring the direct thermal efficiency from a hydronic heater or boiler in the laboratory is a simpler process.

Workshop 3 (Adoption of new wood heater technology and integration with other renewables) focused on the adoption of new wood heater technology and integration with other renewables. Participants discussed barriers to adoption and how wood heaters could play a long-term role as a renewable energy option. The plenary sessions presented ideas for integrating new wood heater technology into the current market and regulatory frameworks. Breakout sessions included discussions on how wood heaters fit into the larger US market, climatological, and health landscape. Sessions also reviewed how heaters can be integrated into a renewable home energy system. A breakout session was also held to discuss rules and guidelines for applying to the Wood Heater Technology Slam, and answer questions from potential applicants. Key takeaways from the breakout sessions are as follows:

- Automation can significantly reduce variability in the combustion process, improving fuel efficiency and reducing emissions; for users, automation features may also add value to an appliance. However, automation features may add cost and complexity to an appliance, and manufacturers indicated that automation was not necessary to achieve emission certification test limits and may actually lead to delays in compliance testing.

- The scope and scale of Life-Cycle Analysis' must be appropriate for the technology or policy under consideration. Wood heater use and implementation varies widely across regions. Therefore, national or state level analyses may not be appropriate. Regional or local supply chain analysis may be necessary to evaluate the carbon neutrality of using biomass for heat.

- Investing in wood heater technologies that are coupled with solar thermal or heat pump-based systems may support decarbonization of residential energy systems. When attempting to decrease the carbon intensity of a residential energy system, the addition of a new feature should be evaluated holistically, especially when considering the interplay between the existing components of the system. Wood heaters may not be a good fit for all situations; however, wood heaters, especially wood hydronic heating, have strong synergies with solar thermal and heat pump-based systems.

- The Wood Heater Technology Slam competition was well received, with a lively question and answer session. A summary of the discussion, questions, and answers from this session can be found at https://www.bnl.gov/woodheater/questions-answers.php.

In addition to the individual, technical workshop outcomes outlined above, we also identified the following non-technical needs from the community:

- More opportunities for collaboration, especially at the National Laboratories. Working with the National Laboratories could help support design iterations, detailed measurement capabilities for new wood heater technologies, and training students to foster the next generation of engineers and scientists focused on biomass combustion. Collaborations could also support modeling development and development of advanced controls to optimize burn periods.

- Smaller, faster funding mechanisms to test out early-stage innovative ideas to "seed" ideas. This model could rapidly identify successful concepts that could lead to larger funding opportunities.

Following the successful completion of the WHDC workshops, we aim to continue supporting the community by hosting the Wood Heater Technology Slam competition. During this competition, applicants will present their novel wood-heater technologies to judges and the community. The top three teams will have their technologies evaluated at BNL and be eligible for prize money to support further development and commercialization.

Recommendations and Opportunities

Based on the successful community engagement of the three WHDC workshops, it is recommended to continue similar workshops on a regular basis (e.g., annually) that focus on bringing the wood heater community together to identify challenges and opportunities for advancing wood heaters in the US. Audience members seemed to benefit greatly from the panelists' knowledge, as the panelists shared information on instrumentation, measurement methods, quantifying health impacts, and opportunities for improving wood heater technologies. Future workshops should consider engaging homeowners and end-users, with the aim of educating them on how to better operate their appliance. Workshops could also help establish and connect local working groups focused on wood heating in their region.

Additionally, the participants clearly indicated the need for continued support in the R&D of wood heaters for several reasons:

- **Environmental impact**: Wood heaters can contribute to air pollution. R&D can help develop cleaner and more efficient wood heating technologies while reducing environmental impact.

- **Energy efficiency**: R&D can also help improve the energy efficiency of wood heaters, which can reduce energy costs for homeowners and reduce the amount of wood consumed for heating.

- **Safety**: Wood heaters can pose fire and health hazards if not used properly. R&D can help develop safer and more reliable wood heating technologies that can reduce the risk of fires and harmful pollutants.

- **Innovation**: Investing in R&D can lead to the development of new and innovative wood heating technologies, which can provide new opportunities for manufacturers and entrepreneurs.

- **Regulatory compliance**: Many countries have introduced regulations to limit emissions from residential wood heaters. Investing in R&D can help manufacturers develop products that comply with these regulations, ensuring that their products are viable in the marketplace.

From the workshop discussions, we identified the following R&D opportunities for advancing wood-heater technologies:

- Develop an **affordable, portable, and accurate instrument test suite** that could be used to measure heater performance in the laboratory and field (i.e., in homes). This harmonized system must include a portable and reliable dilution system and an accurate method for measuring stack flow rate. Furthermore, the suite should include methods for postprocessing collected data to minimize errors and ensure consistency when comparing performance to regulations or between heaters. This system would enable emissions measurement comparisons between the laboratory and field, as well as minimize variability between laboratory facilities.

- Commission **a field study to better characterize wood heater usage and performance**. Specifically, data is needed to understand the fuel supply chain, consumer fuel characteristics (e.g., type, size, moisture content, quantities, etc.), consumer loading patterns, and actual performance (i.e., emissions and efficiency) of the appliance in homes.

- Conduct a **techno-economic analysis to quantify the impact of lower PM regulations** on air quality and health. This should also include exploring the impact of lowered PM regulations on vulnerable populations (e.g., higher-cost heaters).

- Communicate the results of past projects and research that highlights the **successes or best practices and challenges of automation**. What is the minimum suite of sensors needed to automate wood heaters and optimize their performance in transient burn periods? There is a need to understand how automation is challenged by user behavior such as overloading burn chambers with wet fuels or the ability to override controls. What feedback is helpful to users from "smart" heaters to help address negative behaviors that relate to decreased performance in terms of emissions and efficiency—can this be used to help educate the user.

- Validate the product-market suitability of European **wood heater-heat pump integrated technologies** in the US. The integration of a wood heater and heat pump is a promising solution to achieve the goals of electrification and decrease the usage of fossil fuel-based heating systems. European manufacturers have already made strides in developing designs that enable homeowners to switch between the two heating sources based on fuel prices and load demands. By incorporating smart controls, integration can be optimized to minimize transient periods associated with high emissions.

- Develop **best practices for whole system integration** of wood heaters combined with other energy efficient or low carbon technologies.

- Reduce barriers to adopting **the use of computational fluid dynamics (CFD) and other modeling tools** to optimize wood heater combustion chamber designs by utilizing the expertise at National Laboratories, colleges, or universities. This can help wood heater manufacturers accelerate R&D by predicting the performance of changes in combustion chamber geometries, before building and testing the heater. For example, small changes to the air injection points can be visualized and thermal distribution of the combustion chamber can be resolved to determine if this was an advantageous design iteration.

- Invest in **post combustion strategies** such as catalysts and electrostatic precipitators (ESPs) to further reduce emissions and de-risk the technology in terms of performance and cost. These technologies have the potential to reduce emissions however, there remains a question of how "clean" a wood heater must be before an ESP is effective for example. While ESPs are simple to use and do not require any additional fuel or energy input and can be easily installed on existing wood heaters, their cost remains an issue. Specifically, wood heaters provide a low-cost alternative to many families and the integration of an ESP may drive wood heater costs up significantly and even double the price of a stove. Further, as ESPs do not remove gaseous pollutants, design and operation must also be optimized to maximize emission reduction. It is important to demonstrate these technologies in the real world to show that these are real technologies that are proven to work and be safe.

Appendix A: Notes taken for Workshop 1 Breakout Sessions: Advances in wood heater design and technology

Breakout Session A – Fuels of the Future

Date of workshop: January 11th, 2022
Number of participants: 15-20
Panelists: Mark Knaebe (US Department of Agriculture Forest Service); Jillian Mittlestaedt (Tribal Healthy Homes Network)
Note Taker: Julien Caubel (Lawrence Berkeley National Laboratory)

Introduction/Prompt:
With the push to an electrified heating sector will there be a shift towards pellets and chips from cordwood as they've been encouraged as cleaner fuels already? Perhaps the future is beyond and includes other fuels such as biochar as byproduct from other biofuel industries to reduce emissions? Can we pre-treat wood to decrease emissions? What does this mean in terms of design and flexibility of systems?

Questions and Responses from Panelists:

Q1: While cordwood can be locally sourced with minimal processing, thereby largely eliminating embodied emissions and impacts, cordwood combustion is typically highly polluting. How do we support isolated and often disadvantaged communities as residential heating technologies and environmental regulations increasingly move away from cordwood fuels? How do we make cordwood cleaner and less impactful to the natural environment?

- When it comes to fuels, one size does NOT fit all. Local supply chains, natural resources, economic status, and social/cultural backgrounds vary widely from one region to another.
- Localized bioenergy portfolios should address local land uses, consumer profiles, and distribution models.
- There is no single biomass fuel or feedstock that will be economical, environmentally responsible, and culturally appropriate in all areas of the nation.

Q2: Increasingly, new residential heaters are built to burn pellets and other processed fuels. During this process, are we simply exporting emissions over the length of the supply chain? Is the processing of virgin wood for pellet production desirable or responsible?

- Currently, the fuels of the future are the fuels of the past: Cordwood, pellets, and wood chips.
- Current fuel development efforts should probably focus on optimizing the collection, processing, distribution, and ultimate combustion of existing, established feedstocks, as there is still a lot of room for improvement in these traditional supply chains.
- Over reliance on any one energy solution leaves the system open to vulnerabilities. The major advantages of biomass fuels is that they provide energy on demand, they are widely available, and their processing/use can be both economical and environmentally responsible.

Poll Questions and Results:
None used.

Presentation Slides:

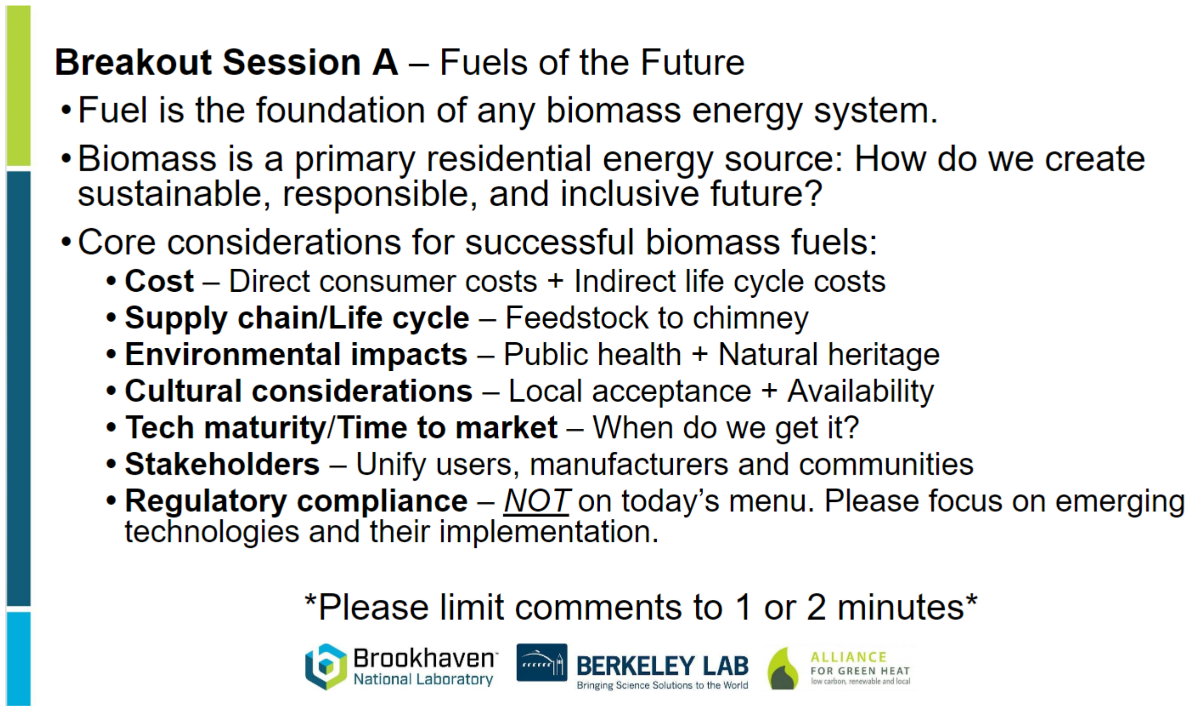
Breakout Session A – Fuels of the Future

Moderators: Mark Knaebe and Gillian Mittelstaedt

Breakout Session Moderators

Mark Knaebe is a Natural Resources Specialist at the USDA Forest Service Forest Products Marketing Unit, located at the Forest Products Laboratory in Madison, Wisconsin. His work includes Bioenergy-- from comparisons of value to environmental and health consequences. Mark tests and evaluates wood gasification systems that are used to generate electricity from wood pellets. He advises on kiln heating systems and has designed wood heating systems for residential use. Currently, he is constructing a super-efficient condensing wood boiler that he designed to force flue gas temperature as low as possible after burning everything at high temperature.

Gillian Mittelstaedt, DrPH, MPA, is an Air Quality and Environmental Health Professional, and Director of the Tribal Healthy Homes Network, a consortium that works to prevent exposure to indoor air hazards through research, training, and culturally tailored interventions. Dr. Mittelstaedt also directs the Partnership for Air Matters, providing low-cost indoor air diagnostic and educational toolkits to at-risk communities. Her research interests include health disparities associated with indoor air pollution and strategies for reducing exposure to fine and ultrafine particles of ambient and indoor origin.



Breakout Session B – Advanced Control Strategies

Date of workshop: January 11th, 2022
Number of participants: 23+
Panelists: Jeff Hallowell (Biomass Controls Ltd.); Jessica Tryner (Colorado State University)
Note Taker: Jake Lindberg (Brookhaven National Laboratory)

Introduction/Prompt:
Controls – specifically electronic control systems, including integrated sensors and microcontroller-based systems have improved the efficiency and reduced pollution within many combustion appliances including conventionally-fueled heating appliances and automobiles. In this Breakout Session, the ability of control systems to contribute to the development of low-emission biomass combustion appliances, and the preferred pathway for integration of controls into these appliances will be discussed.

Questions and Responses from Panelists:

Q1: Are sensors a necessary component of a control system?
If so, which sensors are most important to include? What sensor data would be most helpful for controlling combustion?

- Temperature and Oxygen (Lambda) sensors seem to stand out above the others as important for wood combustion controls.
- Airflow rate and IR camera measurements can be good for design purposes, but are less useful control measurements.
- Pollutant emission sensors are good for evaluation, but not for process optimization and controls.
- Indoor Air Quality sensors could mitigate safety concerns regarding wood heaters and CO poisoning and PM health effects.

Q2: Should data from the sensors be shared with the consumer? Should in-use data from the sensors be recorded and used by the manufacturer? Should that data be made available to local Government agencies? To what extent could manufacturers/researchers/regulators benefit from sensor data?

- Different groups (Homeowners/Manufacturers/Regulators) want different data
    - Homeowners want actionable data (%eff, output, fuel eco.)
    - Manufacturers want indicator data (T,O_2, flow rates, etc.)
    - Regulators want output metrics (usage, PM emission, etc.)

Poll Questions and Results:

P1: What is your background?

- Academia [52%]
- Industry [26%]
- Policy or Regulation [13%]
- Other [9%]

P2: What topic under "advanced controls" are you most interested in?

- Inputs/Outputs: Sensors, User-interface, and Electrical Requirements [68%]
- Data Collection: What kind, who can see it, and what's it for? [18%]
- Design Parameters: Safety, Regulatory, and Economic Concerns [14%]

Presentation Slides:

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Breakout Session B

POLL #1

What is your background?

1) Academia
2) Industry
3) Policy or regulation
4) Other

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Breakout Session B

POLL #2

What facet of "advanced controls" are you most interested in?

1) Inputs & Outputs: Sensors, user-interface, and electrical requirements
2) Data Collection: What kind, who can see it, and what's it for?
3) Design Parameters: Safety, regulatory, and economic concerns

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Breakout Session B

Breakout Session Logistics:

- Schedule – 10:50 to 12:00pm
- ZOOM format to be used
- Use the raise hand feature to ask for the mic
- Facilitators will be leading discussions and switching direction as appropriate
- There is a designated scribe in the breakout session taking notes. Notes will represent a collective summary and not specifically apply to individuals
- These sessions will **NOT** be recorded
- A summary and highlights of the session will be presented by one or more of the facilitators at the closing remarks
- Be bold, ask questions, bring up innovative solutions, identify problems
- Overall Goal of the Session –

1. How much can the topic area contribute to achieving far cleaner biomass combustion systems
2. What technology areas within this topic have the most potential to be impactful

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Breakout Session B

Meet the Facilitators:

Jeff Hallowell
Founder and Exec Chair
Biomass Controls PBC, a Public Benefit Corporation

Jessica Tryner, PhD
Research Scientist
Department of Mechanical Engineering, Colorado State University

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Breakout Session B

Topic # 1 Advanced Control Strategy – Inputs & Outputs

1. Sensors
2. User interface
3. External power sources

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Breakout Session B

Topic # 2 Advanced Control Strategy - Data

1. What kind?
2. Who can see it?
3. What's it for?

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Breakout Session C – Advanced combustion strategies

Date of workshop: January 11th, 2022
Number of participants: 45-48
Panelists: Elliot Levine (US Department of Energy, retired); Ingo Hartmann (Deutsches Biomasseforschungszentrum, gemeinnützige GmbH [DBFZ])
Note Taker: Vi Rapp (Lawrence Berkeley National Laboratory)

Introduction/Prompt:
Gasification and the use of combustion staging have shown improvements in emissions and efficiency. Direct air injection such as swirled air injection or swirled air direct injection are examples which have shown reductions in emissions and increases in efficiency. However, are there further improvements with novel airflow designs? What works and doesn't? This session also focused on using advanced control strategies to minimize emissions during startup and shutdown periods.

Questions and Responses from Panelists:

Q1: Direct air injection: How much more can we get out of this approach? What is the magnitude of the design change needed for integration? How will integration impact cost?

- Increasing velocity and maintaining low air volumes to reduce emissions and maintain thermal efficiency
- Automated control strategies to optimize combustion process
- Preheating secondary air

Q2: Improving startup/shutdown emissions: How much more can we get out of this approach? What is the magnitude of the design change needed for integration? How will integration impact cost?

- Accelerate startup/shutdown and reach steady-state faster

- Explore other combustion strategies from engines, turbines, etc. and see how they can be adapted (e.g., oxygen sensors, cold-start control strategies, etc.)
- Explore advanced sensors to characterize wood combustion and integrate with control strategies to optimize operation (e.g., measure hydrogen/carbon ratio).

Q3: Minimizing user interactions: How much more can we get out of this approach? What is the magnitude of the design change needed for integration? How will integration impact cost?

- Explore advanced sensors to characterize wood combustion and integrate with control strategies to optimize operation (e.g., measure hydrogen/carbon ratio).
  - Wood drying
  - Ensuring logs are loaded properly (split side down)
- Pull technologies from other industries. Identify what might work best with wood heaters and how they need to be modified.

Poll Questions and Results:
Not Used.

Presentation Slides:

Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session C - Advanced combustion strategies

Facilitators:

Elliott Levine
Board Member
Alliance For Green Heat

Ingo Hartmann
Prof. Dr.
DBFZ ("German Biomass Research Center")

Breakout Session Logistics:

Dialogue is encouraged: Please use the raise hand feature or chat with questions and comments

Be bold, ask questions, bring up innovative solutions, identify problems

A note taker will be recording collective ideas not specifically attributing to individuals. Zoom transcriptions may be logged for note taker to accurately summarize discussion. Sessions will **NOT** be recorded

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2

Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session C - Advanced combustion strategies

How to benefit from this Advanced Combustion Strategies session

Opportunities:

- Acquire knowledge of technology areas
- Access to experts
- Opportunity for collaboration and partnering (when speaking, identify yourself and your organization)

Outcomes:

- Guide focus areas for future FOA's
- Better proposals via teaming arrangements

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3

Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session C - Advanced combustion strategies

Potential Discussion Topics	Example State of the Art Methods
Direct air injection	Swirled air injection Secondary air direct injection
Improve air flow/path design (increasing exhaust residence time with firebox and heat exchanger designs)	Exhaust gas recirculation Gasification Twin flame design
Improving startup/shutdown emissions	
Other improvements	Novel materials to reduce heat transfer losses
Fuel type and loading	Continuous fuel feed
Minimizing user interaction	Continuous fuel feed Advanced controls

Note: Sensors and catalysts such as advanced control via O_2 or temp sensors are discussed in another session

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Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session C - Advanced combustion strategies

Performance Metrics for State of the Art

Type	PM Emission Rate (g/hr)	Efficiency (%)	Carbon Monoxide (g/min)
Non-catalytic Pellet Stove	0.2 - 0.4	75 - 85	0.004 - 0.04
Non-catalytic Wood Stove	0.5 - 1.0	70 - 80	0.38 – 1.2

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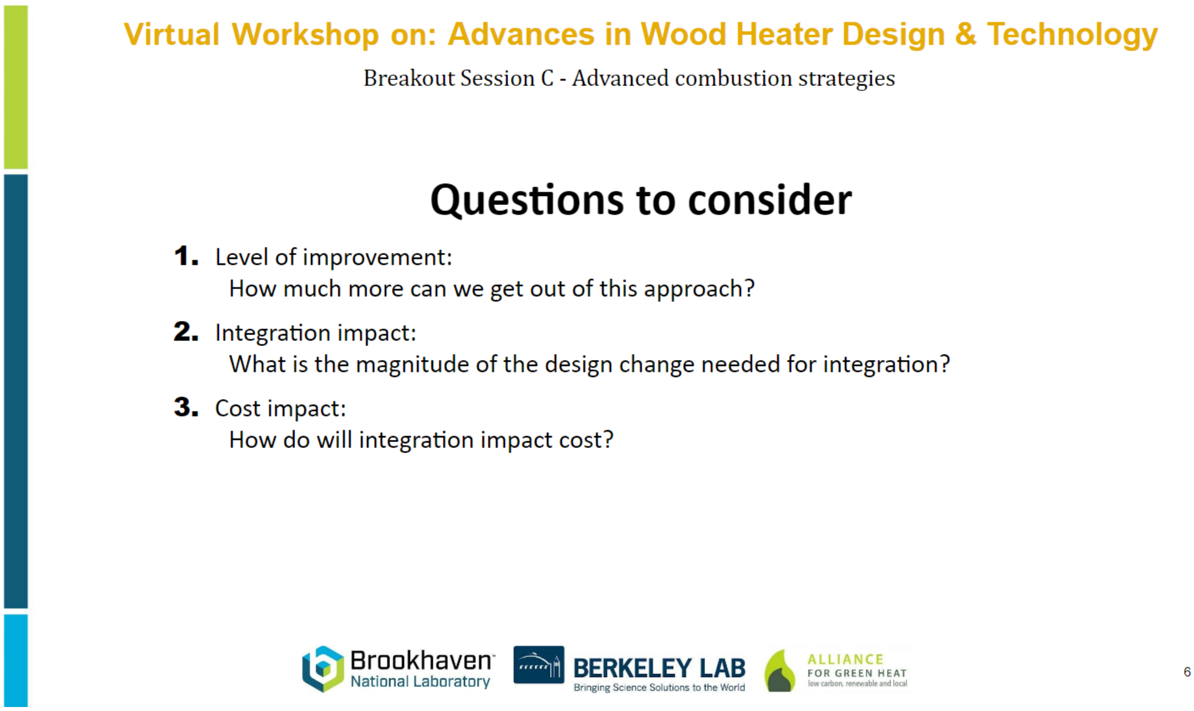


Breakout Session D – Improving Biomass Combustion Through Modeling

Date of workshop: January 12th, 2022
Number of participants: 20-25
Panelists: Paul DesJardin (SUNY Buffalo); Dimitris Assanis (Stony Brook University)
Note Taker: Thomas Butcher (Brookhaven National Laboratory)

Introduction/Prompt:
Modeling – including Computational Fluid Dynamics with Chemical Reactions – has contributed to the advancement of gas- and oil-burners and led to new, low-emission designs. In this Breakout Session, the potential for modeling to contribute in a similar way to future, low emission biomass combustion will be discussed.

Questions and Responses from Panelists:

Q1: What is most desirable from a residential biomass heating appliance modeling effort? What are specific metrics of interest from a modeling effort? Burn rate? Temperature? CO? PM? NOx? All equally important?

- Modeling should focus on robust design – being able to predict performance under off-design conditions. This includes wet fuels, poor loading practices, bad draft for example.
- It is not always clear what are the most important parameters are to focus on. Temperature is clearly important, but can we simplify other areas?

Q2: What are the greatest sources of uncertainty for modeling combustion of biomass heating appliances? What are the greatest sources of uncertainty for predicting emissions?

- Uncertainty about user interaction can lead to significant differences between model results and field experience.

- In modeling, natural draft stoves boundary conditions and modeling transient draft conditions is an important challenge.
- The boundary conditions for modeling are also a special challenge. Beyond draft, this includes the room that a wood stove is in, what the temperature and comfort profiles area, and how this all impacts performance.
- The modeling of soot / incomplete combustion products is particularly difficult and can impose significant computational costs.
- The coal bed is also very difficult to handle from a modeling perspective and has a large impact on performance.

Q3: To what extent can combustion modeling approaches from other communities, e.g., coal, solid rocket fuels, etc. be useful for biomass heating appliances?

- There was considerable discussion about the important role that modeling has played advancing the technology and reducing emissions from engines. In comparison the modeling of biomass combustion and heating appliances is at a very early stage.
- It would be valuable to document clear examples of the success of modeling in predicting the performance of a biomass combustion appliance.

Poll Questions and Results:

P1: Tell us about yourself – what is your background? Response (%)

- Academia [25%]
- National Laboratory [4%]
- Independent Laboratory [13%]
- Manufacturer [38%]
- Distributor [0%]
- End User [0%]
- Federal/State Regulatory Agency [13%]
- Other [13%]

P2: What is your experience with modeling? Response (%)

- Have sculpted Play-doh before [43%]
- Familiar with existence of/received training to use modeling software or CAE [29%]
- Used finite element analysis (FEA) software [7%]
- Use CAD software [57%]
- Use multidimensional modeling software (e.g. 2D/3D <u>non-reacting</u> flow) [21%]
- Perform <u>reacting</u> multidimensional simulations [21%]

P3: What is the largest hurdle to incorporate more modeling efforts for residential wood heaters / biomass combustion? Response (%)

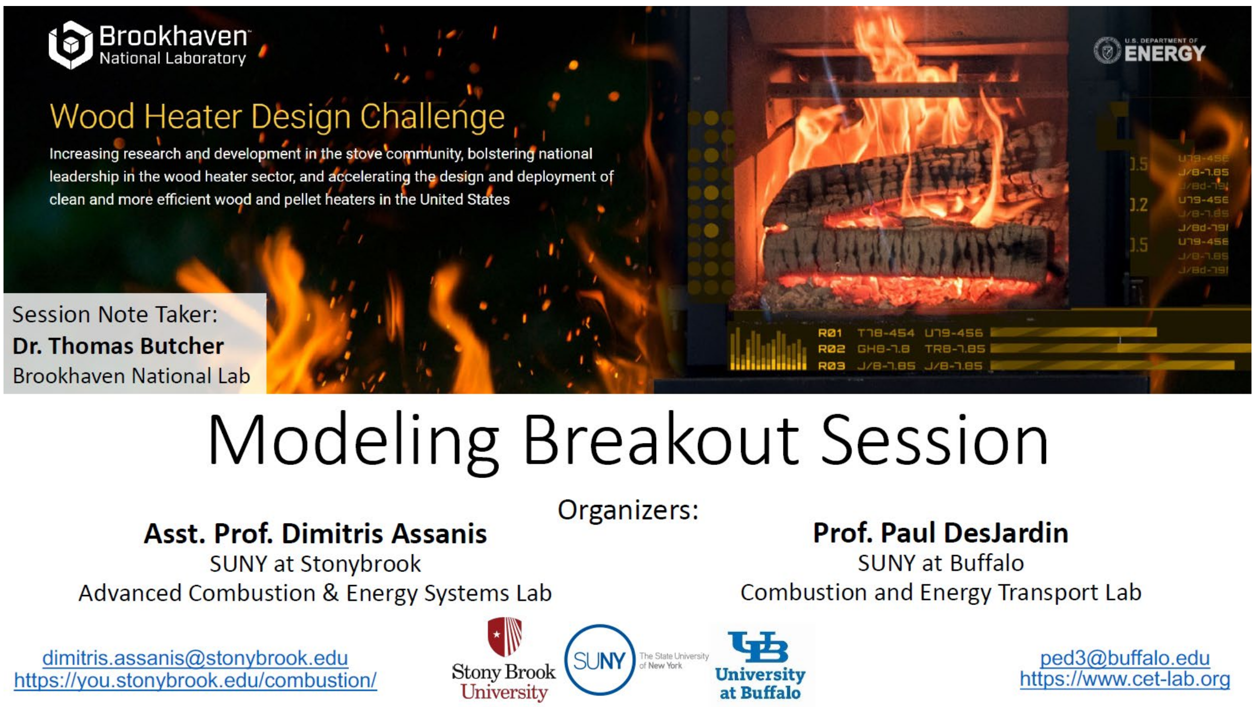
- Relevant experience [55%]
- Financials / cost [18%]
- Not enough time [27%]
- Models cannot address my problem [0%]

- My design does not need improvement [0%]

P4: Has your appreciation for incorporating modeling efforts into residential wood heaters/biomass combustion improved (Single Choice)? Response (%)

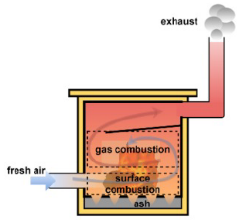
- I'm even more confused – I don't know how this will help me [0%]
- You've got me interested, but not enough to commit [10%]
- I'm cautiously optimistic to investigate modeling further [30%]
- Yes – I am ready for the fashion show [60%]

Presentation Slides:

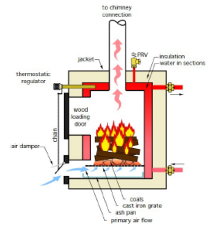


Residential Biomass Heating Systems

Cordwood Stoves [4,6]



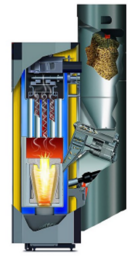
Cordwood Boilers [1,7]



Pellet Stoves [3]

Wood Chip Systems [2]

Pellet Boilers [5]



[1] Trojanowski, R. & Fthenakis, V. (2019). *Schematic of hydronic wood heater* [image] https://doi.org/10.1016/j.rser.2019.01.007

[2] Windhager (2016) *puroWIN* [Brochure]

[3] Quadura Fire (2022) CB 1200 [Brochure]

[4] Koraiem, M. & Assanis, A. (2021). *Schematic diagram of wood stove* [image] https://doi.org/10.1016/j.icheatmasstransfer.2021.105423

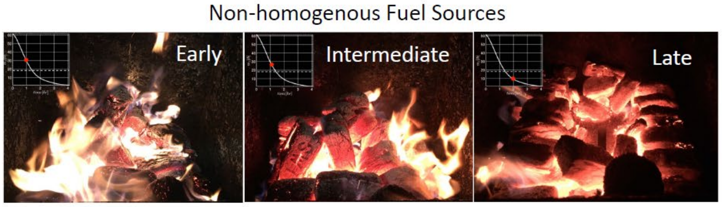
[5] Guntamatic (2013) *Product Overview [Brochure]*

[6] Quadura Fire (2022) *2100 Millennium Wood Stove* [Brochure]

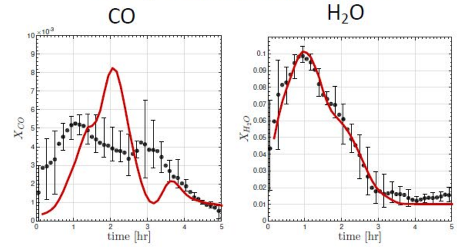
[7] Fröling (2022) *S3 turbo* [Brochure]

Modeling Challenges (to name just a few!)

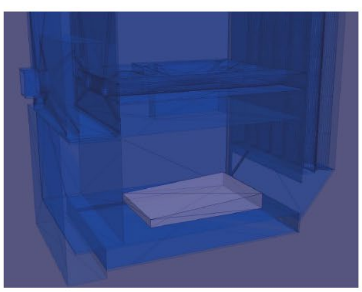
Non-homogenous Fuel Sources



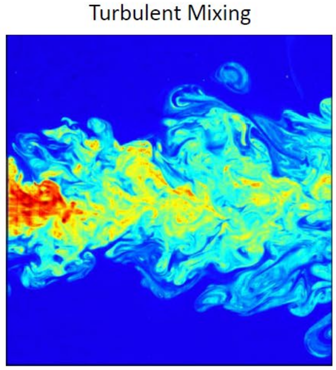
Multiple Chemical Time Scales



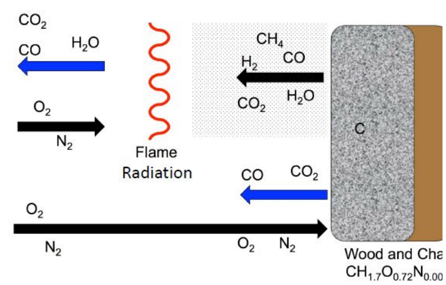
Complex Geometry and Coupling with Exterior Environment



Turbulent Mixing



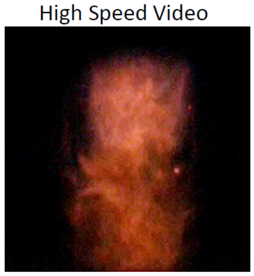
Radiation Heat Transfer



Example: Two-Stage Hydronic Heater

Upper Chamber

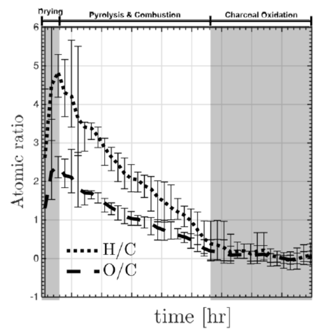
Lower Chamber
High Speed Video

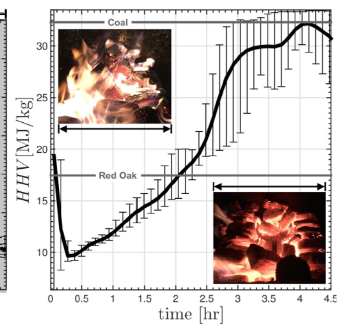


- Slowed down 300 times
- Approximate flow velocity (10 m/s)

Measurements

- Fuel mass (and rate) via load cells
- Air flow rate entering the blower
- Temperatures in upper/lower chamber and stack
- Stack using hand-held gas analyzer and laser absorption measurements
- Time dependent fuel decomposition defined by inverse methodology using measurements*

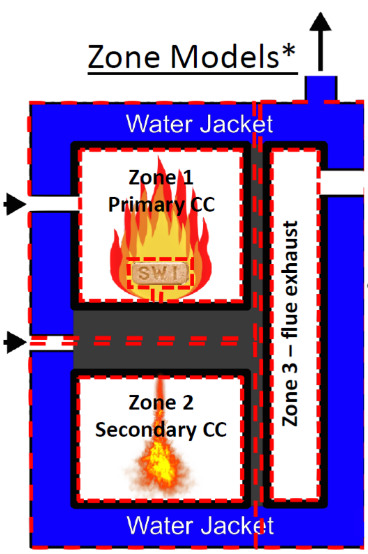




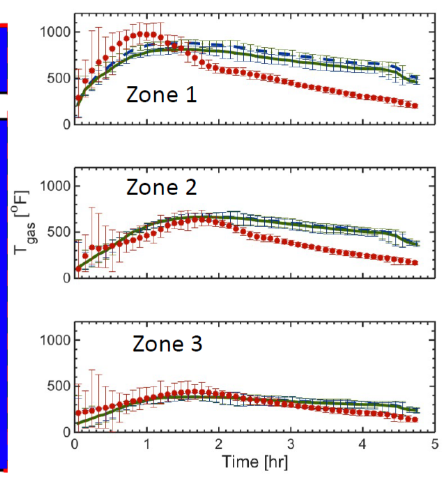
*"Emissions from a domestic two-stage wood-fired hydronic heater: Effects of non-homogeneous fuel decomposition," Renewable Energy, 112, pp. 187-196, 2017

Example: Two-Stage Hydronic Heater

Zone Models*

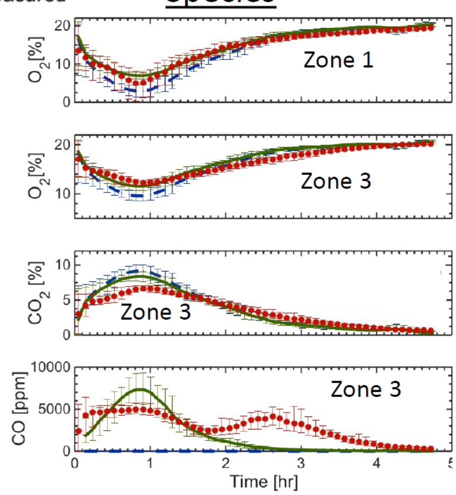


Temperature



- Model (Equilibrium)
- Model (Flamelet)
- Measured

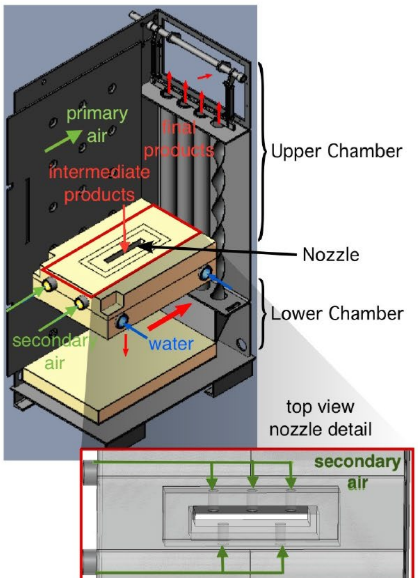
Species

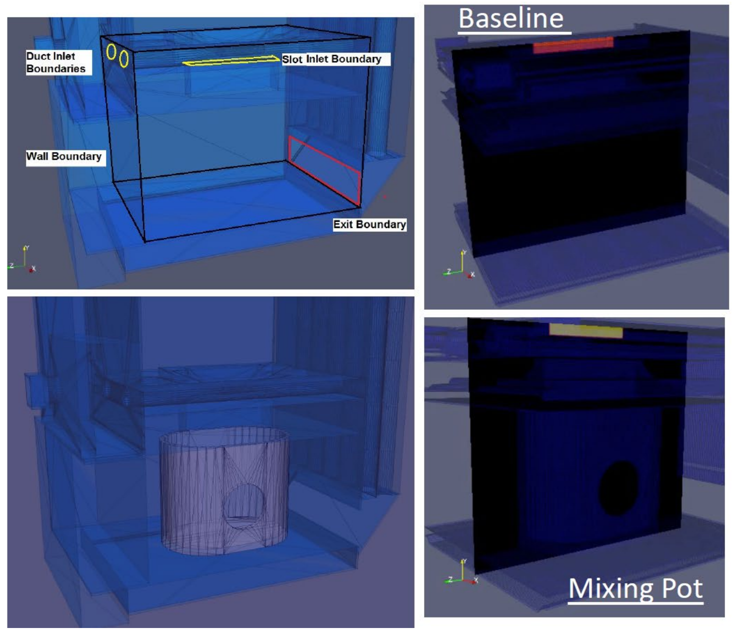


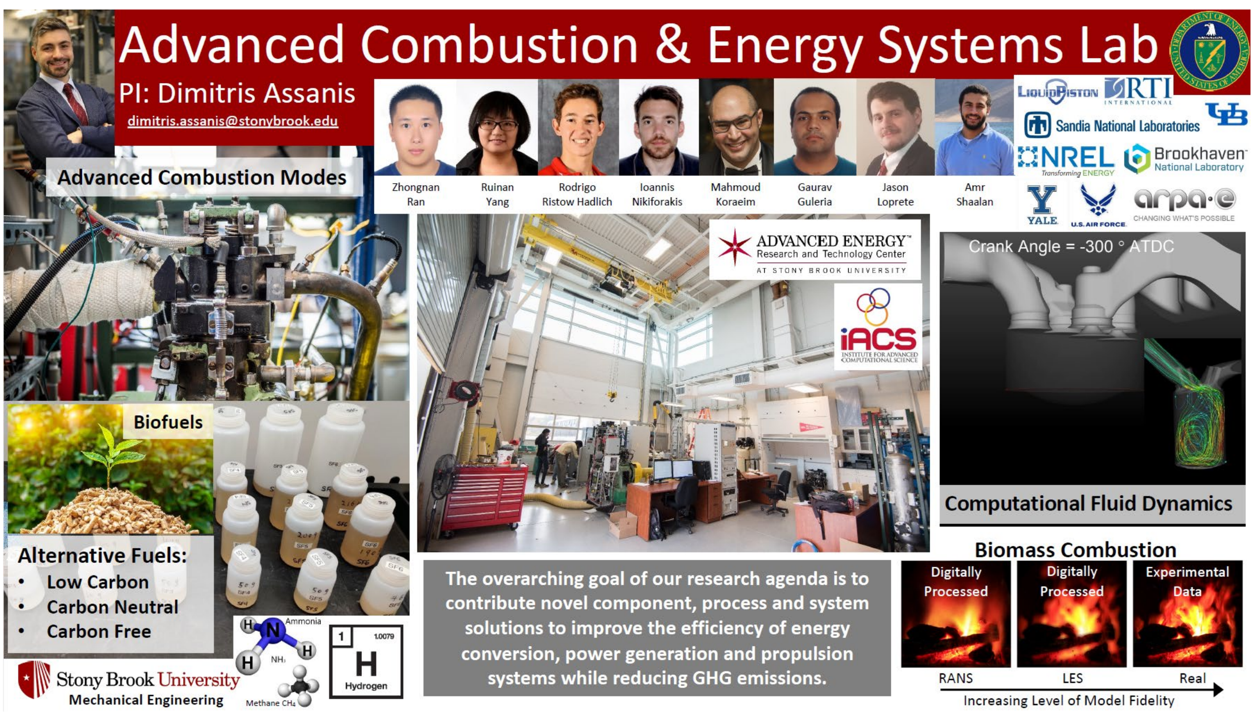
* "Measurements of fuel burn rate, emissions and thermal efficiency from a domestic two-stage wood-fired hydronic heater," Renewable Energy, 96, pp. 400-409, 2016
"Numerical modeling of homogeneous gas and heterogeneous char combustion for a wood-fired hydronic heater" Renewable Energy, 131, pp. 890-899, 2019

Example: Two-Stage Hydronic Heater

CFD Models (LES)







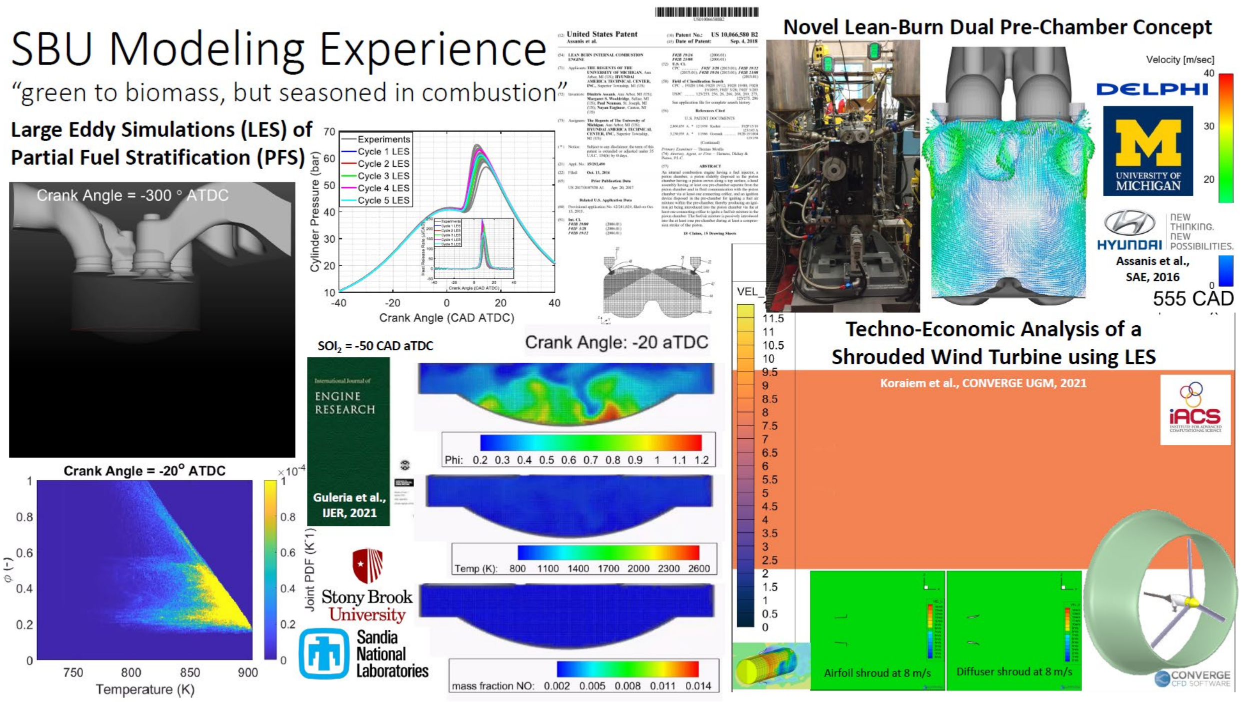
SBU Modeling Experience

"green to biomass, but seasoned in combustion"

Large Eddy Simulations (LES) of Partial Fuel Stratification (PFS)

Novel Lean-Burn Dual Pre-Chamber Concept

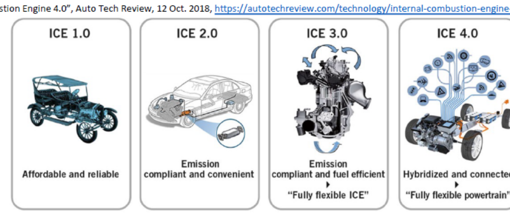
Techno-Economic Analysis of a Shrouded Wind Turbine using LES

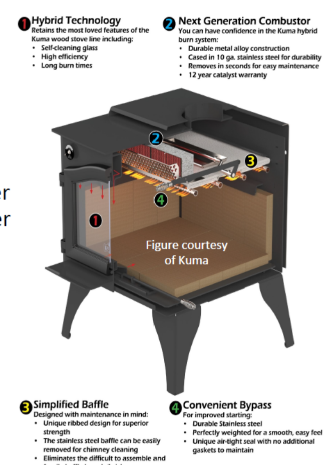


Dr. Dr Günter Fraidl, "Internal Combustion Engine 4.0", Auto Tech Review, 12 Oct. 2018, https://autotechreview.com/technology/internal-combustion-engine-4-0

What can modeling do for us?

- Experimental speciation measurements are needed to validate kinetic mechanisms. This is difficult environment because: "the fuel itself changes as we burn it!" (refer to Advanced Combustion breakout by Prof. DesJardin on O/C and H/C evolution as a function of burn duration)
- More detailed chemical kinetic mechanisms are needed for increases combustion accuracy
- What can 3-D reacting flow modeling do for us?
  - Improve our understanding of **Time**, **Turbulence**, and **Temperature** effects.
  - Redesign the combustion chamber geometry to improve heat transfer effects: Rectangular vs. Cylindrical vs. Spherical, single main chamber vs. multiple main chambers vs. multiple pre/main chambers.
  - Improve fluid motion and increase turbulence.
  - Modify airflow pathways => increase resonance time of incomplete combustion products => improve η_{comb}
- Detailed emission speciation needed for aftertreatment device modeling, specifically catalyst-surface based technologies.
  - Modeling chemical species inside chamber a different problem than inside the stack.





Where do modern residential wood stoves fall?

1.0?

2.0?

3.0?

4.0?

What can enable the advance?

Discussion Topics

- What is most desirable from a residential biomass heating appliance modeling effort?
- Are there examples of successful modeling efforts that have led to significant impact in the design and development of residential biomass heating appliances?
- What are specific metrics of interest from a modeling effort? Burn rate? Temperature? CO? PM? NOx? All equally important?
- What are the greatest sources of uncertainty for modeling combustion of biomass heating appliances?
- What are the most important processes to describe in porous media representations of chips and pellets? Are the internal dynamics of heat transfer, diffusion of water through pores, internal reactions, etc. equally important? Are Darcy law descriptions sufficient?
- Where is the role of flow turbulence most important? Pyrolysis region? Oxidation region? Both? Neither?
- What are the greatest sources of uncertainty for predicting emissions?
- How much can modeling contribute to achieving dramatically lower future emissions?
- To what extent can combustion modeling approaches from other communities, e.g., coal, solid rocket fuels, etc. be useful for biomass heating appliances?

Breakout Session E – Post combustion control strategies

Date of workshop: January 12th, 2022
Number of participants: 40-45
Panelists: Nordica MacCarty (Oregon State University); Mirjam Muller (Deutsches Biomasseforschungszentrum, gemeinnützige GmbH [DBFZ])
Note Taker: Caroline Solomon and John Ackerly (Alliance for Green Heat)

Introduction/Prompt:
Post control strategies such as catalysts and electrostatic precipitators (ESPs) can help mitigate emissions and recent trends in small scale ESPs and novel catalyst designs can help achieve lower emissions. What is the current state of the art, and how can we continue to advance this area?

Questions and Responses from Panelists:
Q1: Which technologies are available in practice and in science? What barriers exist to the action and implementation of post-combustion controls?

- One example - energy-efficient thermolytic afterburner developed years ago in Washington State Department of Ecology Retrofit Challenge/Stanford Mechanical Engineering Department - matched or exceeded emissions reductions associated with catalytic technologies
    - The thermolytic didn't have aging problem - performance doesn't deteriorate with use
    - Has to go immediately after the firebox - no secondary air, just stick it on the stack, create the afterburner directly in the exhaust stack this assumes there is enough oxygen left, but if not you could introduce secondary air
    - Not widely implemented although more demonstration could lead to increased utilization.
- Another example – catalysts which use high-temperature to oxidize wood smoke particulate matter. This solution sees widespread implementation in the US market, but it is an inefficient solution for start-up and catalysts require maintenance
    - The majority of emissions come during startup and it takes 3-5 minutes for catalysts to get to a temperature high enough for the catalyst to work
    - Black carbon and soot would be hard to get rid of with a catalyst, but if you get everything to 1500 Fahrenheit everything should burn
    - Metal oxide (manganese or copper) are good for oxidizing volatile gases and soot, i.e. generally reducing particle concentration
    - Noble metal catalysts (Platinum, palladium, rhodium) are good for oxidation of CO and volatile gaseous pollutants.
- Another example – Electrostatic precipitators (ESPs) which use high voltage to attract particles together or to collection substrates, thus removing the particulate from the flue gas. These systems are used commonly at industrial scales and in the residential scale in Europe. These devices also require maintenance.
    - In Germany and Switzerland, ESPs are required, but the U.S. has a lack of standards/information on how a European manufacturer should test an ESP, so European manufacturers are reluctant to sell in the U.S. Thus there is a need to engage EPA to determine if an ESP integrated in a stove will have any testing complications with M28
    - ESPs are incredibly effective, capable of 99% reduction in PM, but come at a high cost, on the order of 500-1000$ price increase.

        - One opinion (Germany) - In the future, all biomass combustion systems will need ESPs to reach zero emissions. In 5-10 years, stoves will not be sold without ESPs.
        - Another opinion (UK) – Due to heater use case and requirements, regulators and manufacturers are not expecting for ESPs to become common anytime soon.
        - Another opinion (US) - Regulations don't require ESPs, or the level of pollution control ESPs provide, so most assume they are not needed.
- It is important to demonstrate these technologies in the real world to show that these are real technologies that are proven to work and be safe. The reason this technology may not be so widespread right now is because there's still apprehension about it, but without adequate funding, it's hard to do risk assessment.

Q2: What are the critical points of failure which post combustion controls can address?

- In modern countries looking to electrify and reduce combustion emissions from all sources, biomass combustion will soon become only source of particulate emissions. Post-combustion controls are required to achieve near-zero PM emissions. Some in the group think this step must be taken or biomass won't be accepted as renewable heating option in the future.
- To reduce emissions to near-zero combustion has to be optimized for all draft levels and be impervious to poor user-practices, then to reduce emissions to a higher extent a catalyst or thermolytic and/or an ESP could be added.

Poll Questions and Results:
None used.

Presentation Slides:
None used.

Breakout Session F – Advanced hydronic heater design concepts

Date of workshop: January 12th, 2022
Number of participants: 45-48
Panelists: Marc Caluwe (Caluwe Inc.); Scott Nichols (Tarm USA, Inc.)
Note Taker: Rebecca Trojanowski (Brookhaven National Laboratory)

Introduction/Prompt:
Thermal storage and modulation have shown to have a positive effect in terms of emissions and efficiency performance, but their added cost continues to be a barrier.
can we move past that? What are the biggest advancements hydronic heaters have seen and how can we continue to do better?

Questions and Responses from Panelists:

Q1: Thermal storage: Does it matter / do we need it?

- Doesn't matter how big/small—we need it; Not because of emissions but we need water for units to "play" with. However if it is poorly installed, thermal storage can lead to poor performance
- Audience member said they were involved in a project with EPA to build an OWHH that produced 200,000 Btu's. Some units are too big for thermal distribution, however in these cases water storage was an optional

Q2: Are lambda sensors needed? How do they actually work?

- Lambda sensors are relatively uncommon and while their operation is intuitive and provides useful information, they are prone to failure. They can be undercut by temperature measurement, which provides less useful information, but are more robust sensors. Further in pellet systems fuel feed can be adjusted with temperature to get a similar result to using a lambda sensor.
- Lambda sensors require electricity and include a self-heating circuit and data connection. These multiple required functions can each fail suddenly, any one of which will result in a non-operational appliance. Further maintenance of the lambda sensor is required, but can result in damage.

Q3: Do we need to focus on “new” fuels

- Ultimately people consider their location, fuel costs, storage and site availability when choosing an appliance/fuel.
- People buy wood-fired appliances to save $ (primary reason). Sometime there is an environmental aspect but that is of lesser concern. Sometimes political reasons too (off-grid). But cost is the major driver.
- Wood chips are often an ideal fuel, because they are easier to handle, automate, and burn efficiently than cordwood, but are less expensive than pellets. However quality wood chips are often unavailable as drying the chips requires a near industrial process.
- The scale of the system often determines what you can burn

Q4: What does automation mean to in the context of Hydronic Heaters? Are we ahead already or what can we do?

- There are two sides to automating a hydronic heater, the combustion side, and the hydronic controls. Automation for hydronic heater combustion controls is still at a nacient stage, yet there was hesitation regarding what could be improved. It follows combustion control improvements may need to be addressed on an appliance-by-appliance basis. Hydronic controls are a universal component of all hydronic heating systems and thus improvements to these systems may provide wide-reaching benefits.
- For updraft-gasification pellet-fired devices the audience felt that these units fall short in regard to cleaning and refueling cycles/periods and suggested that a cascading combustion chamber design or thermal storage instead of back-up heat could reduce the burden of cleaning and refueling
- Safety is a primary concern for hydronic heater controls. In a power outage scenario the hydronic system must be failsafe to overheating, over-pressurization, and issues caused by pumps cycling off.

Poll Questions and Results:
None used.

Presentation Slides:

Virtual Workshop on
Advances in Wood Heater Design & Technology

Welcome to Breakout Session F

Advanced Hydronic Heater Design Concepts

Thank you for joining us.

We will begin our session shortly.

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Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session F - Advanced hydronic heater design concepts

Breakout Session Logistics:

- Schedule – 10:50 to 12:00pm
- Encourage dialogue – via raise hand feature or chat
- Facilitators will be leading discussions and switching direction as appropriate
- These sessions will **NOT** be recorded
- A summary and highlights of the session will be presented at the closing remarks
- Be bold, ask questions, bring up innovative solutions, identify problems

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Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session F - Advanced hydronic heater design concepts

Meet the Facilitators:

Marc Caluwe
President
Caluwe, Inc.
Biomass Heat and Power Solutions

CAL·U·WE
Biomass Heat & Power Solutions

Scott Nichols
President
Tarm Biomass, USA

TARM BIOMASS
Innovative Leaders in Alternative Heating Solutions

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Virtual Workshop on: Advances in Wood Heater Design & Technology

Breakout Session F - Advanced hydronic heater design concepts

How to benefit from this session

Opportunities:

- Acquire knowledge of technology areas
- Access to experts
- Opportunity for collaboration and partnering (when speaking, identify yourself and your organization)

Outcomes:

- Guide focus areas for future FOA's
- Better proposals via teaming arrangements

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4

Tell us about you!

- In the chat function, please indicate what your affiliation is:
- Manufacturer/Distributor
- Research Institution
- Academia
- Policy/Regulator
- Student
- General attendee

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Scott Nichols, Tarm Biomass

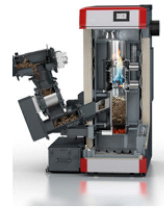
"feeling good about wood"

- 26 years in the wood-fueled hydronic heating business, which spans technology concepts from natural draft wood boilers to dry wood chip boilers with integrated ESP.
- Active participant in 5 oil and/or economic shocks- 2000, 2005, 2008, 2011, 2020. Watched 2010 "Peak Oil" come and go.
- Introduced the first Lambda controlled wood boiler in the U.S (2008).
- "Early" proponent of thermal storage as a second wave adoptee after knowledge base of the 1970s faded (1998).
- Introduced the first automatic, residential pellet boiler (2009).
- Introduced the first dry chip boiler (2013).
- Helped create ASTM 2618, especially the annex on PTS.
- Member of UL2523 Committee.
- Long term commercial relationships with 3 European boiler suppliers.
- Less scientist and more businessperson, with 26 years of real-world application experience.

1 800 STAY WARM
TARM BIOMASS®
Innovative Leaders in Alternative Heating Solutions

Learn more: https://woodboilers.com/

Mark Caluwe



- Caluwe Inc. was started in 2005 with a focus on residential heating with small European hydronic wood stoves.
- In 2010 Caluwe expanded its product offerings to include one of Austria's premier wood pellet boiler lines through an exclusive North American relationship with Windhager.
- Recognizing the need for proven wood chip technology, Caluwe expanded his line to include Heizomat, one of Germany's leading wood chip boiler manufacturers with over 35,000 installations globally.
- Windhager and Heizomat provide Caluwe with the ability to use diverse woody biomass fuels in a wide range of applications. In 2015 Caluwe entered a relationship with Spanner-RE2 to bring their micro-scale biomass fueled combined heat and power systems to the U.S. market.
- Through strategic relationships with numerous partner companies, Caluwe has the capacity to design, develop, install, and service projects throughout the country. Caluwe's 350+ installations stand as testament to its success as one of America's leading biomass system design/build companies.

Learn more: https://caluweinc.com/

CAL·U·WE
Biomass Heat & Power Solutions

Virtual Workshop on: **Advances in Wood Heater Design & Technology**

Breakout Session F - Advanced hydronic heater design concepts

Discussion Topics

- Best practices and advancements in wood-fired hydronic heaters
- Modulation
- Cold starts & burn out periods
- Hydronic stoves/room heaters
- Post combustion & retrofit technologies

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Appendix B: Notes taken for Workshop 2 Breakout Sessions: Advances in Instrumentation Used for Wood Heater Testing and Field Data Collection

Breakout Session A – Emissions sampling: Dilution tunnel vs. flue

Date of workshop: March 28, 2022
Number of participants: 53
Panelists: George Allen (The Northeast States for Coordinated Air Use Management - NESCAUM); Henrik Persson (RISE Research Institutes of Sweden); John Steinert (PFS TECO Hearth Products Group)
Moderator: Rebecca Trojanowski (Brookhaven National Laboratory)
Note Taker: Vi Rapp (Lawrence Berkely National Laboratory)

Introduction/Prompt:

Many countries have adopted national standards that limit pollution emissions from residential wood heaters, however these standards differ from country to country. This session will focus on the common experimental objectives and major components of such standardized methods as well as how they differ. The session will provide an understanding of the challenges and successes associated with different methods of testing– specifically focused on dilution sampling vs direct stack sampling. One question remains at large; whether or not direct stack sampling can be correlated to dilution tunnel sampling– this session will provide valuable insight into this question. Additionally, this session will also discuss ways to help simplify and modernize methods.

Questions and Responses from Panelists:

Q1: What are the advantages and disadvantages of testing directly in the stack vs in a dilution tunnel?

- Dilution tunnel is the only way to get a robust measurement of total and combustible PM. PM condenses in the atmosphere, especially for cord wood stoves, and a dilution tunnel more accurately measures/captures this process.
- Both have advantages and disadvantages. If you have good combustion with low HC, then you may have good correlation between stack and dilution tunnel. The worse the combustion, then the bigger difference between the two methods.
- Europe – measure particles in the stack without the condensable. Probe is heated, and then add measurement of hydrocarbons and particles. A dilution tunnel allows you to do both.
- Following Method 5A, a dilution tunnel is more widely accepted and gives a more accurate idea of PM emissions in the atmosphere.
- Method depends on interest. If comparing heater emissions, a dilution tunnel is the best option. For developing a computational model of the heater, then stack emissions may be better. Need to define what is the intended purpose is of the measurements. The strengths of each method depend on application.

Q2: What portion of the PM is condensable? Is measuring the condensable PM directly more accurate than measuring it separately in the gas phase and adding by calculation? If measuring directly in stack and getting total PM by calculation that means that we need to add a heated total hydrocarbons (HC) analyzer. Is that really easier than a dilution tunnel?

- Adding stack PM and HC together is not a great idea. Will add a level of uncertainty when doing calculations. Especially if combustion is bad. Recommend measuring both and establishing separate requirements.

- What portion of the emissions is condensable, depends on appliance and what is used to measure emissions. Measurements may be up to a factor of 2 difference for some portions of the burn. This measurement is most important for higher emitting (dirty) heaters.
- If measuring HC and PM separately, one would need to let the aerosol condense and condense properly (Note Method 5H using bubblers, which could be problematic for water soluble emissions). A heated PM and total HC analyzer is also needed to prevent particle formation. Given the complexity of measuring PM and HC separately in a stack, a dilution tunnel may be the better option.

Q3: Direct stack sampling is far simpler than setting up a dilution tunnel and so for manufacturers who have the ability to sample emissions from their heater's hot stack, how can we translate these results to what they may experience during compliance testing? Does sampling from a stack correlate at all to dilution tunnel tests? If not, why do we see differences?

- Do not recommend correlating stack emissions with dilution tunnel emissions. Past experience demonstrated that too many variables affected the correlation and results, which is why the industry dropped this approach.
- If you are a manufacturer, then need to account for condensables when doing R&D work. Unless it is a super clean pellet stove, the two methods may not track very well. To measure stack flow rate, an anemometer may provide better measurements than a pitot tube, given the low pressures.
- Semi-volatile PM is challenging to measure and the only robust method is using a dilution tunnel at high flowrates to prevent water condensation.
- Using a dilution tunnel in the field will be challenging.

Q4: As we transition to cleaner, more efficient units, we've seen in some cases that there is not enough PM captured and the amount that is captured is within the resolution of the scale. In this sense, hot stack sampling may be beneficial. Should we consider sampling in the stack to account for this?

- Do not change the method. Recommend a dilution tunnel over hot stack sampling, and also purchasing a more accurate balance.
- Method is robust. Do not cut corners. Also, do not reduce dilution tunnel flows to increase PM mass because water from combustion may condense in the sample train (<500-600 cfm).
- A TEOM has plenty of precision and could also help.

Q5: As we see shifts in tests methods that consider multiple load profiles with varying burn rates, do we need to think about how to accurately measure the emissions over an entire burn event. For instance, the dilution tunnel test method in this sense provides a nearly constant sampling conditions regardless of the burn rate while sampling from the stack does not allow for as easy of an evaluation with the changing mass flow of the flue gas. A great advantage of a dilution tunnel is the velocity is high and nearly constant, so easy to measure. That gives us the ability to calculate things like CO emission rate real time. When measuring in the stack we have a challenge to deal with integrating over different load (burn rate) conditions. Is stack measuring only good for steady state tests?

- Measure CO in all places, stack and dilution tunnel.

Q6: Considering both hot stack sampling or dilution tunnel methods, do the emissions measurements accurately reflect the emissions that would come out of the stack? Are our 'bottom up' emission inventories accurate for modelers—do they match 'top down'?

- Other factors may impact emissions inventories in models more than PM measurements. For example, fuel usage, condensables, and establishing methods that provide repeatable/reproducible measurements.
- Challenging to get a good, repeatable measurement from the stack from test to test.
- For characterizing real-world use, several variables may have a significant impact but may be hard to quantify or repeat. For example, user-interaction/loading. Consumers may not operate their stoves like we do in the lab.
- Automated wood heaters may be a good option for minimizing human error/use on emissions.

Closing Remarks from Panelists:

- Do not recommend trying to correlate stack and dilution tunnel emissions, especially more polluting heaters.
- PM is defined by how you measure it. If the goal is to reduce impact on human health, then measuring condensable PM is critical. Consistency is also very important when doing test procedures.
- Keep asking questions so we can better quantify and address issues. This will help improve test methods, and figure out how to make ends meet.

<u>Questions from audience:</u>

Q1: What do the models look at for a complete picture of PM? How do you convert DT measurements to an EF to an inventory that could get fit into a model that then gets speciated? Concerned dilution measurement might not give an accurate representation of VOCs. Need an EF to feed into AQ models and AQ management system.

- Emission factor drops out from methods, so you should be able to use those directly. Dilution factor is a variable. The more dilution, the lower the measurement of PM will be.

Q2: Confused by last poll, where majority of participants say there isn't an easy correlation between DT and stack. If the accepted knowledge is that they don't correlate easily, then how do we know what is coming out of the DT has any relevance to the appliance? In theory they should correlate, right? How do you correlate dilution tunnel measurements from one facility to another? Should they compare at all?

- Defining a standard dilution tunnel setup would help minimize variability between test facilities. Currently, dilution tunnel parameters are not well controlled by the test methods. Every lab does not have the same dilution tunnel.
- Particles will change once they hit ambient air. Requirements of particle is set to specific method. To understand impact on ambient air is more difficult and more complicated.
- What is the PM measurement for? Need to understand the purpose of your measurements and what you are trying to optimize (see stack vs dilution tunnel from Q1).

Poll Questions and Results:

P1: Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid)

- Certified Test Lab [4%]
- Research Organization [26%]
- Federal or State Agency [22%]
- University / College [15%]
- Manufacturer of wood heater stoves, furnace, hydronic, hybrid) [30%]
- Non-Governmental Agency (NGO) [0%]
- Other [4%]

P2: What is one thing you hope to gain from this session?

- To discuss the accuracy and end-metrics of Flue Stack and Dilution Tunneling sampling [50%]
- To learn more about how one might apply one of these sampling techniques to their own wood heating appliance [36%]
- Networking/Partnering/Teaming [4%]
- Other [%]

P3: Which method gives PM emission measurement closest to real-life exposure numbers Flue Stack or Dilution Tunnel (DT).

- Flue [22%]
- DT [78%]

P4: Which method is easier to accomplish Flue Stack or Dilution Tunnel (DT)?

- Flue [65%]
- DT [35%]

P5: Which sampling method is most cost effective?

- Flue [52%]
- DT [48%]

P6: Do Flue Stack and Dilution Tunnel test methods truly correlate, can the Flue Stack measurement methods be related to Dilution Tunnel methods with a simple formula?Yes. DT = m*FS+b.

- Yes. [4%]
- Yes, but the correlation is not simple. [63%]
- No correlation, or too many variables. [33%]

P7: For Dilution Tunnel sampling of wood heaters, what portion of the PM measurement technique contributes most to error in the emissions factor?

- Filter weight measurements [17%]
- Gas flow measurements [30%]
- Source conditions (flow pattern/stratification) [39%]
- Temperatures [9%]
- Other [4%]

P8: For Flue Stack sampling of wood heaters, what portion of the PM measurement technique contributes most to error in the emissions factor?

- Filter weight measurements [22%]
- Gas flow measurements [35%]
- Source conditions (flow pattern/stratification) [22%]
- Temperatures [13%]
- Other [9%]

Comments: The errors between the DT and stack differ.

Presentation Slides:

Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Welcome to

Breakout Session A

Emissions sampling:

Dilution tunnel vs. Flue Stack

Thank you for joining us.

We will begin our session shortly.

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Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Breakout Session Logistics:

- Schedule – 12:00 to 1:00pm
- ZOOM format to be used
- Use the raise hand feature to ask for the mic
- Facilitators will be leading discussions and switching direction as appropriate
- There is a designated scribe in the breakout session taking notes. Notes will represent a collective summary and not specifically apply to individuals
- These sessions will **NOT** be recorded
- A summary and highlights of the session will be presented by one or more of the facilitators at the closing remarks
- Be bold, ask questions, bring up innovative solutions, identify problems

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Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

PRE-SESSION POLL QUESTION

What is your area of expertise/background (one-choice)?

- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid)
- Certified Test Lab
- Research Organization
- Federal or State Agency
- University / College
- Non-Governmental Agency (NGO)
- Other

What is one thing you hope to gain from this session?

- To discuss the accuracy and end-metrics of flue stack and dilution tunnel sampling
- To learn more about how one might apply one of these sampling techniques to their own wood heating appliances
- Networking/Partnering/Teaming
- Other

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Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Meet the Panelists:

George Allen
Chief Scientist
Northeast States for Coordinated Air Use Management (NESCAUM)

Henrik Persson
Senior Technical Advisor
Research Institutes of Sweden (RISE)

John Steinert
Vice President, Hearth Products Division
PFS TECO Hearth Products Group

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Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

SESSION POLL #1 QUESTIONS

Which sampling method gives a PM emission measurement closest to real-life exposure?
- Flue stack
- Dilution tunnel

Which sampling method is easier to accomplish?
- Flue stack
- Dilution tunnel

Which sampling method is most cost effective?
- Flue stack
- Dilution tunnel

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Breakout Session A

Question # 1:

Speaking very generally for perhaps the folks who are not familiar with testing, what are the advantages and disadvantages of testing directly in the stack vs in a dilution tunnel?

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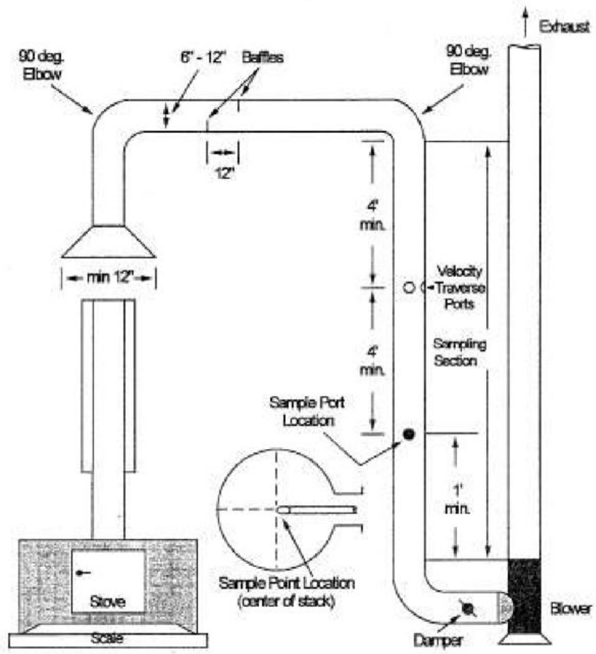

Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Question # 2: (*two-part*)

- **What portion of the PM is condensable?**
- **Is measuring the condensable PM directly more accurate than measuring it separately in the gas phase and adding by calculation? If measuring directly in stack and getting total PM by calculation that means that we need to add a heated total hydrocarbons analyzer. Is that *really easier* than a dilution tunnel?**

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Breakout Session A

SESSION POLL #2 QUESTIONS

Do Flue Stack and Dilution Tunnel test methods truly correlate, can the Flue Stack measurement methods be related to Dilution Tunnel methods with a simple formula?

- Yes.
- Yes, but the correlation is not simple.
- No correlation, or too many variables

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Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Question # 3: (three-*part*)

- **Direct stack sampling is far simpler than setting up a dilution tunnel and so for manufacturers who have the ability to sample emissions from their heater's hot stack, how can we translate these results to what they may experience during compliance testing?**
- **Does sampling from a stack correlate at all to dilution tunnel tests?**
- **If not, why do we see differences?**

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Breakout Session A

SESSION POLL #3 QUESTIONS

For Dilution Tunnel sampling of wood heaters, what portion of the PM measurement technique contributes most to error in the emissions factor?

- Filter weight measurements
- Gas flow measurements
- Temperatures
- Source conditions (flow patter/stratification)
- Other

For Flue Stack sampling of wood heaters, what portion of the PM measurement technique contributes most to error in the emissions factor?

- Filter weight measurements
- Gas flow measurements
- Temperatures
- Source conditions (flow patter/stratification)
- Other

Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Question # 4:

As we transition to cleaner, more efficient units, we've seen in some cases that there is not enough PM captured and the amount that is captured is within the resolution of the scale. In this sense, hot stack sampling may be beneficial. Should we consider sampling in the stack to account for this?

Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Question # 5:

As we see shifts in tests methods that consider multiple load profiles with varying burn rates, do we need to think about how to accurately measure the emissions over an entire burn event. For instance, the dilution tunnel test method in this sense provides a nearly constant sampling conditions regardless of the burn rate while sampling from the stack does not allow for as easy of an evaluation with the changing mass flow of the flue gas. A great advantage of a dilution tunnel is the velocity is high and nearly constant, so easy to measure. That gives us the ability to calculate things like CO emission rate real time. When measuring in the stack we have a challenge to deal with integrating over different load (burn rate) conditions. Is stack measuring only good for steady state tests?

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Virtual Workshop on: Advances in Instrumentation used for wood heater testing and field data collection

Breakout Session A

Question # 6:

Considering both hot stack sampling or dilution tunnel methods, do the emissions measurements accurately reflect the emissions that would come out of the stack? Are our 'bottom up' emission inventories accurate for modelers—do they match 'top down'?

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Breakout Session B – Thermal performance: Direct and indirect methods

Date of workshop: March 28, 2022
Number of participants: 20-30
Panelists: Phil Hopke (Clarkson University) and Sebastian Button (PFS TECO)
Moderator: Thomas Butcher (Brookhaven National Laboratory)
Note Taker: John Ackerly (Alliance for Green Heat)

Introduction/Prompt:
Direct methods for determining energy output, burn rate, and thermal efficiency typically involve direct fuel input and direct heat output rate measurement. Indirect methods involve measurement of flue gas and (possibly) jacket losses. In this session measurement options and accuracy issues for the use of both of these measurements will be discussed. Applications can strongly impact the selection of the method, and this includes stoves, hydronic heaters, warm air furnaces, and emerging hybrid systems.

Questions and Responses from Panelists:

Q1: Moisture content can affect thermal performance. How do we handle it?

- Firewood in the top of stove much colder than bottom and moisture content is variable.
- Pellets generally have more uniform and similar average moisture content
- Wood chips can have variabile moisture content between individual chips. It would be challenging to measure moisture content of each chip.

Q2: How can we accurately measure CO and CO2 in the flue?

- Challenge is obtaining the right instruments and also knowing where to measure in the flue. Also need to know emissions variability (i.e., if pollutants are uniformly mixed) and range in the flue
- One recommendation to place flue gas probe in center of flue. Not sure if its significant in different parts of flue.
- Some believe the flue should be turbulent enough to uniformly mix gases - unless there is an air leak.
- When sampling, one should be careful about having impact on draft. There should not be air leaks in a new boiler but may be leaks in appliances in the field.
- Non-uniform flue gas is difficult to quantify. Also could have rapid changes in flue gas composition during cycling in pellet stoves or during start-up.
- Is unburned fuel loss in ash sufficiently accounted for?

Q3: Is it better to measure thermal efficiency directly or indirectly? It is trickier to measure thermal performance from a heater since we have radiation from stack and the heater. Should we apply indirect methods for one class of heater and direct for another?

- Direct methods for measuring thermal efficiency require measurements of radiative emissions, necessitating a calorimeter room, which are accurate but expensive facilities. In contrast indirect measurements are less accurate, but can be made without expensive facilities. Both methods are more accurate than the standard assumption of 75% which is included in the certification method.
- Best to measure direct. Indirect is easier because you can ignore some sources of error. For boilers - direct method works.
- As we go to the Integrated Duty Cycle (IDC), trying to determine efficiencies for different phases will be problematic. Unclear if this is important for overall certification, but it is an important tool for improving technology.

Q4: In warm air furnaces, how well can we measure exhaust flow?

- We can reasonably measure exhaust flow, but it still challenging to do accurately.

Q5: For real-time mass flow rate of the exhaust gases, what are the most effective methods?

- a high temp vane anemometer can be used to get idea of burn rate. You could also measure air flow on the input side.

Questions from Audience:

Q1: There seems to be an inverse relationship between cleanliness and efficiency because you need more heat to get clean, leading to higher stack temps. How do we balance between long burn times and cleanliness?

- Manufacturers are incentivized to say they can get long burn times. Not sure how to address this.

Q2: Will the NYSERDA Integrated Duty Cycle (IDC) Protocols for EPA Wood Stove Test Methods change operation?

- End point of burn cycles)is at 90% so it cuts off tail.
- Integrated Duty Cycle test methods may eliminate low-temperature, charcoal combustion phase of tests.

Q3: Does UK ban stoves with low burn rates?

- Unanswered

Q4: Can you back-calculate mass flow rate if you know air flow?

- Yes, CSA B415 includes a calculation spreadsheet and relevant data to use.

Q5. Can you use feed augur burns for input rate?

- Size of pellets can vary federate dramatically. Up to 20% difference with different brands. Maybe PFI pellets are more uniform.

Poll questions and Results:

None used.

Presentation Slides:

None used.

Breakout Session C – Emission measurement instrumentation: PM and gaseous pollutants

Date of workshop: March 28, 2022
Number of participants: 24-39
Panelists: Amara Holder (US Environmental Protection Agency), Casey Quinn (Colorado State University), Jake Lindberg (Brookhaven National Laboratory)
Moderator: Julien Caubel (Lawrence Berkeley National Laboratory)
Note Taker: Amanda Sirna (Stony Brook University)

Introduction/Prompt:
Traditionally, laboratory testing of biomass heaters has focused on measuring the mass of particulate matter (PM) pollution emitted from the chimney using gravimetric filters. While gravimetric PM measurements are certainly an important indicator of air quality impacts and combustion performance, biomass appliances emit other harmful pollutants that merit monitoring, and instrumentation has advanced significantly in recent years. In this session, we will discuss the particulate and gaseous pollutants that are key to characterizing the emissions performance of wood heaters, and new or novel methods for measuring these emissions in the lab. An accurate and expanded understanding of air pollution from wood heaters is critical to informing the development of improved combustion technologies, and effective public policy to protect human health and the environment.

Questions and Responses from Panelists:

Q1: What do you think is the "best" way of collecting real-time PM mass concentration data to supplement gravimetric filter readings?

- All panelists saw great value in time-resolved PM data, as it allows for characterization of emissions during different combustion and use phases: Start-up, steady state, shutdown, and others. Emission levels can vary by over an order magnitude during different phases, so it is important to characterize them individually such that they can be effectively targeted for improvement. Typically, cold start emissions are much greater than those during steady state, for example.

- TEOM is an instrument commonly used for ambient pollution monitoring in regulatory circles, and can be effectively leveraged for characterizing wood heater emissions. It collects PM on a disposable filter, which must be changed regularly. Since PM levels are so high during heater testing (relative to ambient), this means that filter in TEOM must be changed often – this can be problematic during testing, as data is lost during the filter changes, and standardized protocols dictating the frequency of filter changes are lacking – some efforts are underway at IDC to publish such protocols. The TEOM measurements must be calibrated relative to gravimetric filters. Precision of the instrument has been demonstrated for concentrations as low as 0.1 mg/m^3.

- Optical instruments are good assessing qualitative trends over time, but it can be hard to get good quantitative results relative to gravimetric results – the measurement proxy is just too far removed from mass concentration, and dependent on a wide range of external factors: chemical composition, size distribution, etc. Some instruments, like PDR, come with back-up gravimetric filters built right into the unit so that calibrations can be readily conducted. Two main types optical instruments are used: (1) Nephelometer, which uses light scattering to infer particle number concentrations, and (2) Optical particle counter (OPC), which uses interruption of the laser beam to infer particle size and number concentration. Both are common in combustion studies.

- None of the panelists or audience members have experience using BAM (Beta Attenuation Monitor) for heater testing – this class of instrument does not seem to well adapted for combustion studies.

Q2: Besides measuring the mass of PM emitted (either time-integrated or time-resolved), what other PM characteristics are important to monitor?

- Currently, the main focus of biomass emission studies are PM and the six other air toxics regulated by the EPA.

- $PM_{2.5}$ is an important emission metrics relevant to health and environmental impacts, but biomass heater testing could be overly reliant on this single measurement. Ultrafine particles, black carbon, carbon monoxide, and other metrics should be considered for widespread integration into the testing process.
    - PM2.5 is the key measurement metric for heater testing because there are decades of data showing that elevated PM2.5 concentrations are closely related to adverse health outcomes. As such, it generally serves as a health indicator, rather than a means of gauging combustion quality.
    - One audience member mentioned that PM10 is really a measure of the wood ash in the emissions, and does not serve as meaningful health metric because it is too large for ingestion and made of inert chemicals – the validity of this statement is uncertain, but worth mentioning here. The same audience member suggested that PM10 can be reduced by simply reducing turbulence in the combustion chamber, thereby reducing entrainment of ash into the exhaust. Again this observation is probably not so clear cut, and it should be noted that since turbulence is a key ingredient for clean and efficient fuel combustion, reductions may not provide straightforward benefits.

- Ultrafine particles, with a diameter < 100 nm (0.1 um) are of increasing interest to measure. Ultrafine particles are more readily inhaled and deposited in the lungs, and so may be more important drivers of adverse health impacts. Ultrafine concentration measurements are relatively new, however, and so more data is needed to establish clear health correlations, and establish this measurement as a regulatory metric.

- Smoke opacity measurements are regulated emissions metrics in some regions, but measurement techniques are not commonly used in laboratory (Note: None of the panelists include opacity in their lab instrumentation).
    - Opacity can be useful for evaluating combustion quality. Measuring the opacity of heater emissions is an old technique first introduced in UK in the 1950's. The measurement is quantified in terms of 'smoke number' where the higher the number, the more opaque (light-absorbing or 'black') the smoke is.
    - Opacity is an enforcement metric is some European countries and US states – heaters can be reported for emitting smoke that is too black.
    - Opacity is not part of EU regulations, but some countries (including UK) still regulate this metric.
    - Opacity can be measured relatively easily and in real-time.

- Opacity is driven by particle size, concentration, and light-absorption cross section. In lab setting, these underlying factors are measured directly, rather than opacity.
- Note that aethalometer is used to measure the light-absorption properties of particles, but does not measure opacity. Opacity is the light-absorption of the particles suspended in exhaust flow, and is driven by airborne concentration and other factors, while the aethalometer measures the absorption cross section of the particles collected on filter. For example, highly absorbing particles (as measured using aethalometer) do not necessarily result in very opaque emissions given low concentrations.
- Opacity and particle absorption are both indicators of poor combustion.

- Black carbon is the light-absorbing portion of particulate matter emissions. Elevated black carbon concentrations are a strong indicator of poor combustion processes. As such, black carbon may also a be health-relevant metric, as other toxic emissions are released by poor combustion. Like ultrafine particles, black carbon is not a regulated metric, and more data is needed to establish its influence on human health. It's impact on climate is well-known, however: Black carbon is the second stronger driver of climate change, after carbon dioxide. It is a powerful absorber of infrared radiation (by definition), and therefore contributes to the greenhouse effect.

Q3: Which gaseous emissions do you monitor?

- Carbon monoxide is another strong indicator for gauging combustion quality and health impacts. Carbon monoxide is formed when combustion conditions are insufficient to fully oxidize the carbon fuel into carbon dioxide (too cold, insufficient oxygen or mixing). Other pollutants, such as hydrocarbons and VOCs, oxidize in roughly the same conditions as carbon monoxide. Therefore, reducing carbon monoxide emissions is generally a good way of quantifying combustion improvements, and reducing harmful emissions as a whole. It is also well known that carbon monoxide is toxic, so emission reductions have clear benefits for human health.
- Organic PM precursor gas emissions are new and emerging field. Biomass combustion emissions contain high levels of toxic, volatile organic compounds (VOC) that can form particulates in the atmosphere under the right conditions (after emission from the flue in gaseous form). Currently, it is difficult to quantify or characterize VOC emissions. In order to get a meaningful understanding of these emissions and how they contribute to PM pollution, it is necessary to characterize their chemical composition and volatility. Currently, time-resolved measurements of these factors can only be gathered using mass spectrometers and other expensive equipment that is difficult to operate and interpret. Some studies also use filters in combination with sorbent tubes to provide time-integrated measurements. Even when these measurements exists, it is difficult to quantify how much secondary PM formation will result from these emissions, as the underlying pathway are not well understood.
    - Biomass heaters are certainly a significant source of oxygenated VOCs relative to other pollution sources, such as transportation, and early studies to better quantify these emissions are ongoing.

Q4: How do we accurately characterize heater performance? How do we balance thermal and emissions performance?

- Effective heaters must address both thermal performance and emissions reductions. Neither of these aspects can be treated alone. Since the high efficiency heater may be operated for shorter periods with less fuel (given the same demand), improvements in one performance area may translate to the others, and vice-versa.

- To provide quantifiable metrics that address thermal and emissions performance simultaneously, emission metrics should be normalized by the thermal power delivered (KWd). For example, instead of reporting the total mass of PM emitted per hour or mass of fuel consumed (as is traditionally done in regulatory circles), these mass emissions should be reported in g of PM per KW of heat delivered to the user. This normalization captures the heater's end utility, and provides an accurate means of quantifying both emissions and thermal performance simultaneously.

- Note: This topic was discussed briefly but did not inspire much conversation amongst participants. Generally, it seemed that the audience agreed with normalizing performance by power delivered, but there was no discussion of why these metrics are not currently adopted for regulatory reports or heater evaluations in general.

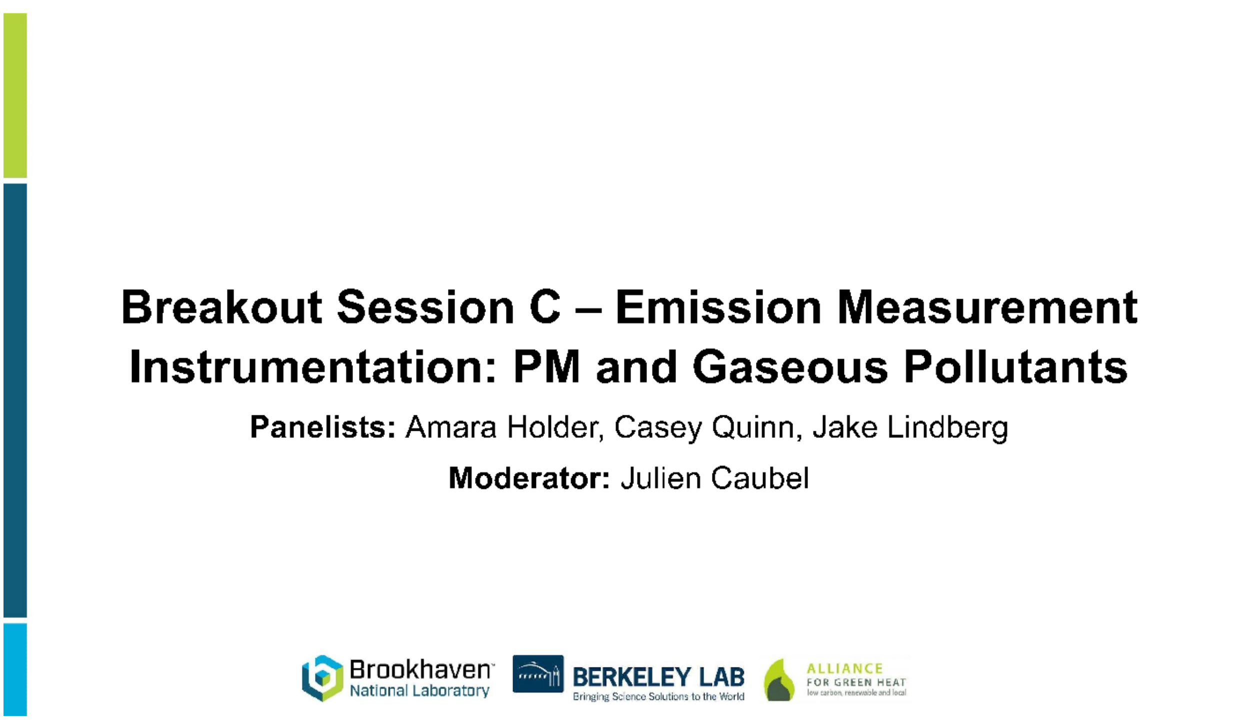
Q4: What equipment is needed to evaluate heater performance sufficiently and accurately?

- Meaningful heater testing can be conducted with a relatively limited set of instruments o Oxygen and carbon monoxide measurements are the basic metrics needed to evaluate combustion quality and thermal performance. Using these data and information on the fuel energy input, thermal efficiency can be calculated using the indirect method. o PM is the most important emissions measurements for evaluating health and environmental impacts. Other toxic pollutants (as defined by EPA) can be added for more in depth evaluation.

Poll Questions and Results:

- None used.

Presentation Slides:



Amara Holder is a research mechanical engineer with the U. S. Environmental Protection Agency Office of Research and Development. Her research is on understanding the physical, chemical, and optical properties of combustion generated particles and the processes that determine these characteristics. She has studied numerous combustion systems including woodstoves, cookstoves, wildland fires, diesel generators, and crude oil burns.

Casey Quinn is a Research Scientist at Colorado State University and a Mechatronics Engineer for Access Sensor Technologies. He holds a B.S. and M.S. in Mechanical Engineering and a Ph.D. in Environmental Health with an Industrial Hygiene specialization. His research focuses on the development of low-cost sensors for use in exposure science to evaluate air and water quality.

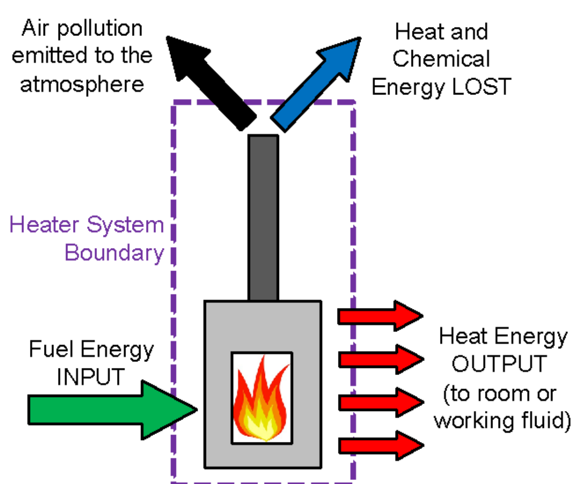
Dr. Jake Lindberg (he/him/his) is a recent graduate from the Chemical and Molecular Engineering Department at SUNY Stony Brook. He did his PhD research in biomass combustion, in conjunction with BNL, with a focus on combustion particle emissions, including measurements of particle mass, number, size and composition.

Emissions Characterization

"What"
- How much MASS of pollution emitted per:
  - Unit of time
  - Mass of fuel
  - Energy (or power) delivered

"Why"
- Impact evaluation: Health and environment
- Heater design development: Data to improve
- Regulatory compliance: Am I in spec?

"How"
- Lab facility
- Instrumentation
- Data analysis and interpretation
- Reporting and action



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Emissions Characterization

1. Which pollutants are important to measure?

- Particulate matter
  - Mass concentration
  - Chemical composition
  - Optical properties
  - Size distribution
- Gaseous pollutants
  - CO, CO2, NOx, CH4, etc.

2. What types of instruments are required?

- Real time vs. Time-integrated

3. What do we do with these measurements?

- Health, the environment, and design

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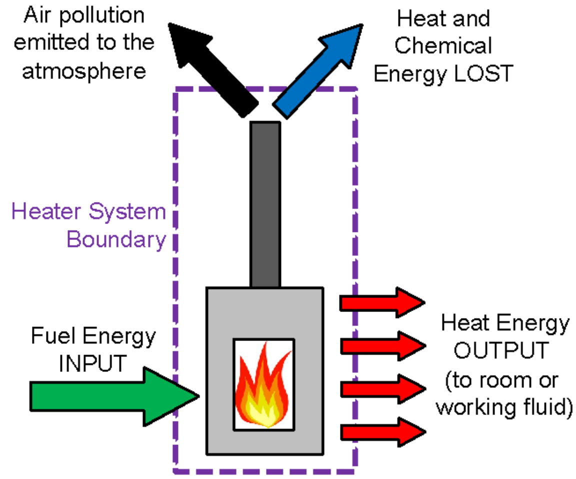
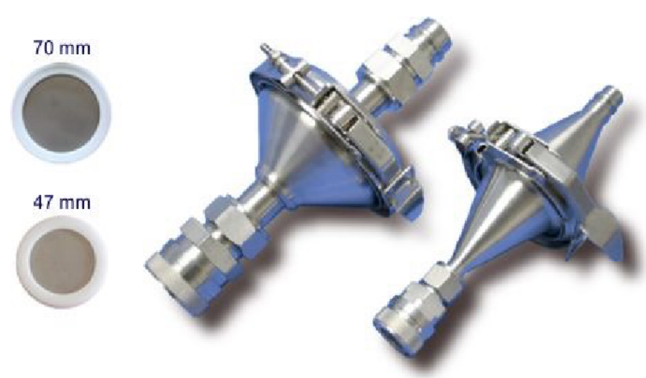


Gravimetric PM Filters

- Cornerstone of heater emissions evaluation
- Reliable, accurate, and time-tested
- Only provide one time-integrated measurement of emitted PM mass
- How do we go further?



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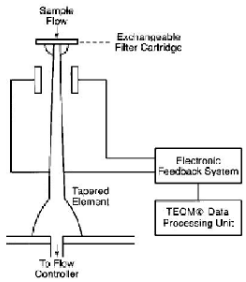
Real-time PM measurements

TEOM



Tapered Element Oscillating Microbalance

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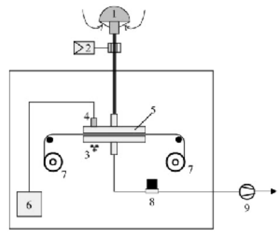
BAM



1 Sample Inlet
2 Tube Heating
3 Beta Source
4 Geiger-Müller-Counter
5 Filter Housing
6 Microprocessor, Data Evaluation
7 Filter Tape
8 Mass Flow Controller
9 Vacuum Pump

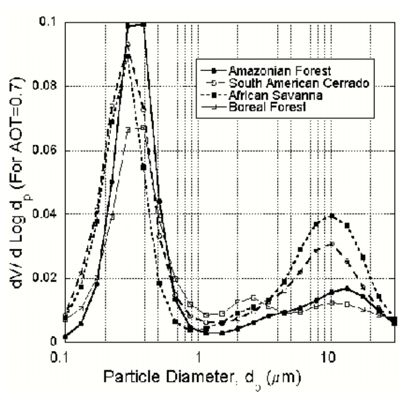
Beta Attenuation Monitor

Light Scattering

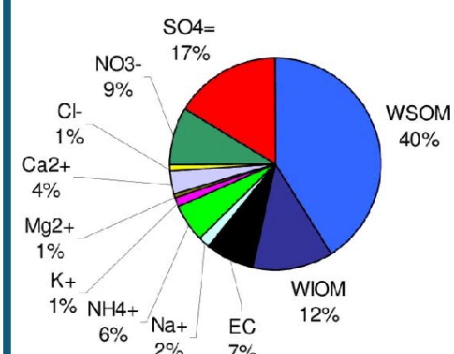
PM characteristics

Optical properties

Size distribution

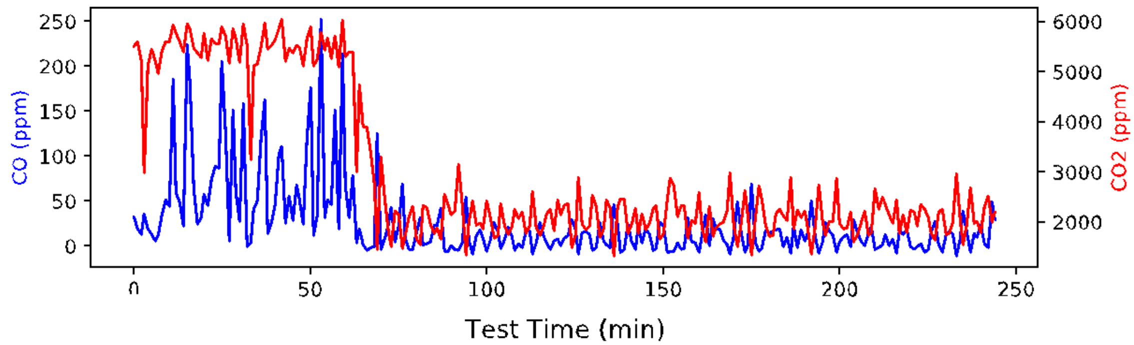


Chemical composition



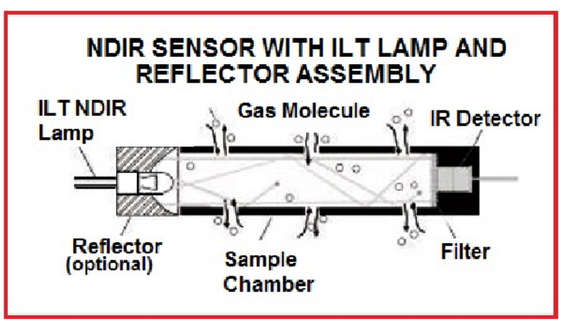
Gaseous emissions

- Ideal emissions: only CO_2 and H_2O
- Toxic emissions: CO, VOCs, NO_x, H_2S, SO_x
- Other emissions: CH_4, HCl, NH_3



Gas instruments

Nondispersive Infrared (NDIR) Sensor



Photoionization Detector (PID)

Electrochemical cells

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Breakout Session D – Emissions sampling: Instrumentation and dilution

Date of workshop: March 29, 2022
Number of participants: 37
Panelists: Ryan Thompson (Mountain Air Engineering), George Allen (NESCAUM), and Woody Delp (Lawrence Berkeley National Laboratory)
Moderator: Vi Rapp (Lawrence Berkeley National Laboratory)
Note Taker: Jake Lindberg (Brookhaven National Laboratory)

Introduction/Prompt:
During this session we will discuss the logistics and challenges with measuring emissions in the field. This includes discussing emission measurement instrumentation and dilution methods. We will also review what emissions are critical and what me might be able to do without.

Questions and Responses from Panelists:

Q1: What would the ideal instrumentation suite contain to fully evaluate a wood heater?

- There is no ideal instrument suite
- A micro GCMS would be ideal, but there are many other factors to consider such as cost, portability, and accuracy.

Q2: What are the minimum required emissions measurements?

- PM is the most important
- Some argue gravimetric is critical and real-time is ideal due to limitations of optical instruments.
- cumulative/aggregate property measurements (light absorption/scattering) work well
- Counter-sizer type instruments cannot see small particles (< 300 nm)
- Others argue Realtime PM instrument is critical. TEOM is ideal because:
- TEOM provides real-time mass w/o optical issues
- ~30 minutes to setup
- Requires sample conditioning
- semi-volatile evaporation is an issue for mass based methods
- CO, CO2 are good to have
- Dilution system is critical because concentrations are too high for most PM instruments
- Dekati eDilutor is a packaged unit good for this purpose
- FDMS (automotive dilution sampler) is not good for stack sampling
- Stack flow rate
- High-Temperature Vane Anemometer is a good choice for this
- Challenge with this ideal kit is the cost. Easily 60-70k$ (eDilutor is $60k, all 3 instruments mentioned above likely >150k$).
- A possible low cost option could be a TESTO for low accuracy measurements. The concern is the limited dynamic range

Q3: What are some of the biggest pitfalls in making measurements in the field?

- Sharing and interpreting results
- Isokinetic issues
- Saturating instruments
- Coincidence losses
- Loss of measurement sensitivity near bounds (especially for PM)

Q4: Knowing that field sampling is difficult and prone to variations (~30%) due to operations, where should we focus our sampling efforts?

- Informing an audience; what is a dirty stove
- Finding bad actors in a local setting

Question from Audience:

Q1: What is an ideal instrument range? Is 20,000 ppm CO enough, or is it too high?

- For undiluted exhaust, 20,000 ppm is fine. For diluted exhaust you can use a much lower range sensor and a better price point with better accuracy

Q2: How good is transparent, odorless, smoke as an indicator of good combustion?

- Most panelists agree it is a bad indicator and we need more quantitative results.
- One said it could be a good indicator for identifying which appliances may be under-performing

Q3: Can you see a visible plume at around 10g/hr?

- One panelist indicated there may be a correlation between opacity and concentration.
- Most panelists agreed opacity cannot be a quantitative measurement and may also be influenced by ambient temperature and relative humidity.

Q4: Should particle number, temperature, and emission factor be measured to help quantify semi-volatiles and secondary organic aerosol?

- Panelists agreed it could be challenging measuring these in a field setting and there are many other important measurements that can cover this measurement. For example, gravimetric filter measurements could be used for semi-volatiles and secondary organic aerosols if filter temperature and sampling time are considered. Semi-volatiles may also increase the uncertainty in PM mass measurements.

Q5: Does a vane anemometer really work?

- Yes. Vane anemometers for flue gas emissions exist on the market and work well. Note: these are high-temperature, fouling resistant, and low speed/flow, i.e. very particular instruments
- Minimum measurement speed of ~0.5m/s
- Capable of 10-12 hours of runtime between cleanings, with an average stove and even longer with pellets. May need more frequent cleaning with poor performing heaters

Q6: Is there a difference between direct stack measurements and dilution based measurements?

- Dilution based measurements give better air-quality/health-impacts answers
- Flue Stack based measurements give better combustion and optimization answers
- However, the results will be similar for some appliances (pellet stoves) and different for others (wood stoves)
- Semi-volatile content in the PM/gas may also play a role

Q7: What kind of real-time dilution do you use?

- HEPA filtered air with mixing components
- Dilution of all exhaust also allows for use of lower cost sensors. For example, CO in particular is interesting as it can be used to correct for dilution factor

Q8: Will your dilution based measurements compare to gravimetric filter results?

- Yes, to one degree or another.

Q9: Would two low-cost dilution samplers compare to each other? To an expensive dilutor? To real-time dilution tunnel measurements?

- Theoretically yes after cross-calibration. However, some instruments may have more issues than others

Q10: Has any thought been put into measurements of laminar and turbulent flame measurements?

- At previous WSDC the moderators told him he had good PM numbers but bad CO numbers. Are these two things correlated/related to laminar/turbulent?
- PM/CO uncorrelated in this case; CO is not a perfect indicator for PM
- Not real answer to this since wood heater flames are generally turbulent or buoyancy driven

Q11: Is a candle flame dirty?

- Candle flames can-be/are very dirty.
- Laminar flames are not good by default.
- The particle size of candle flames is particularly health relevant.

Q12: Can we use automotive tools in stove design?

- Yes. Automotive measurement equipment will likely work for wood stoves. Concentration range and required flow rates are important to check.
- Calibration of the equipment will also allow it to work better in transition

Questions from Audience:

None Recorded.

Poll Questions and Results:
Note: response results in percentages are in square brackets

P1: What is your area of expertise/background?

- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid) [10%]
- Certified Test Lab [10%]
- Research Organization [20%]
- Federal or State Agency [20%]
- University / College [20%]
- Non-Governmental Agency (NGO) [20%]
- Other

P2: What is one thing you hope to gain from this session?

- Appropriate emissions equipment for field testing [40%]
- How to reliably dilute emissions [25%]
- Pitfalls to avoid [17%]
- Networking/partner
- Other [13%]

Presentation Slides:

Virtual Workshop on
Advances in Instrumentation used for Wood Heater Testing and Field Data Collection

Welcome to Breakout Session D

EMISSIONS SAMPLING – INSTRUMENTATION AND DILUTION

Thank you for joining us.

We will begin our session shortly.

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1

Advances in Instrumentation used for Wood Heater Testing and Field Data Collection

Breakout Session D: Emissions sampling – Instrumentation and dilution

Panelists:

George Allen
Chief Scientist
Northeast States for Coordinated Air Use Management (NESCAUM)

Ryan Thompson
Founder
Mountain Air Engineering

Woody Delp
Principal Scientific Engineering Associate
Berkeley Lab

Breakout Session Logistics:

Dialogue is encouraged: Be bold, ask questions, bring up innovative solutions, identify problems

A note taker will be recording collective ideas. Zoom transcriptions may be logged for note taker to accurately summarize discussion. Sessions will **NOT** be recorded

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2

How to benefit from this Session

Opportunities:

- Acquire technical knowledge
- Access to experts
- Opportunity for collaboration and partnering (when speaking, identify yourself and your organization)

Outcomes:

- Guide focus areas for future funding opportunities
- Better proposals via teaming arrangements

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3

Breakout Session E – Performance evaluation: How do you measure performance in the field?

Date of workshop: March 29, 2022
Number of participants:
Panelists: Norbert Senf (Masonry Heater Association of North America), Rene Bindig (Deutsches Biomasseforschungszentrum), Tom Butcher (Brookhaven National Laboratory)
Moderator: John Ackerly (Alliance for Green Heat)
Note Taker: Jason Loprete (Stony Brook University/Brookhaven National Laboratory)

Introduction/Prompt:
Measuring the performance of wood heaters in the field is no simple task. How can one accurately measure the amount of fuel consumed to determine the thermal efficiency? Should field measurements focus on an imposed duty cycle or how the heater is actually operated by the user? This session will focus on what needs to be included in field measurements such as the user comfort evaluation and understanding what goes into a user's decision to purchase a heater. Could this ultimately help us design a better heater?

Questions and Responses from Panelists:
Note: Because panelists gave a presentation, questions were opened to the audience. No questions were prompted like the other sessions.

Q1: What do you think are the "best" ways of collecting emissions data in the field?

- CONDAR Method impacted by real-world issue of wind; to the point of avoiding use on heavily windy days.
- CONDAR gives emission factor number, gives g/kg number. Testers weigh amount of fuel that must have been burned and use burn time to convert to g/h.
- Often use optical sensors for PM to get realtime values.
- How do we know if results are good?
    - If burn rate of 1 kg/hr, at 1 hr, the g/kg and kg/hr should be the same- easy way to check if data is accurate.
    - Average burn rate is 1 kg/hr - can extend to existing test burn rate.

Q2: Does Opacity have value in field testing?

- Simple test: shine light through section of flue and measure with Cadmium-Sulfide sensors.
    - Opacity and Emissions spikes have lagtime, but is still visible - sensor response time is important!
- Correlation with particulate mass with optical methods is not great quantatatively- but good qualitative measure. Can't see finest particles!
- Used by enforcement agencies - if you fall opacity test too many times.. Out of luck!
    - 20% opacity for 6 consecutive minutes is a fineable offense in some areas!
- Just about disappearance of smoke is ~ 2g/hr –> ideally after first 20 mins

- There are devices available for direct measurement in the flue gas
- Can buy low-cost (sub $200) components and install to house wall to check air quality PM10 and PM2.5 for ambient/indoor air quality.
    - Can connect devices to internet and get realtime data!

- Smokeless Chimney uses a 1 W LED to test for opacity.
    - Opacity can sometimes be used to train a controller to actively control air input.
    - Controller sends out a bluetooth/wifi signal.

Q3: Have people used hand-held lasers to test opacity? These will usually pick up smaller particles.

- There are, but even lasers will only go down to about .3 micron (300 nm) - and clean burn produces a significant amount of particles below this size.

Q4: Are there any studies simultaneously measuring stack and outdoor air emissions for wood burning appliances?

- Immediate reactions: there must be! No specific details however beyond a test from BTI.

Q5: Optical PM meters - how are they affected by moisture? Ones I've looked at read moisture droplets as smoke. Which, in England, rather matters as we have a lot of moisture droplets

    - Particles are particles! They can still be picked up, and even dilution may still fall susceptible to this.

Q6: What do you do about drilling holes in the stack?

- Tom: “We like to bore holes”.
- Have to use single wall
- Some folks cover with aluminum tape
- Others replace stacks.
- Some even use large coarsely threaded bolt to fill holes when not in use.
- EPA requirements require a distance of several duct diameters aware, which often limits flexibility in measurement location. PM and stack flow must be measured and mixing issues avoided.
    - Length available is a challenge….
    - Challenge of precision vs accuracy
- CO has increased interest

Q7: How will information discussed today relate to the upcoming competition?

- Form up next week and details still being determined.
    - Pellet and woodstoves? Not sure if pellet stoves will be introduced, but they are eligible.
    - Will involve dilution tunnel

<u>Questions from Audience:</u>

None Recorded.

Poll Questions and Results:
Note: response results in percentages are in square brackets

P1: How would you qualify your role in the wood heater field?

- Manufacturer [28%]
- Researcher [36%]
- Regulator [8%]
- Retailers [4%]
- Other [24%]

P2: What is one thing you hope to gain from this session (one-choice)?
- Find out what field testing data exists to date. [11%]
- Find out how field testing is usually done. [43%]
- Better understand discrepancy between lab data and field data [46%]

P3: What is your level of experience with emissions testing of stoves?
- Frequently review test emission data [24%]
- Have witnessed testing in a lab or field [16%]
- Have assisted or performed testing in lab or field [52%]
- Have been involved in testing emissions but not on wood stoves [8%]

P4: Why are you interested in field testing emissions of stoves (checkbox for multiple selections)
- Better understand health impacts of wood stoves [33%]
- For R&D purposes to improve heater performance [63%]
- For academic or research purposes to assess role of stoves [19%]
- Other [4%]

P5: How much potential is there to integrate basic emissions monitoring equipment in stoves to help consumers better operate and maintain their stoves?
- Very little – too expensive and complicated [17%]
- Some - but it will take more R&D [54%]
- A lot – the tools are there and its affordable [29%]

Presentation Slides:
Panelists gave presentations and slides were not provided. Notes from presentations are below.

Norbert Senf's Presentation:
- Dilution tunnels are big and bulky- is there another way?
    - Introduced Skip Barnett's Condar Portable Dilution Tunnel
        - Consists of a probe connected directly to the stack that draws in sample and dilution air via a pump, depositing the result onto a filter.
        - In a 2006 New Zealand pellet stove field study, CONDAR method comparable to existing official dilution tunnel test method emission numbers.
- Emissions from woodstoves have extremely high variation across different days, and can differ by a factor of 10 from one day to the next.
- New system: flue extension with primary diluter as CONDAR alternative

Rene Bindig:
- Chemist studying catalysts
- Working at German Biomass research center
    - Dealt primarily with energetic use of biomass, but now additionally as materials.
    - Deals with small-scale combustion appliances; stoves/hydronic heaters
    - Cooperates with industrial partners and research institutions.
- Much work consists with emissions reductions from flue gas of all kinds.

Tom Butcher:
- Researcher at Brookhaven National Laboratory in Energy Conversion Group

    - Work focuses on combustion work
- Field tests are HARD! Can't bring a dilution tunnel to the field.
    - Full dilution tunnel gives a better way to integrate over different combustion phases, whereas a field sampler has issues in doing so by just simply pulling samples.
    - Operation – what if the load is not sufficient or cannot be cycled in the way it could be for a traditional dilution tunnel test?
    - Is there access to the stack at required points?
    - Cycling/Load profile testing is hard – but field tests can offer steady-state testing and have value.
    - Field tests provide *real* operation, which is valuable in determining realistic performance over certification test results.
    - Good for validating against poor performing units.
    - Ability to evaluate retrofit devices.
- Expectations should be managed! It is a simple test, but provides value.

Breakout Session F – Impact evaluation methods: Public health and the environment

Date of workshop: March 29, 2022
Number of participants: 21
Panelists: Brian Frank (New York State Department of Environmental Conservation), Nicole Vitillo (New York State Department of Health), and Gillian Mittelstaedt (Tribal Healthy Homes Network)
Moderator: Rebecca Trojanowski (Brookhaven National Laboratory)
Note Taker: Julien Caubel (Lawrence Berkeley National Laboratory)

Introduction/Prompt:
Traditionally, wood heater test methods have focused solely on particulate matter, on a mass basis. Recently, gaseous pollutants such as CO have been required to be reported during compliance tests. As residential wood combustion is often the highest source of PM emissions in states and held responsible for numerous health related issues, should we consider other measurements beyond PM mass, such as speciation, number concentrations, and size? This session will provide a forum that focuses on how to measure emissions related to health and environmental impacts.

Questions and Responses from Panelists:

Q1: What makes gravimetric PM mass measurements the gold standard for particle health effects?
- Has to do with history of monitoring.
- Closed loop on what is important versus what's measured
- Protecting most sensitive populations. Health impacts tied to PM levels.

Q2: What components in woodsmoke (PM and gaseous) impact human health, are any more detrimental than others?
- Ultrafine particles. Characterization of ultrafine particles is much harder than gravimetric, especially characterizing polyaromatic hydrocarbons (PAHs) and other hydrocarbons. Real-time measurements would be most useful to quantify health impacts, but time-integrated methods are easiest to implement.
- High PAH in <1um range is hazardous.
- Chemical composition of the particles is linked to toxicity. Using mass spec with supercritical fluid could help measure but is hard to implement.

- Chronic exposure to ultrafine particles has different health impact mechanisms than what we might be familiar with today. Moving away from looking at just acute impacts, and starting to look at chronic impacts.
- Metrics such as years of life lost may be useful to gauge health impacts.
- Elemental carbon is a harmful component.
- Particle size is a driving factor of health impacts. When you get to very small sizes (<1 um) physical mechanisms change greatly, and we need to look at different metrics.
- Heat pumps are very effective for moving the needle on health impacts. Less polluting on their own, and they also do some filtering on their own of our sources that may be at play. Secondary considerations like maintenance are also important.

Q3: Is there support for other emission metrics correlation to public health / environmental impacts?
- Ultrafine particles and black carbon are at the fore front, but the science is lacking. Methods are being put forward to measure these pollutants and start looking at impacts. Current results are inconclusive.
- LDSA is an important health related metric. Use diffusion charging instruments to measure this. LDSA informs toxicity pathways: e.g. brain-blood barrier.
- Genotoxicity. PAH, methylbenzene are understood to have genotoxic effect.
- Looking at "standard" aerosol in order to ground various measurement methods. This will be important to inform apples-to-apples comparisons, and useful deductions re: health impacts.

<u>Questions from Audience:</u>

None recorded.

Poll Questions and Results:
Note: response results in percentages are in square brackets. For P1, 21 participants responded, while only 11-12 participants responded to the remaining poll questions.

P1: What is your area of expertise/background (one choice)?
- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid) [8%]
- Certified Test Lab [0%]
- Research Organization [17%]
- Federal or State Agency [58%]
- University / College [8%]
- Non-Governmental Agency (NGO) [0%]
- Other [8%]

P2: What is one thing you hope to gain from this session (one choice)?
- To discuss pollutant emission(s) and emission metrics besides PM, which are relevant to health and the environment. [67%]
- To discuss how to measure health relevant pollutant emissions besides PM mass. [25%]
- Networking/Partnering/Teaming [0%]
- Other [8%]

P3: Which particle pollutant measurement metrics do you think are most relevant for health impact evaluation (multiple choice)?
- Particle Mass [22%]

- Gaseous Pollutants (CO/VOC/NOx) [44%]
- Particle Number [44%]
- Particle Surface Area [33%]
- Particle Size [78%]
- Particle Composition [33%]
- Other [0%]

P4: Which particle size range do you think is most important from a health perspective (one choice)?
- PM Coarse (2.5-10 micron diameters) [0%]
- PM Fine (2.5-0.1 micron diameters) [36%]
- Ultrafine PM (<0.1 micron diameters) [64%]

P5: What component of particulate matter do you think is most important (one choice)?
- Elemental Carbon (Black Carbon) [64%]
- Organic Carbon (Brown Carbon) [27%]
- Inorganic Salts (Nitrate/Sulfate/etc) [9%]
- Other [0%]

P6: Which, if any, additional metrics should be evaluated when certifying wood combustion appliances (multiple choice)?
- Fractionated PM Mass (Coarse/Fine/Ultrafine) [25%]
- Speciated PM Mass (Filterable/Condensible) [17%]
- Particle Composition (EC/OC/Salt %) [50%]
- Particle Number Concentration [25%]
- Average Particle Size [50%]
- Trace Gas Emission (NOx/SOx/VOC/etc) [75%]
- Other [17%]

Presentation Slides:

Welcome to

Breakout Session F

Impact Evaluation Methods:

Public Health and the Environment

Thank you for joining us.

We will begin our session shortly.

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Breakout Session F

PRE-SESSION POLL QUESTIONS

What is your area of expertise/background (one-choice)?

- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid)
- Certified Test Lab
- Research Organization
- Federal or State Agency
- University / College
- Non-Governmental Agency (NGO)
- Other

What is one thing you hope to gain from this session (one-choice)?

- To discuss pollutant emission(s) and emission metrics besides PM, which are relevant to health and the environment.
- To discuss how to measure health relevant pollutant emissions besides PM mass.
- Networking/Partnering/Teaming
- Other

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Breakout Session F

Breakout Session Logistics:

- Schedule – 12:00 to 1:00pm
- ZOOM format to be used
- Use the raise hand feature to ask for the mic
- Facilitators will be leading discussions and switching direction as appropriate
- There is a designated scribe in the breakout session taking notes. Notes will represent a collective summary and not specifically apply to individuals
- These sessions will **NOT** be recorded
- A summary and highlights of the session will be presented by one or more of the facilitators at the closing remarks
- Be bold, ask questions, bring up innovative solutions, identify problems

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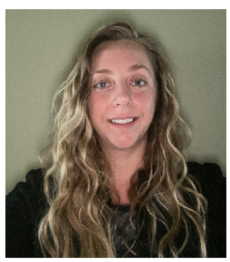
Breakout Session F

Meet the Panelists:

Brian P. Frank
Section Chief
New York State Department of Environmental Conservation,



Nicole Vitillo
Research Scientist
New York State Department of Health,

Gillian Mittelstaedt
Air Quality and Environmental Health Professional
THHNW

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Breakout Session F

Question # 1:

What makes gravimetric PM mass measurements the gold standard for particle health effects?

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Breakout Session F

SESSION POLL #1 QUESTIONS

Which pollutant measurement metrics do you think are most relevant for ***health impact evaluation*** (multi-choice)?

- Particle mass
- Gaseous Pollutants (CO, VOC, NOx)
- Particle number
- Particle Surface Area
- Particle Size
- Particle composition
- Other

Which pollutant measurement metrics do you think are most relevant from an ***environmental perspective*** (multi-choice)?

- Particle mass
- Gaseous Pollutants (CO, VOC, NOx)
- Particle number
- Particle Surface Area
- Particle Size
- Particle composition
- Other

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Breakout Session F

Question # 2:

What components in woodsmoke (PM and gaseous) that can impact human health, are any more detrimental than others?

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Breakout Session F

SESSION POLL #2 QUESTIONS

Which particle size range do you think is most important from a health perspective?

- PM Coarse (2.5-10 micron diameters)
- PM Fine (2.5-0.1 micron diameters)
- Ultrafine PM (<0.1 micron diameters)

What component of particulate matter do you think is most important?

- Elemental Carbon (Black Carbon)
- Organic Carbon (Brown Carbon)
- Inorganic Salts (Nitrate/Sulfate/etc)
- Other

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Breakout Session F

Question # 3:

Is there support for other emission metrics correlation to public health / environmental impacts?

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Breakout Session F

SUMMARY POLL QUESTION

Which, if any, additional metrics should be evaluated when certifying wood combustion appliances (multi-choice)?

- Fractionated PM Mass (Coarse/Fine/Ultrafine)
- Speciated PM Mass (Filterable/Condensible)
- Particle Surface Area
- Particle Composition (EC/OC/Salt %)
- Particle Number Concentration
- Average Particle Size
- Trace Gas Emission (NOx/SOx/VOC/etc)
- Other

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Breakout Session F

Thank you for joining us.

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Appendix C: Notes taken for Workshop 3 Breakout Sessions: Adoption of new wood heater technology and integration with other renewables

Breakout Session A – Adding automation to a wood heater Q&A

Date of workshop: April 26th, 2022
Number of participants: Approximately 40
Panelists: Ryan Fisher and Paul LaPorte (MF Fire); and Guillaume Thibodeau-Fortin (Stove Builders International)
Moderator: John Ackerly (Alliance for Green Heat)
Note Taker: Jake Lindberg (Brookhaven National Laboratory)

Introduction/Prompt:
The effort to begin "automating" wood stoves, usually refers to using sensors and computer chips to adjust airflow after the wood has been loaded by the operator. Automated stoves have the potential to enable the consumer to "load and leave," allowing the stove to maximize efficiency and emissions reductions on its own. Yet, with even with low-cost sensors and extensive expertise in the field of combustion, automating the wood stove has proved challenging for multiple reasons. Making sense of data from sensors and responding to correctly to that data is an engineering challenge, but there is also the issue of whether manufacturers have any significant incentives to automate, if it doesn't help pass the EPA certification testing and if consumers may be reluctant to purchase them. This will primarily be a session for participants to share information, solutions and problems.

Automated stoves are an emerging class that is more well-known in Europe and just starting to enter the US market. MF Fire, a Maryland based company launched an automated stove model in 2016. Charnwood, a British manufacturer is entering the US market in 2020 with their Skye E2700. Napoleon is coming out with an affordable automated smart stove in late 2020. The Canadian manufacturer SBI won an award at the 4th Wood Stove Design Challenge for their progress toward an automated stove. In the single burn rate category, the RSF Delta Fusion is an excellent example of a fast burning stove that cannot be adjusted or made to smolder.

Questions and Responses from Panelists:
Q1: Why is your company pursuing automation when it's easier and cheaper to build a traditional stove?

- We are also excited to implement high-end sensors into heaters, as this could provide interesting results and result in a higher-end product
- Automation reduces variability in the emissions from a wood heater, which results in reduced emissions overall
- Automation increases the heating efficiency of the appliance, which provides fuel savings for the customer

Q2: What are the challenges marketing an automated stove and do you think more consumers may be interested in one in the future?

- The off-grid rugged look has high market appeal and automation goes against that design aesthetic
- Automation adds cost, which is difficult to implement with intense competition
- However some customers prefer automated stoves due to: 1) Fuel savings for the customer and 2) ameliorated climate and health concerns

Q3: If a stove can use sensors to respond to changes in the combustion chamber in real time, it seems logical that using sensors could help pass the EPA emission test. Do you think automation can be a tool for companies to help ensure they pass?

- Automation is not necessary at the current emission level however in the future if emission limits are decreased it may warrant automation.
- Modern automation technology does not incorporate a direct smoke sensor, which would be required to *ensure* a passing certification test, instead smoke proxies are used which are cheaper and provide better information on thermal performance and user-interaction.

Q4: If the DOE wasn't providing funding, would you still be pursuing this stove design?

- Automation is only possible with DOE R&D funds, these types of projects have 3+ year ROI's, which require external funding to make profitable for a manufacturer

Questions from audience:

Q1: Are catalysts required to meet emissions certification limits or can you achieve low emissions through automation and design alone?

- Catalysts are a tool, but are not the end all be all for reducing emissions

Q2: Are CO and PM correlated? Can CO sensors be used to help automate heaters?

- CO and PM can be correlated in some combustion phases/scenarios, but not always.
- CO can vary considerably with appliance size so it is bad to use relating across stoves.
- CO sensors are not used in current automation sensor packages, O2 and temperature sensors are preferred instead.

Poll Questions and Results:

P1: How much potential is there for automated stoves in the marketplace? (single choice)

- Little – too expensive and complicated [15.4%]
- Some - but it will take more R&D [38.5%]
- A lot – the tools are there and they could really take off [46.2%]

P2: Why are do you think consumers will be wary of automated stoves? (multi-choice)

- They don't want stove to need electricity, even if it can operate without it. [42.3%]
- They have positive associations with the low-tech nature of stoves [30.8%]
- They don't want to pay more than they have [53.8%]
- They will be worried that it may break and need more upkeep [57.5%]
- They won't be wary, once they are more common [23.1%]

Presentation Slides:

None Used.

Breakout Session B – Impact evaluation: Quantifying health, energy & climate impacts for biomass heat deployment

Date of workshop: April 26th, 2022
Number of participants: 22-26
Panelists: Tami Bond (Colorado State University), Corinne Scown (Lawrence Berkeley National Laboratory), Stefan Unnasch (Life Cycle Associates), Oleksandra Tryboi (Scientific Engineering Center Biomass)
Moderator: Julien Caubel & Vi Rapp (Lawrence Berkeley National Laboratory)
Note Taker: Jason Loprete (Stony Brook University/Brookhaven National Laboratory)

Introduction/Prompt:

Residential biomass heaters have the potential to be key players in clean energy portfolios of the future, as they leverage renewable and economical energy stocks that may not be useful otherwise. However, the collection and distribution of biomass fuels has inherent impacts (ranging from habitat destruction to transportation), and biomass combustion emits air pollution that contributes to climate change and is harmful to human health. As biomass energy becomes more widespread, it is crucial that both the benefits and impacts be accurately quantified. In this session we will discuss key life cycle analyses to inform responsible adoption of biomass heater technologies at the residential scale. This forum will provide an opportunity for stakeholders to share information on state-of-the-art methods for determining net greenhouse gas emissions over the product lifecycle, evaluating health impacts on surrounding populations, and integrating biomass into renewable energy economies. These considerations depend greatly on the deployment context, so a common toolbox of objective evaluation methods must be established to ensure that biomass heaters provide a net benefit to their local communities and environment.

Questions and Responses from Panelists:

Q1: What are the key aspects of a life cycle analysis for biomass heaters?

- Residential biomass energy can be divided into 2 major sub-components: (1) The appliance and (2) the fuel.
- Major lifecycle phases for consideration:
  - Heater manufacturing and transportation
  - Fuel harvesting, processing, and transportation
  - Heater operation and maintenance
  - Heater disposal and end-of-life
- Major impact areas for consideration:
  - Habitat destruction
  - Fossil fuel and energy use
  - Greenhouse gas emissions
  - Toxic air pollution
- What is the net health, energy, and environmental impact of residential biomass heat over the entire product lifecycle, from initial installation to disposal?

Q2: What methods or tools are available to quantify lifecycle impacts accurately?

- Resources on biomass heat are generally lacking. How we fill the void?
- Are there data sources that we can extrapolate to this application?
- How do we collect primary-source data to populate our models?
- What are the key lifecycle phases that should be prioritized during modeling?

- Are there similar products or energy flows that we can use to inform this analysis?
- What modeling tools are commonly used for lifecycle analysis?

Q3:How do we quantify impacts on human health at the societal scale?

- How you develop a toxic emissions inventory?
- Can laboratory data (e.g., regulatory testing reports) be extrapolated to provide an estimate of fleet-wide emissions in the field?
- Often, emissions testing focuses on particulate matter (PM). Is PM sufficient for health modeling? What about other toxic emissions, like carbon monoxide?
- Once we have an estimate of emissions, how do we correlate this to health impacts? Is there a "safe" level of pollution? Are there functions available to estimate health impacts (e.g. respiratory diseases and mortality) based on pollutant concentrations?

Q4: How do we model the fuel supply chain?

- While biomass heaters themselves are relatively well studied, fuel harvesting, processing, and distribution is not. Information on residential biomass fuels is lacking.
- What tools can we use to measure or estimate the type of fuel used, and how much?
- There are many different fuel types (e.g., cordwood, pellets, briquettes, etc.). How do we account for all of these in the supply chain?
- Often, biomass fuel is collected locally or by individuals – there may be no external record of the supply chain. How you capture these hidden fuel streams?
- Some fuels use virgin materials, others leverage waste streams (e.g., sawdust), and many use a mixture of the two. This further complicates modeling efforts. How do you capture the resulting impact on the environment?

<u>Questions from audience:</u>

None recorded.

Poll Questions and Results:

P1: What is your area of expertise/background (one choice)?

- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid) [5%]
- Certified Test Lab [0%]
- Research Organization [23%]
- Federal or State Agency [32%]
- University / College [23%]
- Non-Governmental Agency (NGO) [9%]
- Other [9%]

P2: What topic are you hoping to learn about in this session (one-choice)?

- Lifecycle analysis
- Health impact modeling
- Climate impact modeling
- Environmental impact modeling

P3: What area of the heater system lifecycle would you like to investigate?

- Heater performance and emissions
- Fuel harvesting
- Fuel processing and transportation
- Other

Presentation Slides:

Virtual Workshop on
Advances in Instrumentation used for Wood Heater Testing and Field Data Collection

Welcome to Breakout Session B

QUANTIFYING HEALTH, ENERGY & CLIMATE IMPACTS FOR BIOMASS HEAT DEPLOYMENT

Thank you for joining us.

We will begin our session shortly.

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1

Advances in Instrumentation used for Wood Heater Testing and Field Data Collection

Breakout Session B: Quantifying health, energy & climate impacts for biomass heat deployment

Panelists:

Tami Bond
Professor, Mechanical Engineering
Colorado State University

Corinne Scown
Staff Scientist
Berkeley Lab

Stefan Unnasch
Managing Director
Life Cycle Associates

Oleksandra Tryboi
Senior Consultant, Scientific Engineering at Centre "Biomass" and Junior Researcher at the Institute of Engineering Thermophysics of the NASU

Breakout Session Logistics:

Dialogue is encouraged: Be bold, ask questions, bring up innovative solutions, identify problems

A note taker will be recording collective ideas. Zoom transcriptions may be logged for note taker to accurately summarize discussion. Sessions will **NOT** be recorded

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2

Advances in Instrumentation used for Wood Heater Testing and Field Data Collection

Breakout Session B: Quantifying health, energy & climate impacts for biomass heat deployment

What?

- Lifecycle analysis is the accounting of **environmental, health, and environmental impacts** incurred from heater manufacturing to final disposal.
- Compare to other energy streams to determine if wood heat provides a net benefit to communities.
- Modeling refers to manipulating datasets for impact characterization. For example, combining pollution concentration measurements and census data to estimate health impacts on population.

Manufacturing Materials, fabrication, distribution → **Use:** Fuel supply (harvesting, processing, distribution) and heater operation → **Disposal:** Heater recycling/disposal, fuel waste disposal

Why?

- Inform policy actions to promote responsible and renewable biomass heat adoption.
- Provide quantifiable insight to manufacturers, regulators and other stakeholders on impact reduction.

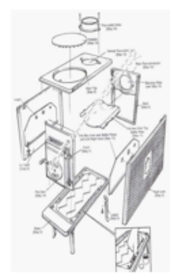
3

Advances in Instrumentation used for Wood Heater Testing and Field Data Collection

Breakout Session B: Quantifying health, energy & climate impacts for biomass heat deployment

How?

- Raw data collection: Government databases, surveys, market analysis, product study, etc.



- LCA databases and software tools: General data on products/processes, modeling/analysis framework.

4

How to benefit from this Session

Opportunities:

- Acquire knowledge on current methods and tools for LCA
- Access to experts and stakeholders
- Collaborations and partnerships (identify yourself when speaking)

Outcomes:

- Better understanding of current LCA field and future research directions
- Introduction to new partners, perspectives, and research areas

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5

Lifecyle of biomass energy (fuel)

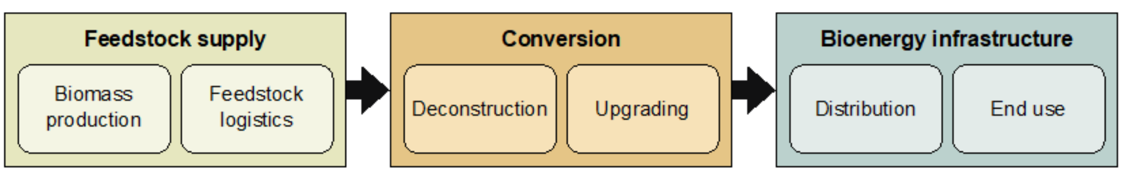


Figure 1. Biomass-to-bioenergy supply chain (USDOE 2014).

LCA for wood briquette fuel

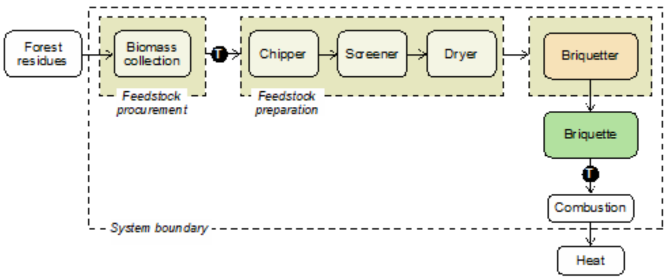


Figure 2. System boundary for briquetted biomass production supply chain (T, transportation).

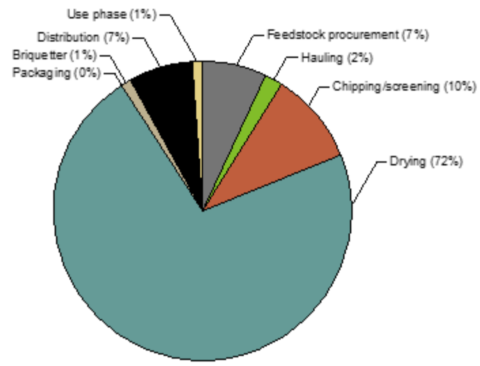
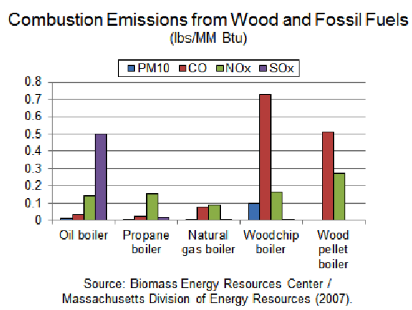
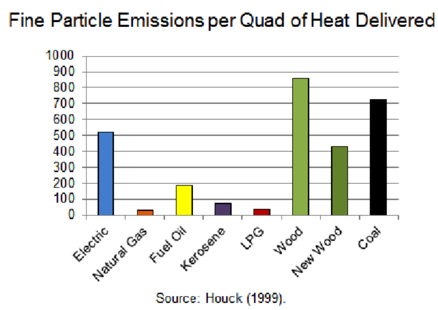
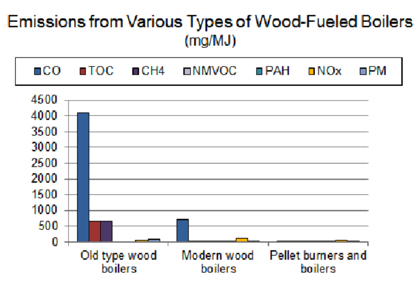


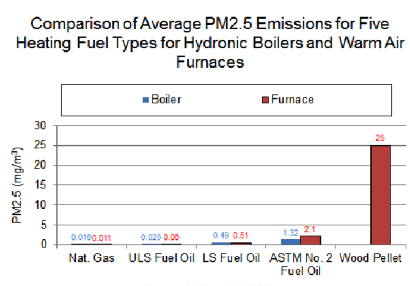
Figure 7. Contribution of processes to overall global warming impact for the wood briquette production system per 1 MJ of thermal energy generated by the wood stove.

Air pollution emissions from biomass



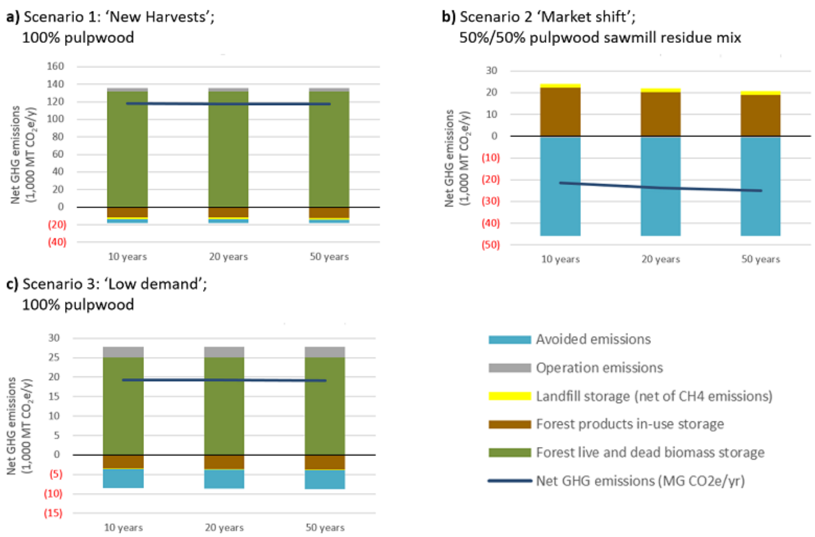






- Generally, biomass is NOT the cleanest
- Are these emissions counterbalanced by other benefits of the biomass system?

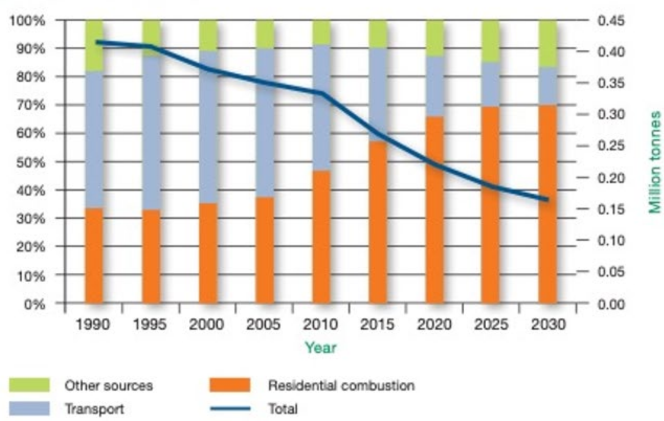
Greenhouse gas emissions: Fuel mixture



- Fuel processed from mixture of virgin materials and waste
- Even waste has impact. For example, sawdust is a byproduct of milling, but still requires wood harvesting.

Climate impacts: Black carbon

Fig. 3. Baseline BC emissions from the common major sources in the EU-28, 1990–2030



Note: EU-28 is countries belonging to the EU after July 2013; current legislation scenario as in Amann et al. (2014), using the carbonaceous particles module (Kupiainen and Klimont, 2007) of the GAINS model (Amann et al., 2011).

Source: reproduced with permission from IIASA.

Quantifying health impacts

Table 3.4. Estimates for population exposure and disease burden attributable to RWC in the studied scenarios

Scenario	$PM_{2.5}$ [kt/a]	PWC [µg/m³]	DALY	Premature Deaths
2015	10.5	0.70	3420	210
2030 Baseline	9.1	0.64	3140	190
1. Infocampaign				
a Cities	9.0	0.62	3010	180
b All areas	8.5	0.59	2880	170
2. Sauna legislation	7.0	0.49	2370	140
3. ESP installations	5.5	0.44	2150	130
4. Urban combustion bans	4.8	0.24	1150	69

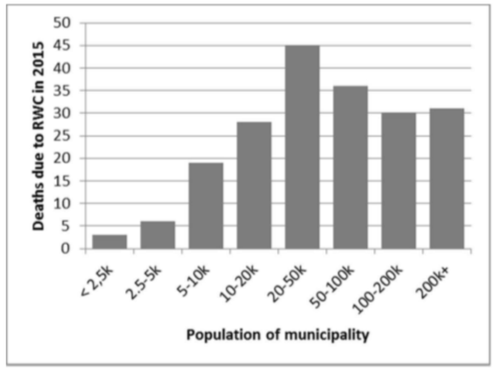
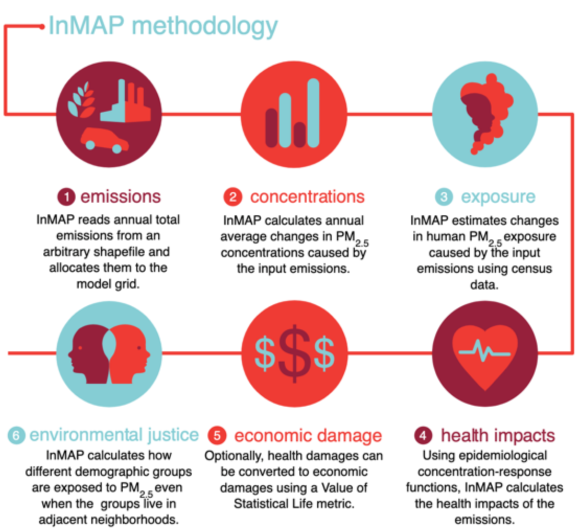


Figure 3.4. Deaths attributable to RWC, classified by population size in a municipality.

- How much do biomass heaters contribute to toxic pollution? (kt/a = Kilotons of pollution per year)
- Who is exposed? How much? (PWC = population-weighted concentration)
- What are the resulting health impacts? (DALY = Disability-adjusted life years)

Health impact modeling tools



INMAP

INTERVENTION MODEL FOR AIR POLLUTION

Health Impacts of Air Pollution: A Tool to Understand the Consequences

Christopher Tessum | Jason Hill | Julian Marshall

Key terms

Life-cycle Analysis: Accounting of environmental, health, and economic impacts incurred from initial product manufacturing to final disposal.

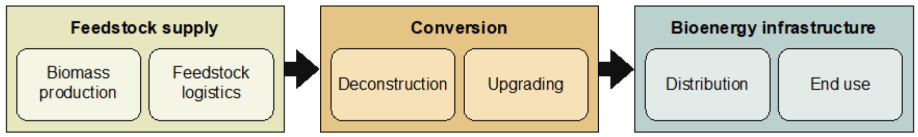
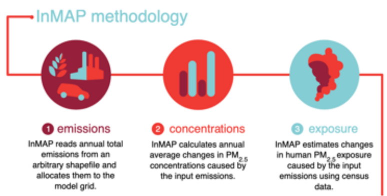


Figure 1. Biomass-to-bioenergy supply chain (USDOE 2014).

Modeling: Manipulating data to answer a question. For example, combining pollution concentration measurements and census data to estimate health impacts.



14

Breakout Session C – DOE/National Laboratory Q&A Tech Slam, 5th Design Challenge, and Future Events

Date of workshop: April 27th, 2022
Number of participants: 22-26
Panelists: Mark Shmorhun (DOE Biomass Energy Technology Office), John Ackerly (Alliance for Green Heat), Tom Butcher (Brookhaven National Laboratory), Vi Rapp (Lawrence Berkeley National Laboratory)
Moderator: John Ackerly (Alliance for Green Heat)
Note Taker: Rebecca Trojanowski (Brookhaven National Laboratory)

Introduction/Prompt:

This breakout session is a more in-depth look into the DOE's strategy to promote R&D in the wood heater sector and to provide more details about the Slam and stove competition. To spice things up, we will have a mock slam, where 2 teams will present their stove ideas and judges will ask questions and identify their strengths and weaknesses.

Questions and Responses from Panelists:
Because this breakout session focused on instructions and guidance for competing in the Technology Slam, the questions and responses were adapted into a living Q&A page hosted on the Wood Heater Design Challenge webpage (https://www.bnl.gov/woodheater/). For a summary of the discussion from this session refer to the Q&A page (https://www.bnl.gov/woodheater/questions-answers.php).

Poll Questions and Results:
P1: What best describes your role in relation to wood heaters? (check one)
- Manufacturer [33%]
- Researcher/non-profit [24%]
- Gov't employee/regulator [14%]
- Retailer [0%]
- Innovator [24%]
- Other [5%]

P2: What is your impression of the planned Slam? (check all that apply)
- I am thinking about participating but have questions [44%]
- I am committed to participating but have questions [19%]
- I am not a stove designer but will definitely watch the teams pitch their ideas [25%]
- I probably won't watch it. [13%]

P3: If you are considering competing in the Slam and were selected to move forward and have you stove tested at BNL, what describes your motivations. (check all that apply)
- N/A, I am not planning on competing [18%]
- I want to participate in the Slam but don't need the testing at Brookhaven [18%]
- I want my stove tested at Brookhaven to learn more about its performance and have the chance to get more publicity for it [36%]
- I want to learn more about the EPA emission testing protocols [9%]
- I want to use the Slam and competition to better prepare myself to apply for a larger R&D grant from the DOE [18%]

P4: Do you think the Slam and competition are effective at motivating manufacturers to modernize stoves? (check all that apply)

- Yes, competitions are a good motivator and this provides some good publicity and recognition for stove innovators [60%]
- Somewhat. Wood stoves need to improve but this isn't necessarily the best way to make it happen. [20%]
- No, manufacturers are too busy dealing with changes in EPA's test methods and certification process [20%]
- Manufacturers still have little motivation to do extensive R&D to automate stoves [0%]
- The market should ultimately decide if advanced, automated stoves will succeed in the marketplace, not government incentives [0%]
- The Slam is a good new way to highlight advances in stove technology [0%]
- The Slam and competition are not sufficiently open and transparent to the large mainstream stove manufacturers [0%]

Presentation Slides:

No slides were used.

Breakout Session D – Integrating wood heat with other residential energy systems

Date of workshop: April 27th, 2022
Number of participants: 23
Panelists: Richard (Dick) Gibbs (NYSDEC ret.) and Scott Nichols (Tarm Biomass)
Moderator: Jake Lindberg (Brookhaven National Laboratory)
Note Taker: Jake Lindberg (Brookhaven National Laboratory)

Introduction/Prompt:

In order to combat climate change CO2 emissions from the heating sector must be reduced. In order to make this change green sustainable heating options must be adopted at a large scale. These options include low-carbon heating options such as electrical heating, heat pumps, and biomass combustion. While there has been much debate as to the extent to which each of these heating options is sustainable, relatively less attention has been paid to combining these types of heating systems together to realize a sustainable and effective low-carbon heating solution.

In this session we would hope to focus on how wood heaters can be integrated with other heating systems (heat pumps, warm air furnaces, existing hydronic heating systems, etc.) and with other home energy systems (solar PV, batteries, etc.). In this vein we would hope to discuss good examples of wood as a primary and secondary heat sources for homes and successes integrating renewable wood heat and renewable electricity. We would also hope to speak about the broader topic of integrating wood heat into the residential heating sector at large including barriers to entry into the wood heater market and barriers limiting the adoption of wood heaters into the residential heating sector in the United States.

This forum will provide an opportunity for the community to discuss how wood heaters can be integrated into an existing home heat and power system and how wood heating fits into the energy system of a low-carbon home in the future.

Questions and Responses from Panelists:
Q1: Can you share your favorite success story for integration of wood heat and other clean heat and/or power generating technologies?

- Panelist 1 shared their experience with a customer who made a number of changes to their home as a “deep energy retrofit” featuring:
  - log-cabin base model
  - re-insulation
    - reduced heat loss through the attic
    - removed rodent problem → better air quality
  - added wood boiler
  - added additional heat emitters (radiant floor)
- Panelist 2 shared their experience integrating wood heat into their homestead featuring:
  - 2-story ranch
  - external wood boiler
  - wood shed housing boiler
  - large volume low-temperature thermal storage
  - solar thermal
  - solar PV
  - decorative fireplace
  - adjacent forested area for sustainable wood harvest

Q2: What sets biomass apart from other renewable energy systems? For you where does biomass stand as a carbon neutral energy source?

- Overall audience and panelists agreed carbon neutrality of wood fuel depends on a variety of factors:
    - where the raw biomass is harvested from
    - how the raw biomass was harvested
    - how the raw biomass is processed (into: logs/chips/pellets/etc.)
    - where the wood is being used
- Panelist 1 had strong opinions that cordwood should be considered carbon neutral by default, with some consideration taken for pellets/chips
- Panelist 2 stated that with forest stewardship and renewable firewood processing/storage/usage biomass can be carbon neutral

Q3: In your opinion, what are the key features that enable a zero/low carbon residential energy system?

- Each feature integrated into a home energy system should be evaluated on a case-by-case basis
- Tightening the building envelop was nearly universally accepted as a requirement to achieve a zero/low carbon home
- Deep synergies exist among low-temperature hydronic systems which are enabled by thermal storage (wood hydronic/solar thermal/heat pumps)

Q4: Where does wood heat fit into a multi-source heating system? What technologies pair best with wood?What percentage of your yearly heat demand can be met with wood heaters?

- The proportion of wood heat in a residential energy system depends on many factors including:
    - local climate/geographic location
    - seasonal weather patterns
    - existing infrastructure (current insulation level/other heat sources)
    - local resources (availability of fuel)
- Audience believes that wood should provided secondary heat; Panelists agree, nothing beats an open wood fire in the winter (fireplace/stove/etc)

Q5: What pitfalls exist integrating wood heating into an existing residential energy system? What upfront cost can be expected?

- There are many pitfalls, but they arise as part of an energy audit, and must be evaluated on a case-by-case basis
- “deep energy retrofits” are expensive and must be planned carefully
    - A low-cost solution for more inclusive integration should be developed
- Wood heat is a lifestyle choice, the physical demand and seasonal planning for this type of system must be accounted for

Q6: How can we as a community facilitate integrating wood heat into more homes? What barriers exist in this path? What tools would be most helpful in this endeavor?

- Facilitating adoption and integration of wood heating is a large problem, especially considering each integration project requires investigation on a case-by-case basis
- The audience believed that investing in new and better integrated technologies was important as well as enacting regulatory change to support new technology and integration

Poll Questions and Results:

P1: What is your area of expertise/background (one-choice)?

- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid) [17%]
- Certified Test Lab [0%]
- Research Organization [11%]
- Federal or State Agency [44%]
- University / College [6%]
- Non-Governmental Agency (NGO) [11%]
- Other [11%]

P2: What is one thing you hope to gain from this session (one-choice)?

- To learn how you can better integrate wood heating into your own home energy system. [50%]
- To discuss the role of wood heating in conjunction with other thermal energy systems. [23%]
- To discuss the integration of wood heating with renewable electrical generation systems. [23%]
- Networking/Partnering/Teaming [5%]
- Other [0%]

P3: In your opinion is wood a carbon neutral energy source?

- Yes. (Strongly Agree) [45%]
- Yes mostly. (Agree) [25%]
- Maybe/depends. [10%]
- Not really. (Disagree) [10%]
- No. (Strongly Disagree) [10%]

P4: In your opinion, what are the key features that enable a zero/low carbon residential energy system? (multi-choice)

- Wood fired boiler [12%]
- Wood stove/heater [53%]
- Pellet stove/heater [18%]
- Heat pumps [64%]
- Good insulation [82%]
- Thermal storage [47%]
- Solar Thermal [47%]
- Solar PV [58%]
- Energy Storage (Battery Backup, etc.) [47%]

P5: In a zero/low carbon home should wood be the primary or secondary form of heat (choose one)?

- Primary heater [31%]
- Secondary heater [69%]

P6: What would be most helpful in facilitating the adoption and integration of wood heat into more homes (choose one)?

- Direct subsidies to homeowners [18%]
- Investment in newer/more-integrated technologies [29%]
- Regulatory changes [29%]
- Other [24%]

Presentation Slides:

Virtual Workshop on: Adoption of new wood heater technology and integration with other renewables

Welcome to

Breakout Session D

Integrating wood heat with other residential energy systems.

Thank you for joining us.

We will begin our session shortly.

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Virtual Workshop on: Adoption of new wood heater technology and integration with other renewables

Breakout Session D

PRE-SESSION POLL QUESTIONS

What is your area of expertise/background (one-choice)?

- Manufacturer of Wood Heater (stoves, furnaces, hydronic, hybrid)
- Certified Test Lab
- Research Organization
- Federal or State Agency
- University / College
- Non-Governmental Agency (NGO)
- Other

What is one thing you hope to gain from this session (one-choice)?

- To discuss pollutant emission(s) and emission metrics besides PM, which are relevant to health and the environment.
- To discuss how to measure health relevant pollutant emissions besides PM mass.
- Networking/Partnering/Teaming
- Other

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Virtual Workshop on: Adoption of new wood heater technology and integration with other renewables

Breakout Session D

Breakout Session Logistics:

- Schedule – 12:00 to 1:00pm
- ZOOM format to be used
- Use the raise hand feature to ask for the mic
- Facilitators will be leading discussions and switching direction as appropriate
- There is a designated scribe in the breakout session taking notes. Notes will represent a collective summary and not specifically apply to individuals
- These sessions will **NOT** be recorded
- A summary and highlights of the session will be presented by one or more of the facilitators at the closing remarks
- Be bold, ask questions, bring up innovative solutions, identify problems
- Overall Goal of the Session –

1. How much can the topic area contribute to achieving far cleaner biomass combustion systems
2. What technology areas within this topic have the most potential to be impactful

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Virtual Workshop on: Adoption of new wood heater technology and integration with other renewables

Breakout Session D

Meet the Panelists:

Scott Nichols
Owner & President
Tarm USA Inc.
Manufacturer of Wood Fired Hydronic Heaters

Richard Gibbs
Owner of Hidely Farms[1] & Retired Research Scientist[2]
1. A demonstration cite for renewable energy in NYS
2. New York State Department of Environmental Conservation

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Breakout Session D

Question # 1:

Can you share your favorite success story for integration of wood heat and other clean heat and/or power generating technologies?

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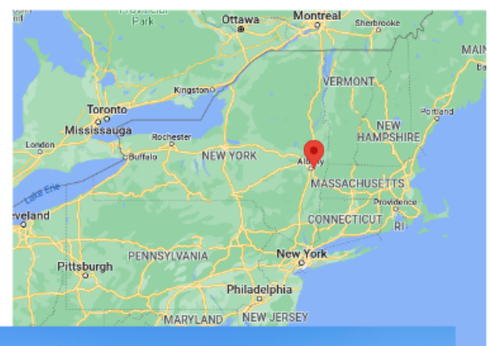
Breakout Session D

Hidley Farm at a Glance:

- Located in North Greenbush, NY
- Demonstration site for Renewable Heat NY
- Features multiple renewable energy technologies



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Virtual Workshop on: Adoption of new wood heater technology and integration with other renewables

Breakout Session D

Hidley Farm Features:

- High Efficiency 200,000 BTU/hr Econburn Cordwood 2-stage gasification combustion boiler
- Wood Storage Shed
- Thermal Storage Tanks
- Solar PV
- Solar Thermal

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Breakout Session D

Question # 2:

What sets biomass apart from other renewable energy systems? For you where does biomass stand as a carbon neutral energy source?

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Breakout Session D

Question # 3:

In your opinion, what are the key features that enable a zero/low carbon residential energy system?

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Breakout Session D

Question # 4:

Where does wood heat fit into a multi-source heating system?

- ***What technologies pair best with wood?***
- ***What percentage of your yearly heat demand can be met with wood heaters?***

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Breakout Session D

Question # 5:

What pitfalls exist integrating wood heating into an existing residential energy system? What upfront cost can be expected?

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Breakout Session D

Question # 6:

How can we as a community facilitate integrating wood heat into more homes?

- *What barriers exist in this path?*
- *What tools would be most helpful in this endeavor?*

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Appendix D: vFairs Description and vFairs Post Event Reports

The vFairs virtual conference platform was used for each workshop and engaged the audience through the interactive event. The platform provides a range of features and tools to help organizations create immersive and engaging online events, including customizable virtual booths, live webinars and video sessions, chat and networking features, interactive polls and surveys, and analytics and reporting. The vFairs platform was designed to be user-friendly for both event organizers and attendees. It required no software installation or downloads, and could be accessed through any web browser on desktop or mobile devices. Additionally, vFairs offered a high level of customization, allowing organizations to tailor their virtual events to their specific needs and branding. The Organizing Committee used vFairs to set up an auditorium for the plenary sessions and individual breakout rooms for each of the sessions. An information desk was also available for participants to help navigate through the virtual platform and a lounge that served as an additional networking tool. Participants were encouraged to continue conversations from the breakout sessions in the lounge at the conclusion of each event.

To further disseminate information, poster sessions and exhibit booths similar to what you might expect at an in-person conference were also arranged. Abstracts were solicited for both poster sessions and exhibit booths to give participants the opportunity to showcase their research or technology related to wood heaters. The exhibit booth allowed participants to create a unique look and feel through the use of graphics, including materials such as flyers, brochures and other documents. Both options gave participants the ability to speak with attendees via traditional chat functions or through video. Participants were asked to not be overly commercial meaning no dollar amounts and "buy now before it's too late" type of advertising. However, hyping the benefits of your product and including your website, phone, email, etc. is acceptable.

The Organizing Committee was especially interested in new and emerging research in:

- Modeling biomass combustion
- Advanced control strategies
- Advanced combustion strategies
- Catalysts
- ESP's
- Advanced hydronic heater design concepts
- Machine Learning/AI in wood heaters
- General information about the company, institution, or university that may help meet others in the industry to establish a strong team for future FOA’s or promote wood heater R&D

For each event a post event report was created to highlight the vFairs platform. Specifically, statistics are reported in terms of overall participation, booth and poster visits and downloaded documents, and individual session attendance.

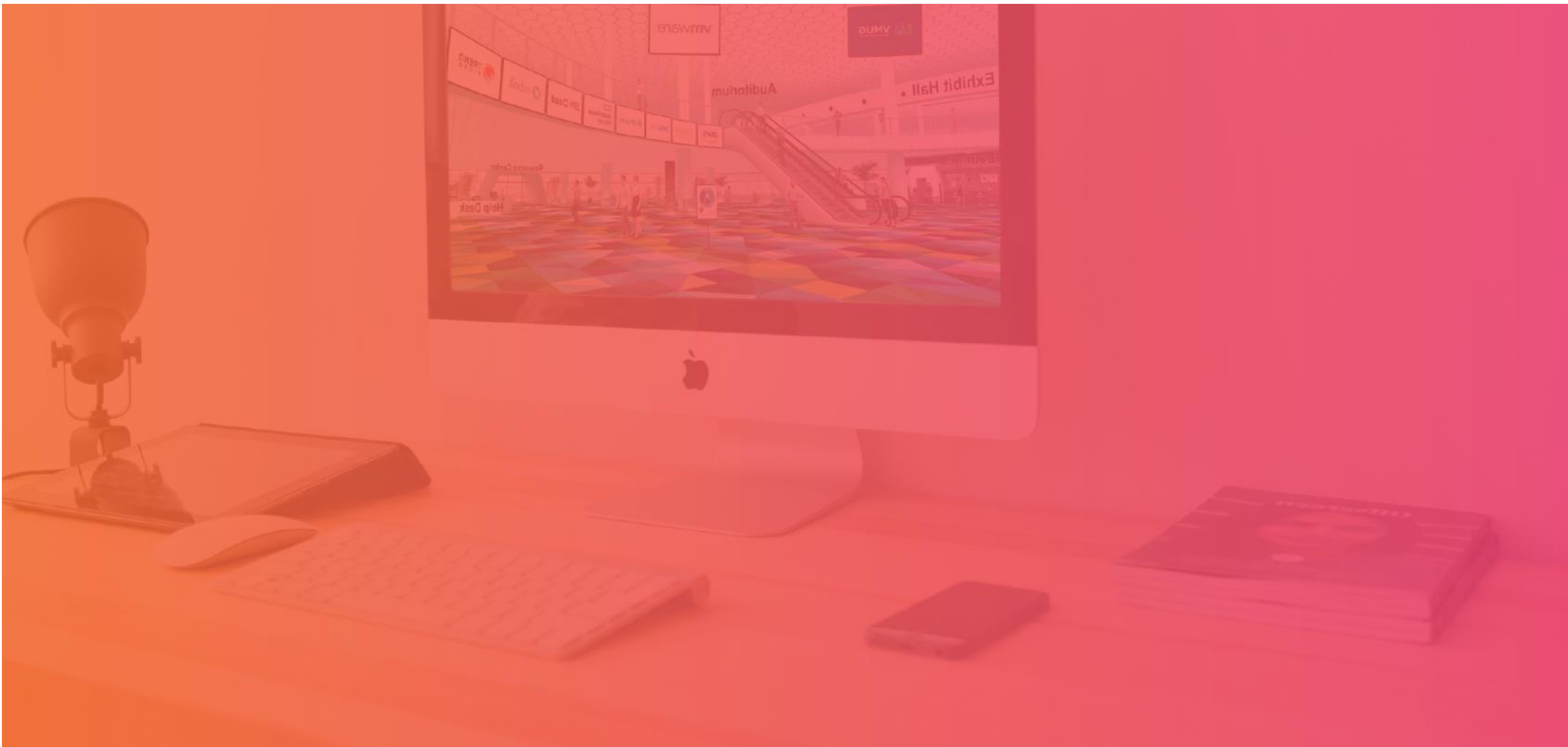
vFAIRS

POST EVENT REPORT

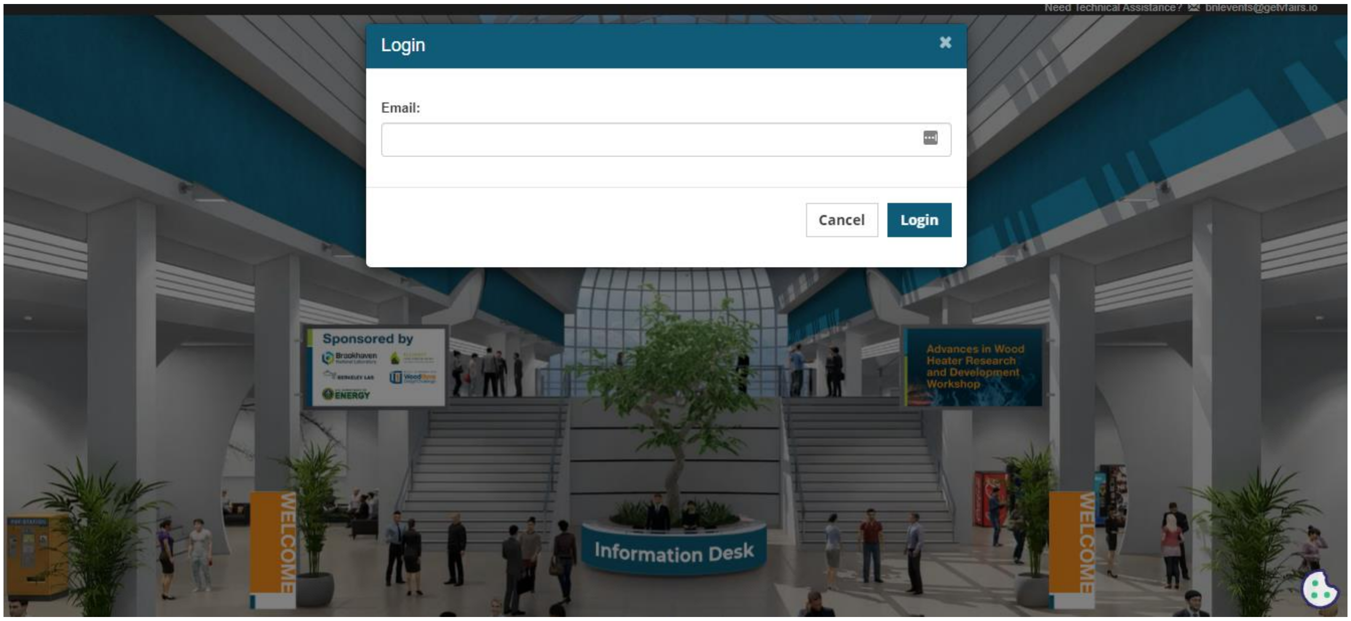
PM: Osama Sarwar
REGION: United States of America

Advances in Wood Heater Research and Development Workshop

11th January to 12th January 2022



LANDING PAGE

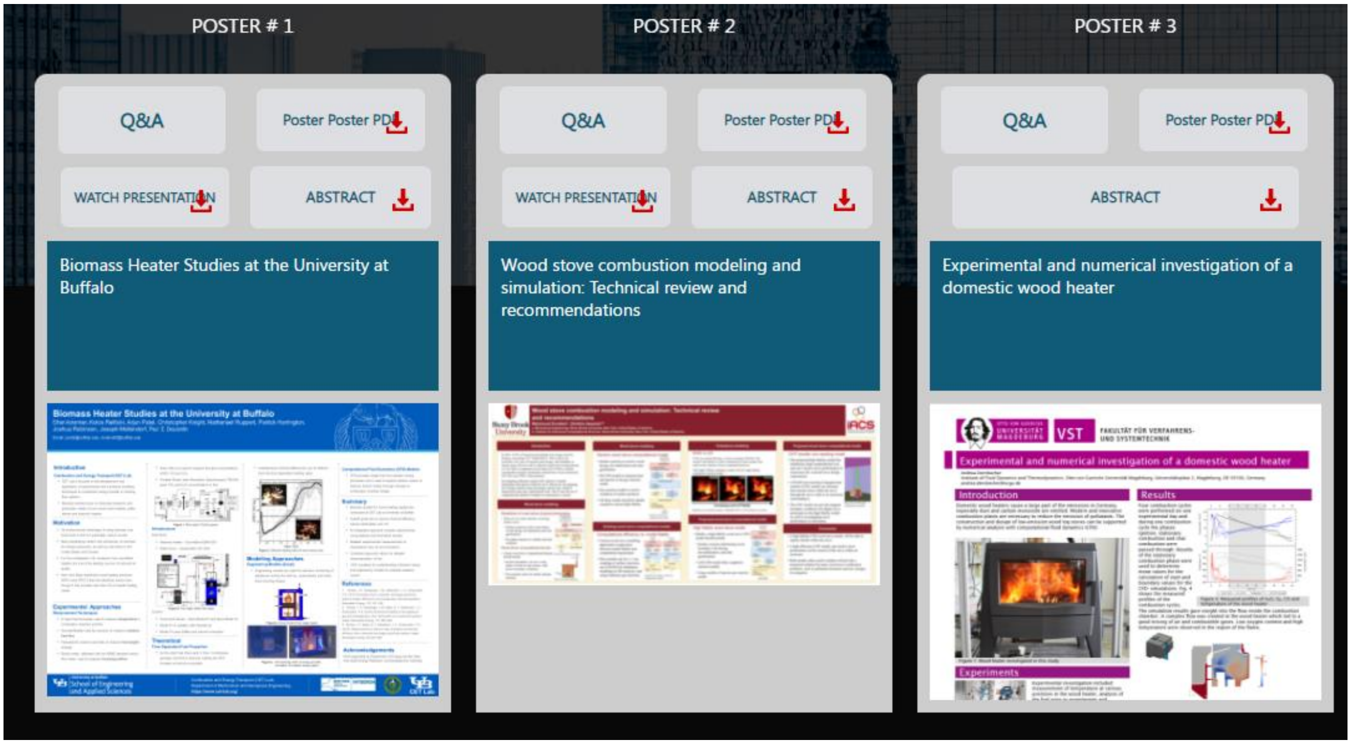


LOBBY

AUDITORIUM

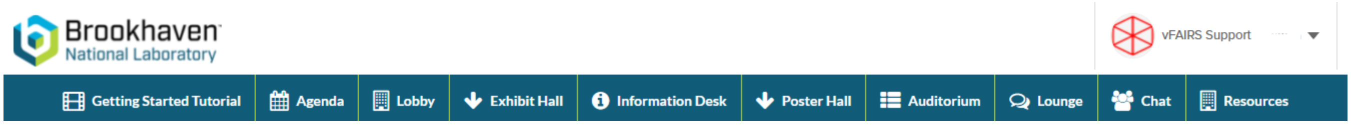
EXHIBIT HALL

POSTER HALL



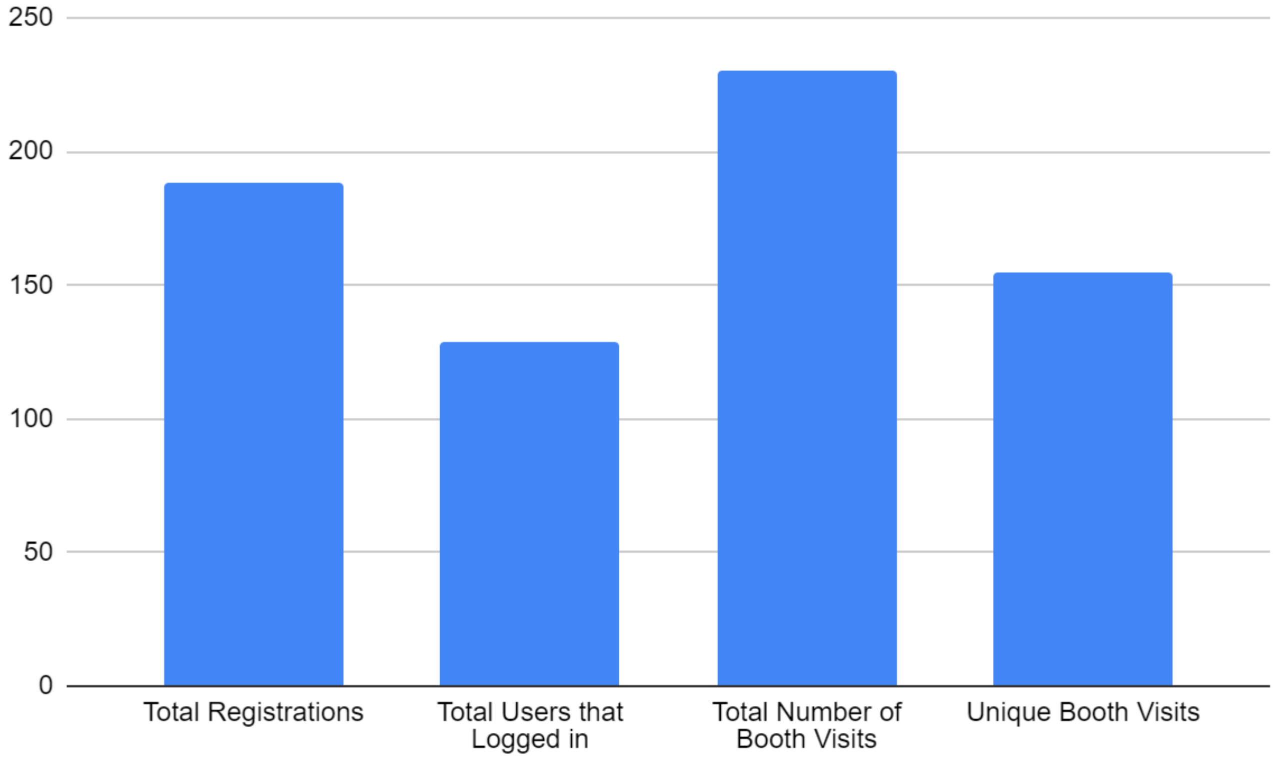
INFORMATION DESK

NAVIGATION BAR

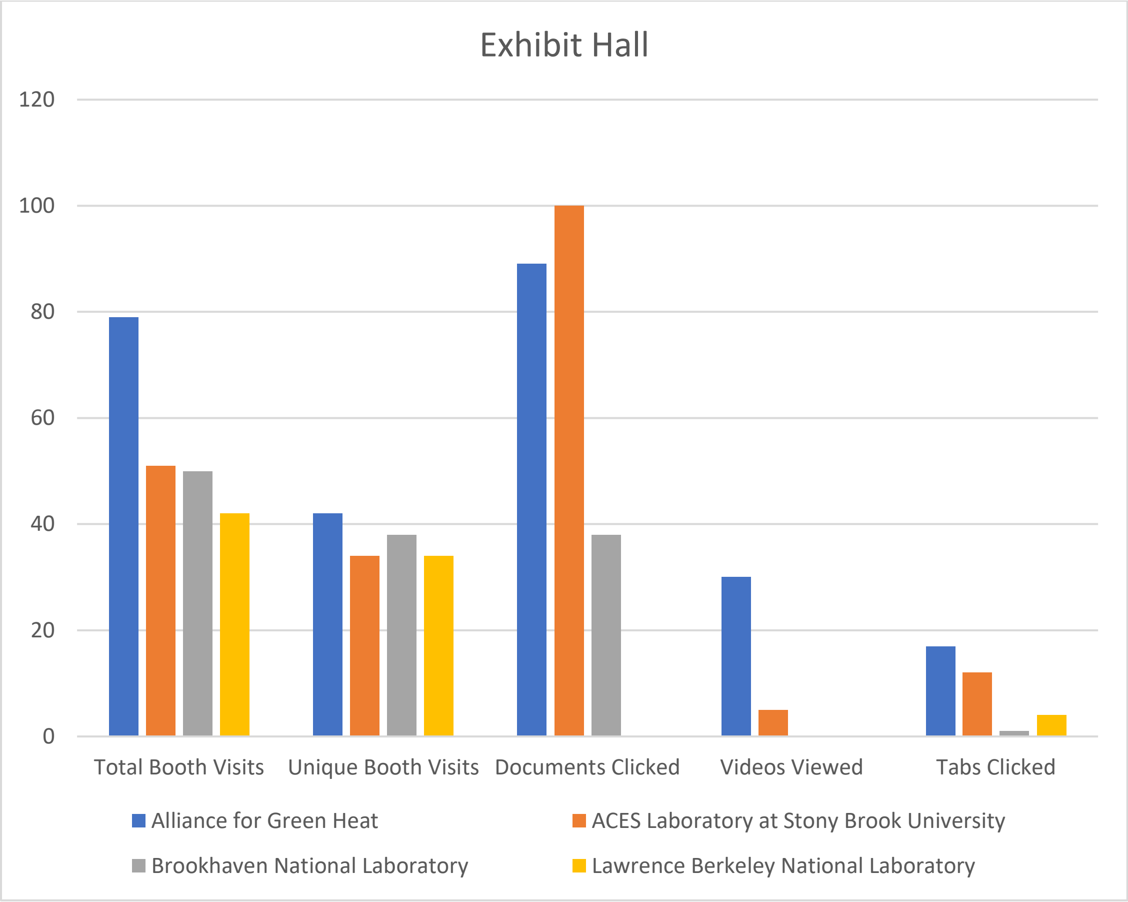


LOUNGE

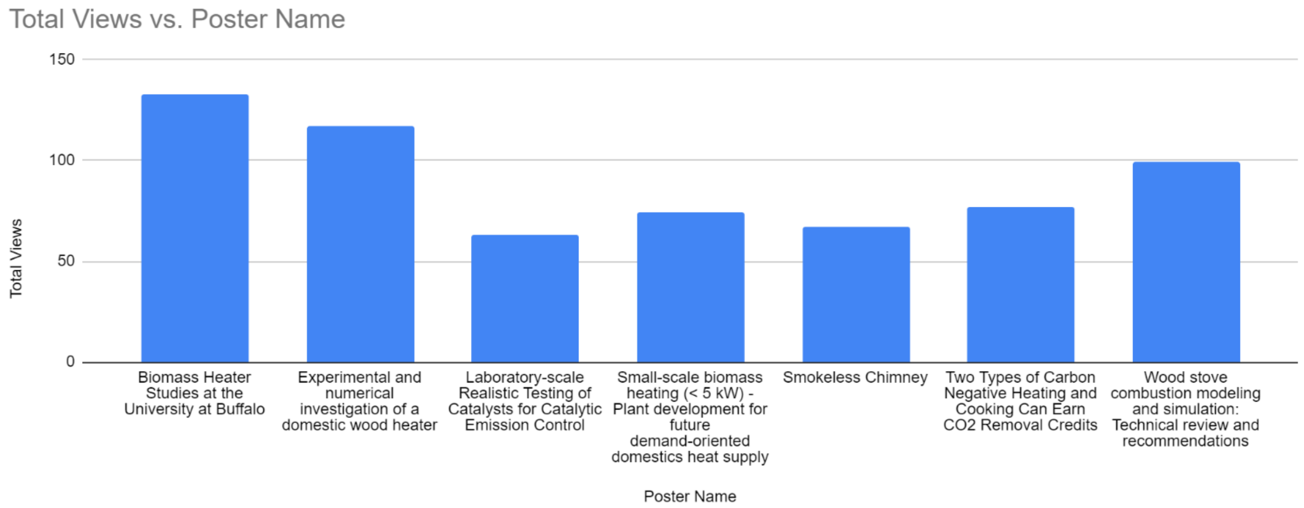
ATTENDEES' PARTICIPATION STATISTICS



GRAPHICAL REPRESENTATION OF BOOTH STATS



GRAPHICAL REPRESENTATION OF POSTER STATS *(Total Views)*

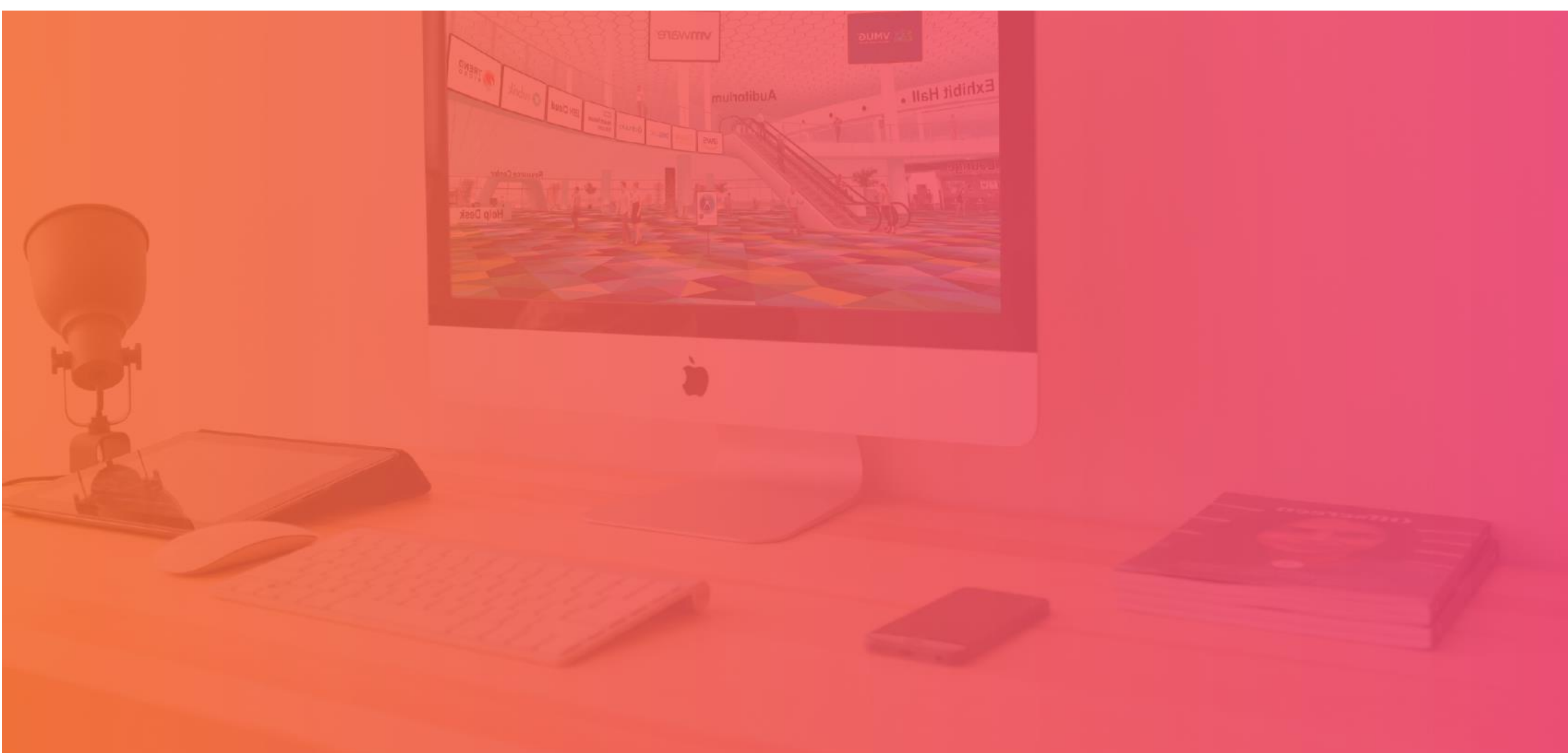


POST EVENT REPORT

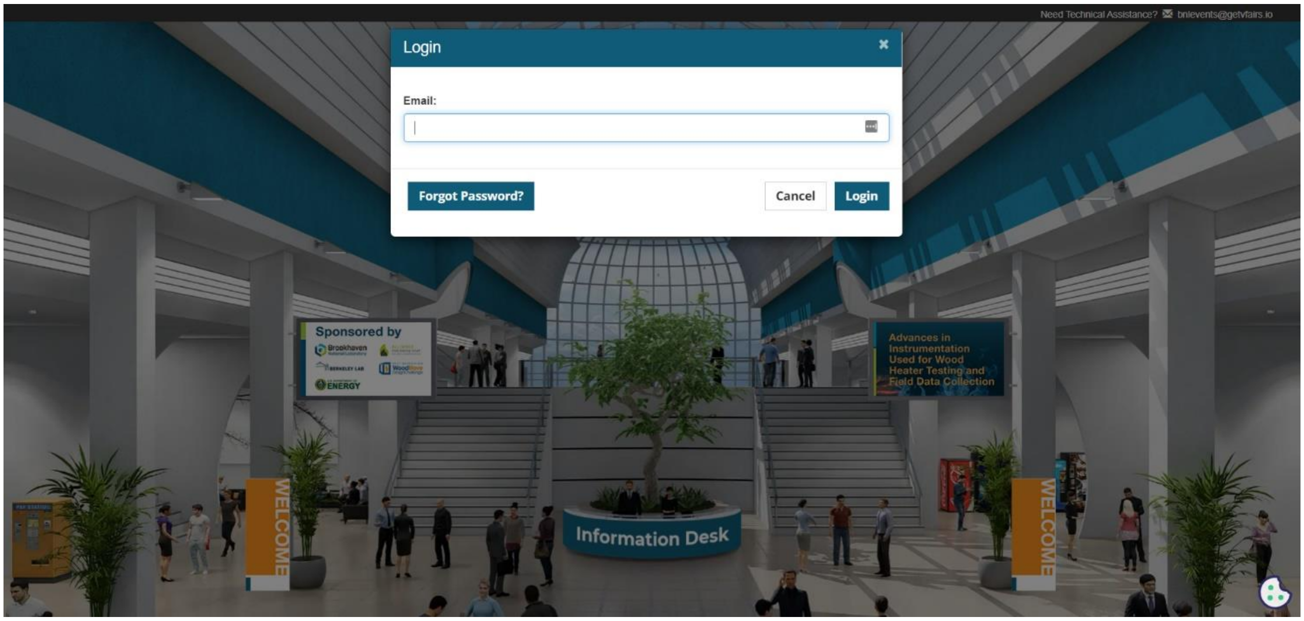
PM: Osama Sarwar
REGION: America/Detroit

Advances in Instrumentation Used for Wood Heater Testing and Field Data Collection

28th March to 29th March 2022



LANDING PAGE



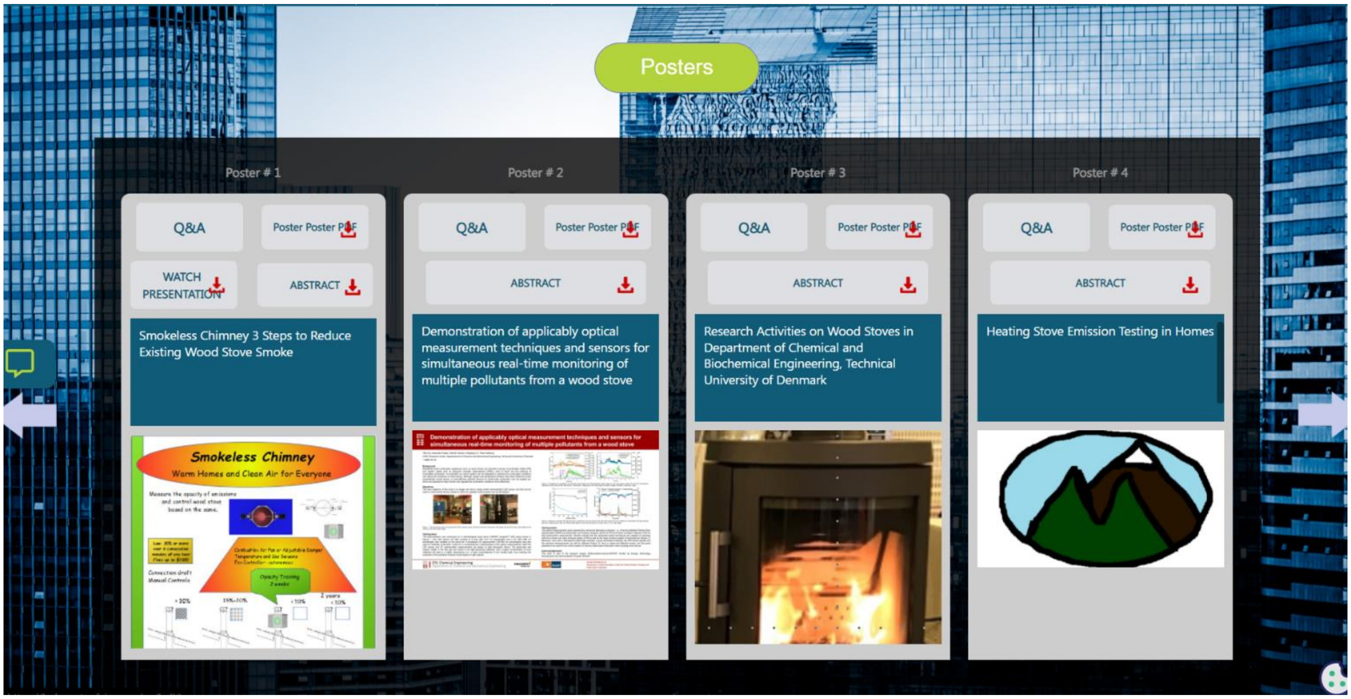
LOBBY

AUDITORIUM


Advances in Instrumentation Used for Wood Heater Testing and Field Data Collection
JOIN EVENT

EXHIBIT HALL

POSTER HALL



INFORMATION DESK

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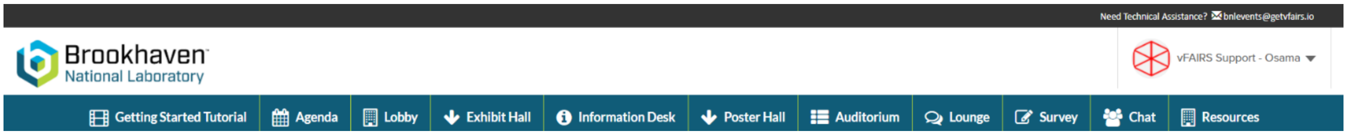
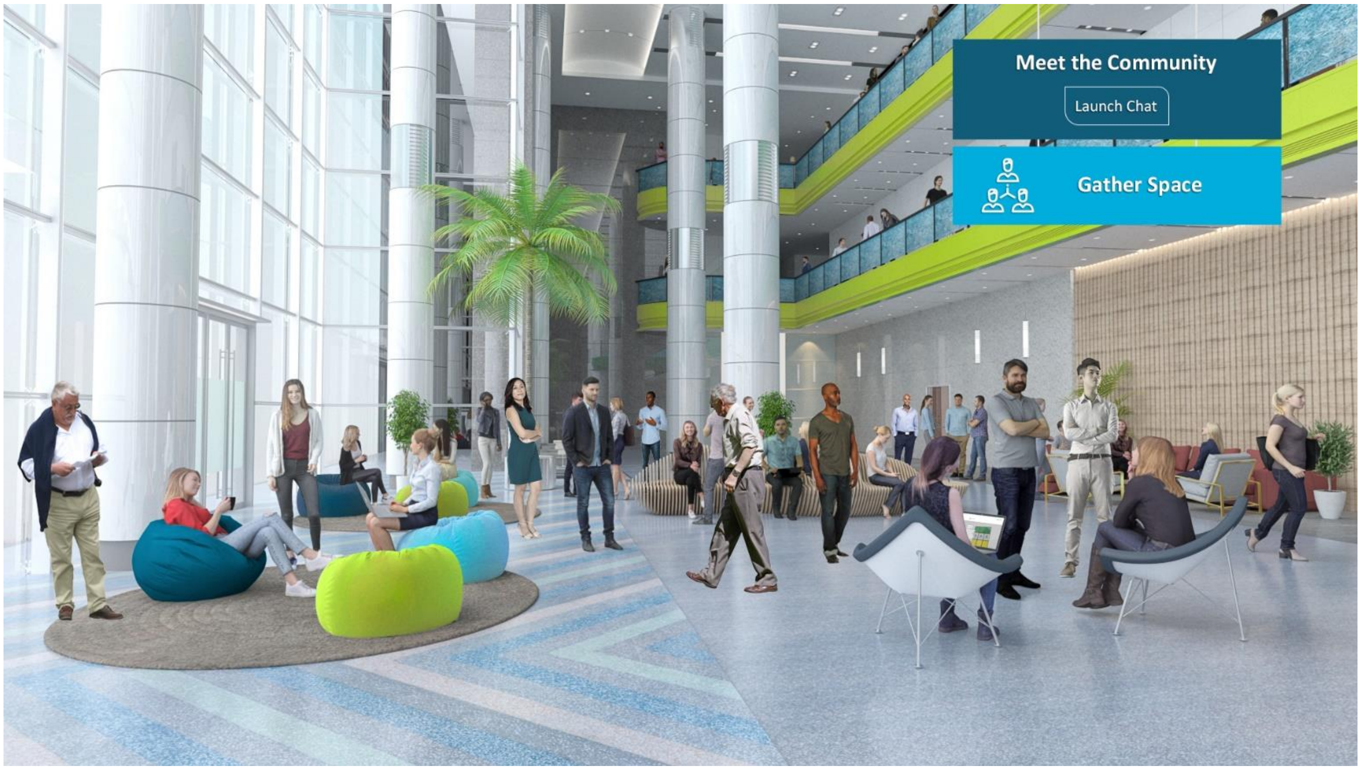


LOUNGE



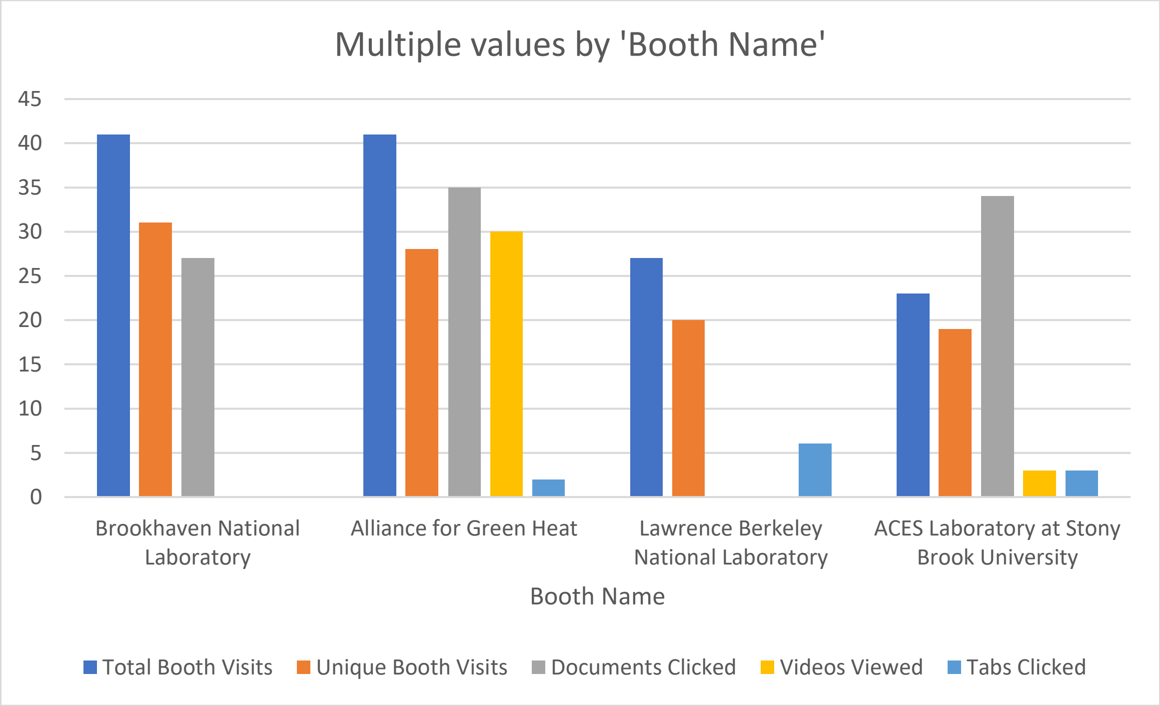
ATTENDEES' PARTICIPATION STATISTICS

Total Registrations	**233**
Total Users that Logged in	155
Total Number of Booth Visits	**136**
Unique Booth Visits	102

Booth Stats

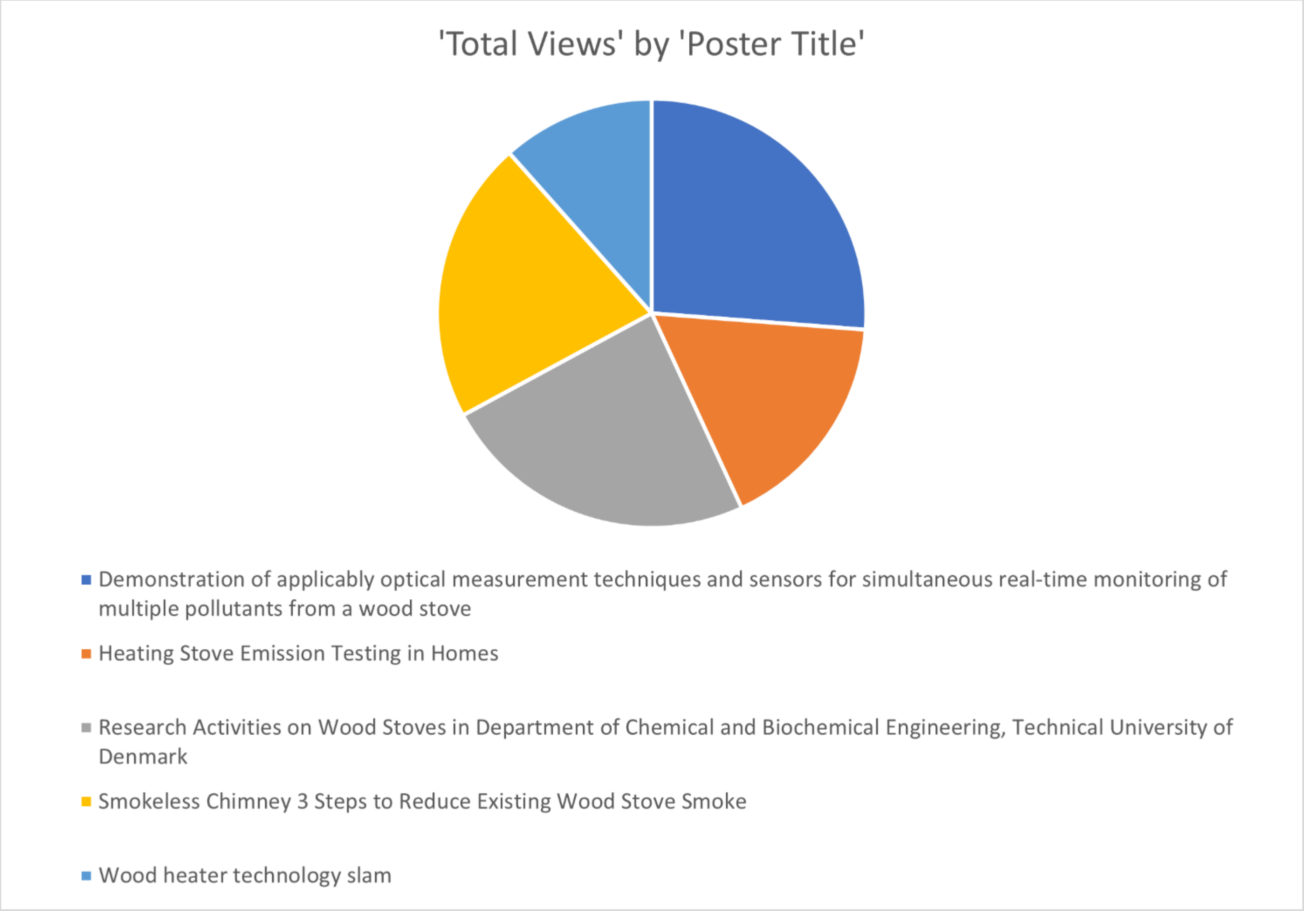
Booth Name	Total Booth Visits	Unique Booth Visits	Documents Clicked	Videos Viewed	Tabs Clicked
Alliance for Green Heat	41	28	35	30	2
ACES Laboratory at Stony Brook University	23	19	34	3	3
Brookhaven National Laboratory	41	31	27	0	0
Lawrence Berkeley National Laboratory	27	20	0	0	6

GRAPHICAL REPRESENTATION OF BOOTH STATS



Poster STATS *(Total Views)*

Poster Title	Total Views
Demonstration of applicably optical measurement techniques and sensors for simultaneous real-time monitoring of multiple pollutants from a wood stove	59
Heating Stove Emission Testing in Homes	38
Research Activities on Wood Stoves in Department of Chemical and Biochemical Engineering, Technical University of Denmark	54
Smokeless Chimney 3 Steps to Reduce Existing Wood Stove Smoke	48
Wood heater technology slam	26

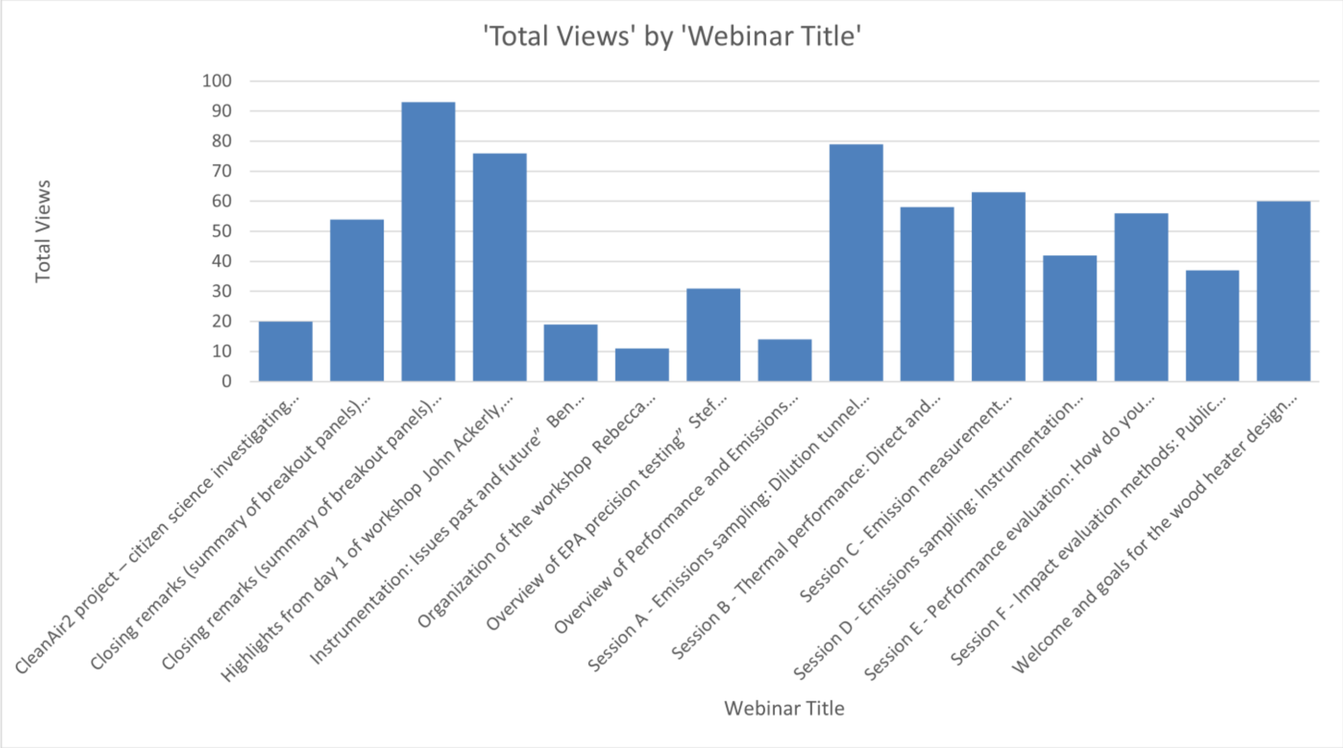


WEBINAR STATS *(Total Views)*

Webinar Title	Total Views
CleanAir2 project – citizen science investigating real-life emission from firewood stoves" Manuel Schwabl, BEST	20
Closing remarks (summary of breakout panels) Jake Lindberg, BNL	54
Closing remarks (summary of breakout panels) Vi Rapp, LBNL	93
Highlights from day 1 of workshop John Ackerly, AGH	76
Instrumentation: Issues past and future" Ben Myren, Myren Consulting, Inc.	19

Organization of the workshop Rebecca Trojanowski, BNL	11
Overview of EPA precision testing" Stef Johnson, US EPA Angelina Brashear, US EPA	31
Overview of Performance and Emissions Evaluation" Julian Caubel, LBNL	14
Session A - Emissions sampling: Dilution tunnel vs. Flue	79
Session B - Thermal performance: Direct and indirect methods	58
Session C - Emission measurement instrumentation: PM and Gaseous pollutants	63
Session D - Emissions sampling: Instrumentation and dilution	42
Session E - Performance evaluation: How do you measure performance in the field?	56
Session F - Impact evaluation methods: Public health and the environment	37
Welcome and goals for the wood heater design challenge and the workshop Mark Shmorhun, DOE	60

GRAPHICAL REPRESENTATION OF WEBINAR STATS *(Total Views)*

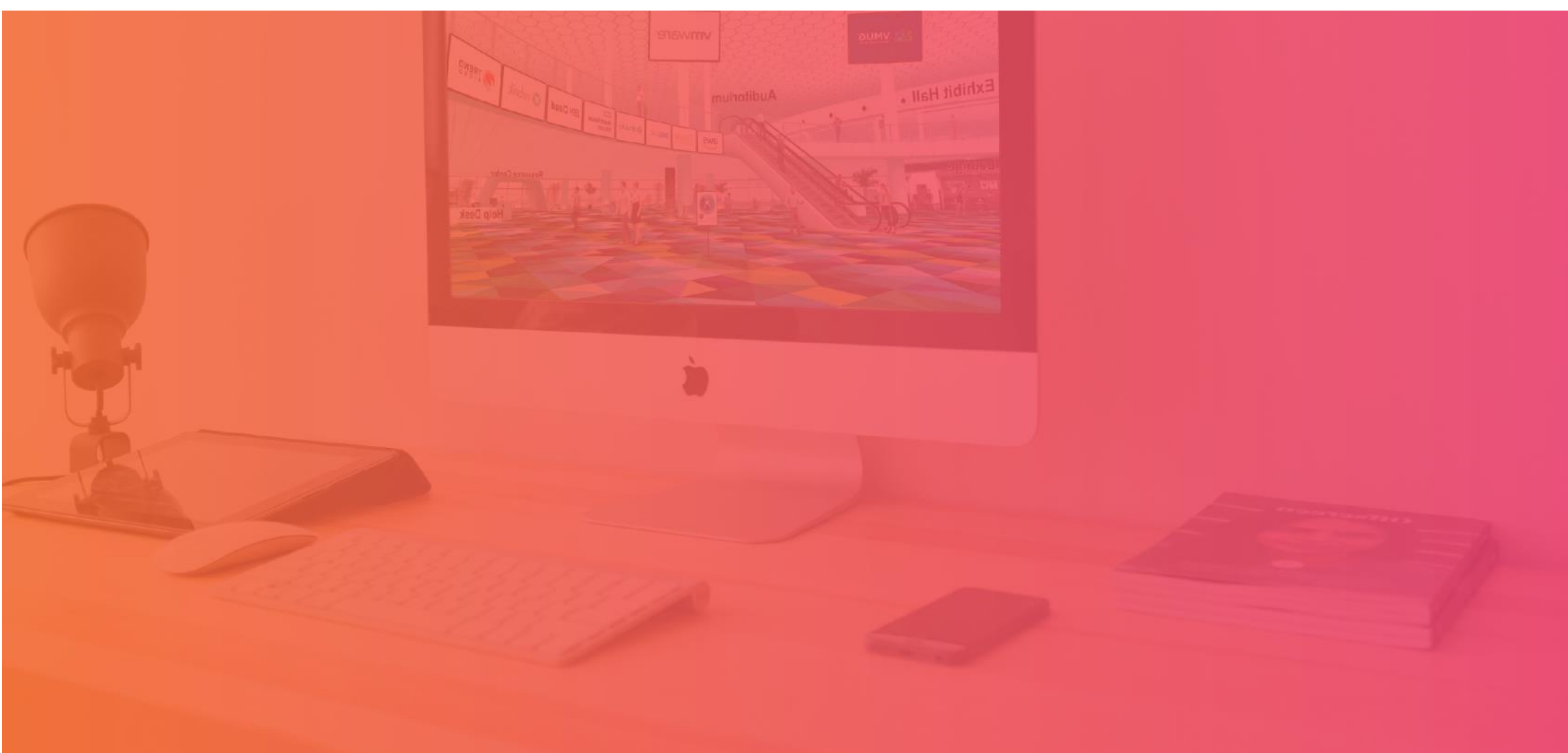


POST EVENT REPORT

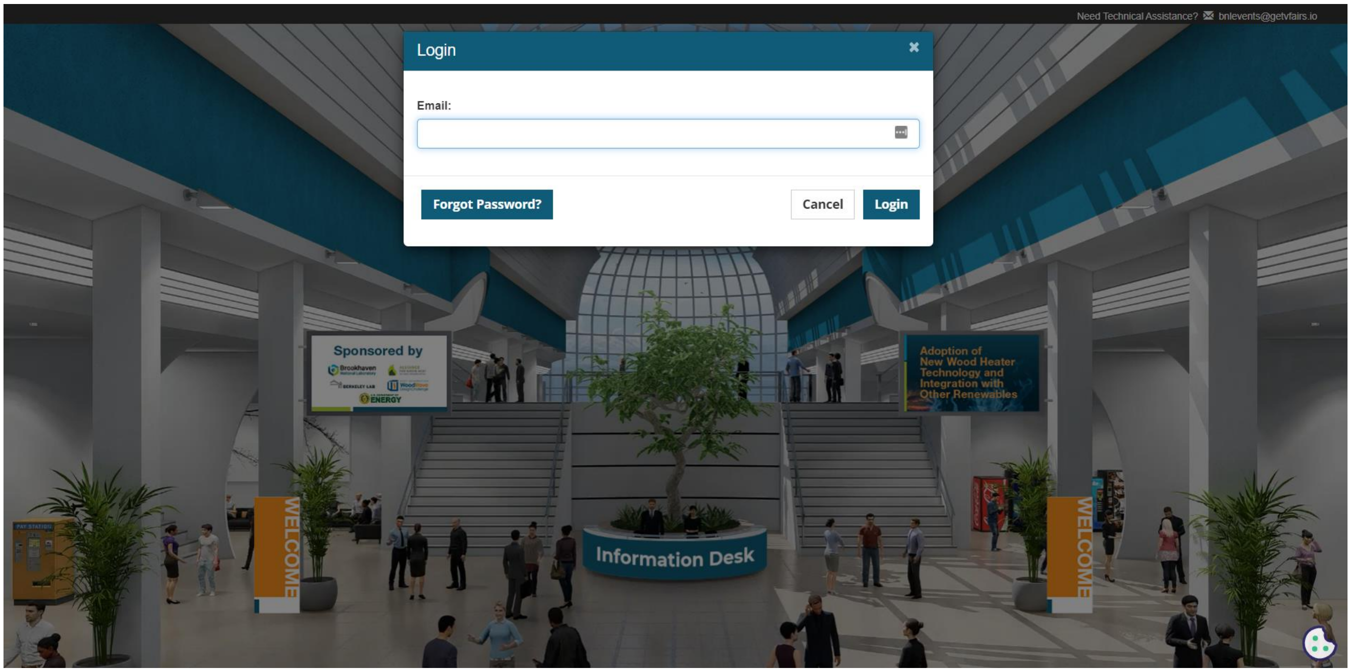
PM: Osama Sarwar
REGION: America/Detroit

Adoption of New Wood Heater Technology and Integration with Other Renewables Workshop

26th April to 27th April 2022



LANDING PAGE



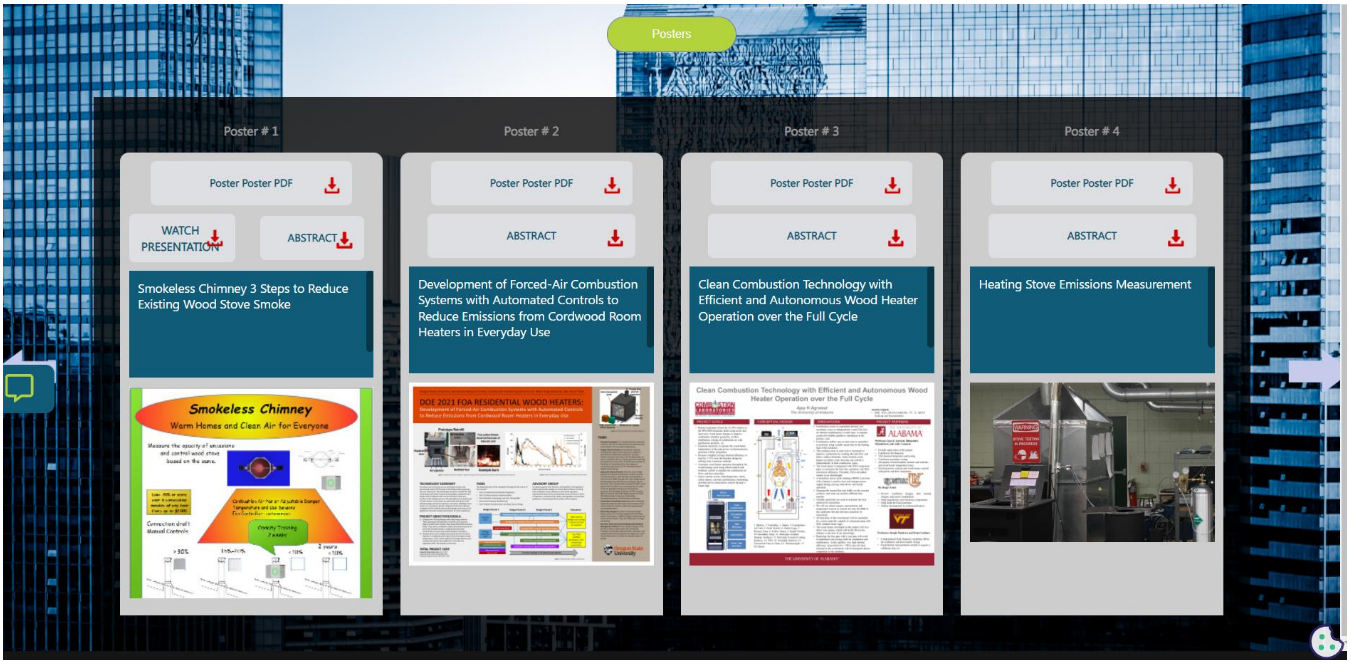
LOBBY

AUDITORIUM


Adoption of
New Wood Heater
Technology and
Integration with
Other Renewables
JOIN EVENT

EXHIBIT HALL

POSTER HALL



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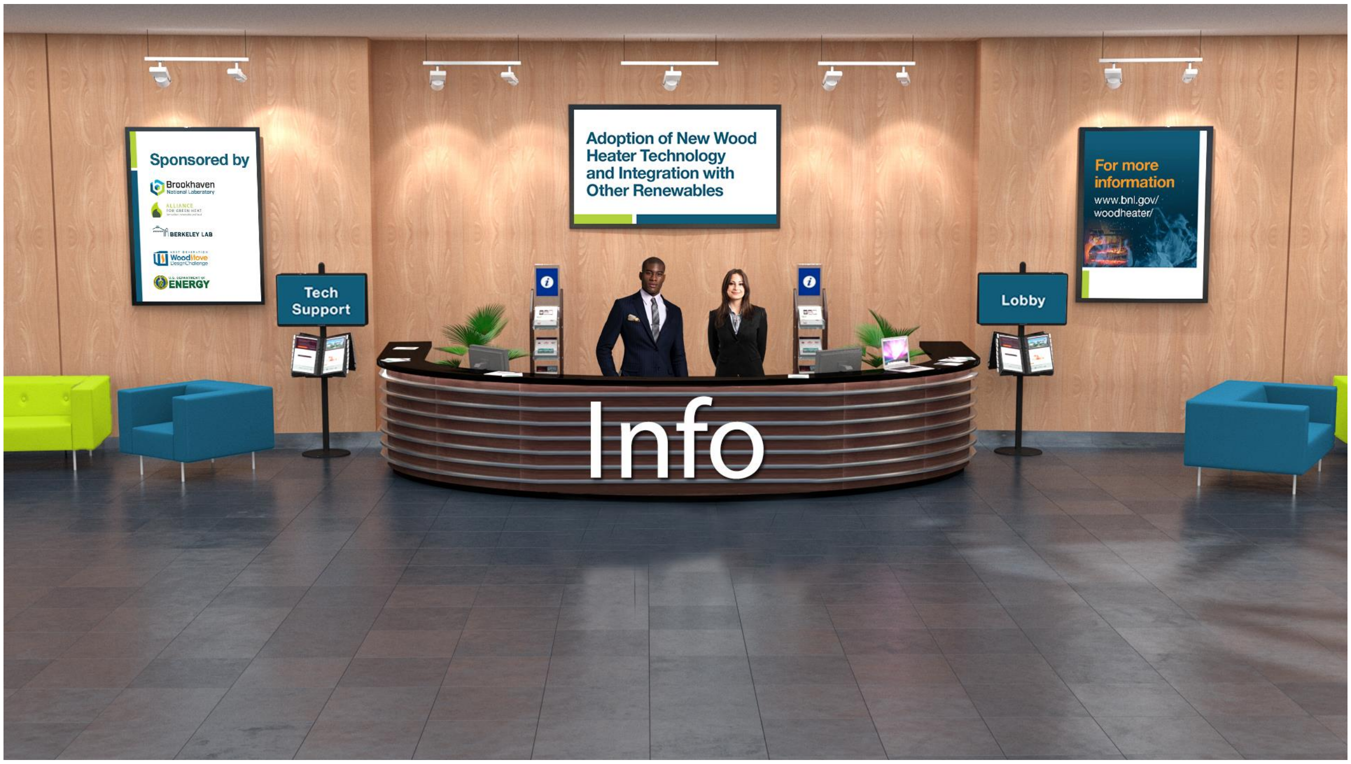
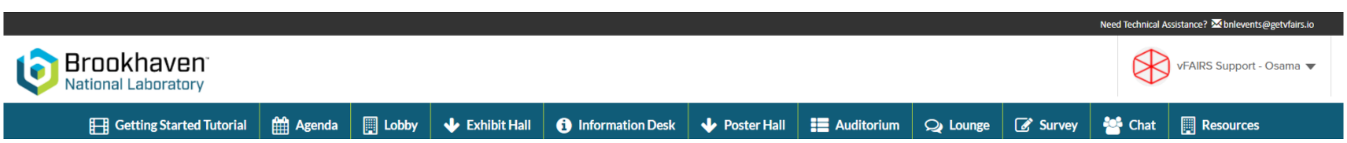
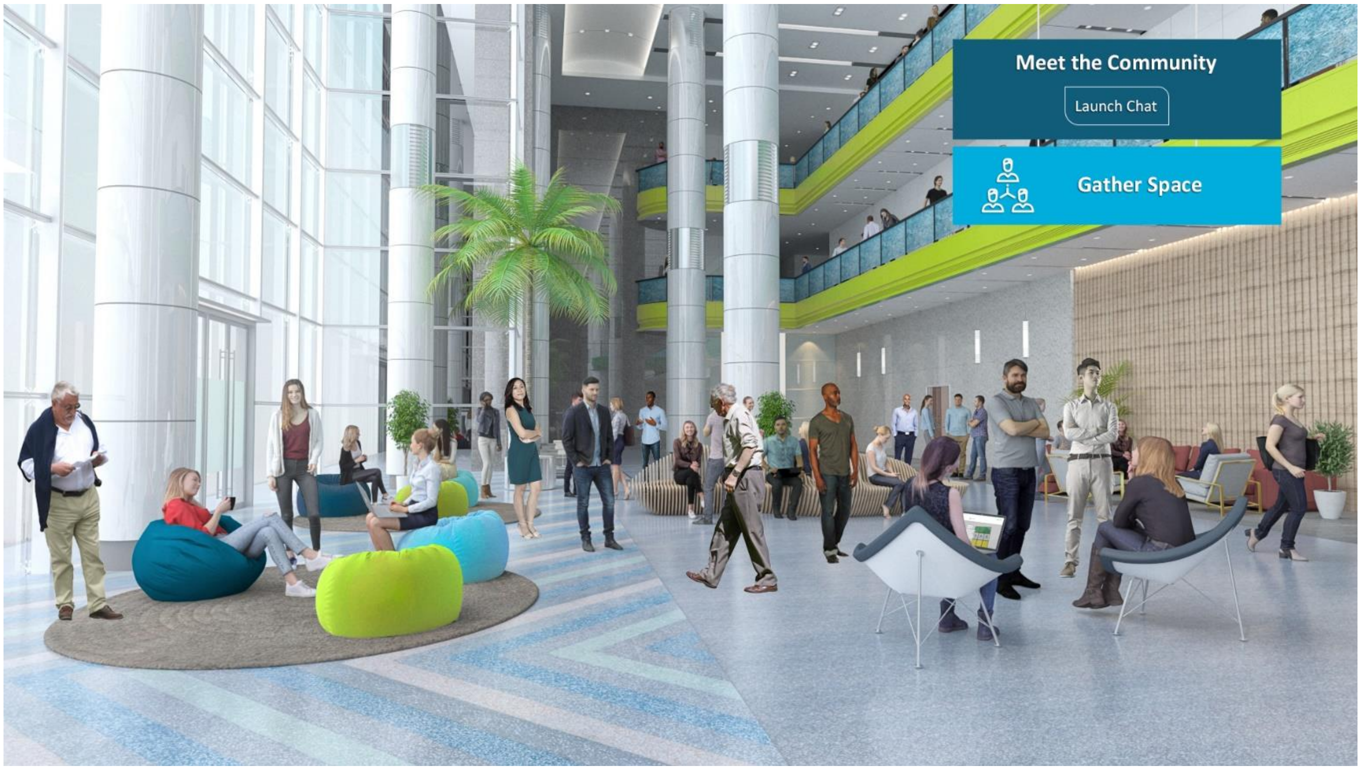


NAVIGATION BAR



LOUNGE



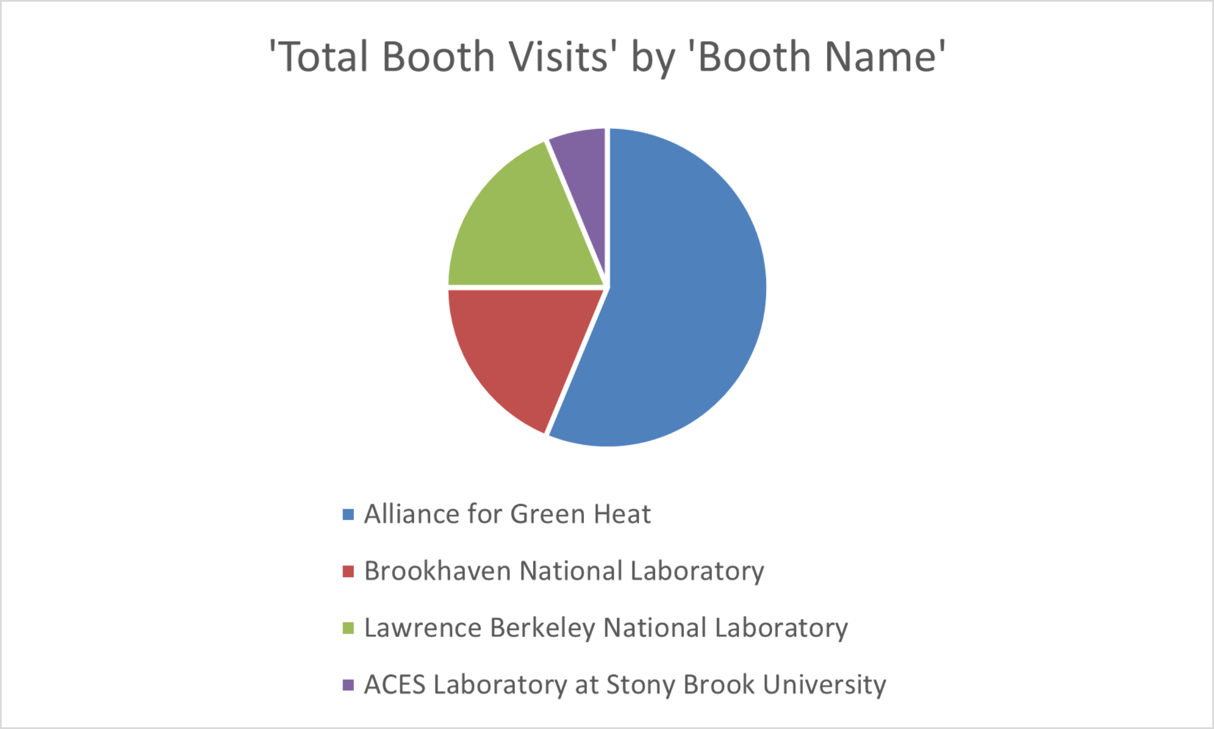
ATTENDEES' PARTICIPATION STATISTICS

Total Registrations	**271**
Total Users that Logged in	**82**
Total Number of Booth Visits	**16**
Unique Booth Visits	**16**

Booth Stats

Booth Name	**Total Booth Visits**
Alliance for Green Heat	9
Brookhaven National Laboratory	3
Lawrence Berkeley National Laboratory	3
ACES Laboratory at Stony Brook University	1

GRAPHICAL REPRESENTATION OF BOOTH STATS



Poster STATS *(Total Views)*

Poster Title	Total Views
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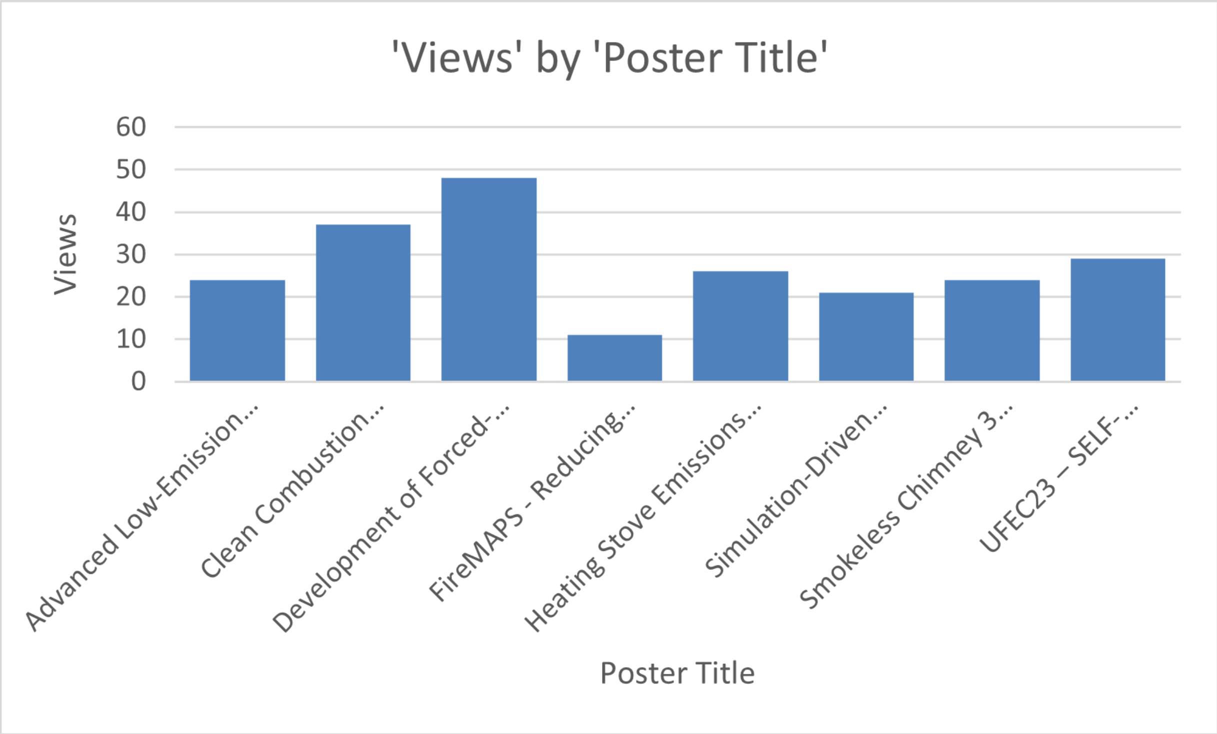

WEBINAR STATS *(Total Views)*

Webinar Title	Total Views
A Review of Field Test Experience Past WHDCs and Beyond	3
Biomass Heat in Renewable Energy Portfolios	5
Closing Remarks (Summary of Breakout Panels)	51
Emerging Technologies From Abroad: A Report From World Sustainable Energy Days 2022	3
Highlights From Day One of Workshop	38
Introducing Integrated Duty Cycle Test Methods	17
Organization of the Workshop	4
Research & Development – Manufacturers' Perspective and DOE Project Updates	15
Session A - Adding Automation to a Wood Heater Q&A	43
Session B - Impact Evaluation: Quantifying Health, Energy, & Climate Impacts for Biomass Heat Deployment	37
Session C - DOE/National Lab Q&A Tech Slam, 5th Design Challenge, and Future Events	25
Session D - Integrating Wood Heat With Other Residential Energy Systems	31
Welcome and Goals for the Wood Heater Design Challenge and Workshop	37

GRAPHICAL REPRESENTATION OF WEBINAR STATS *(Total Views)*