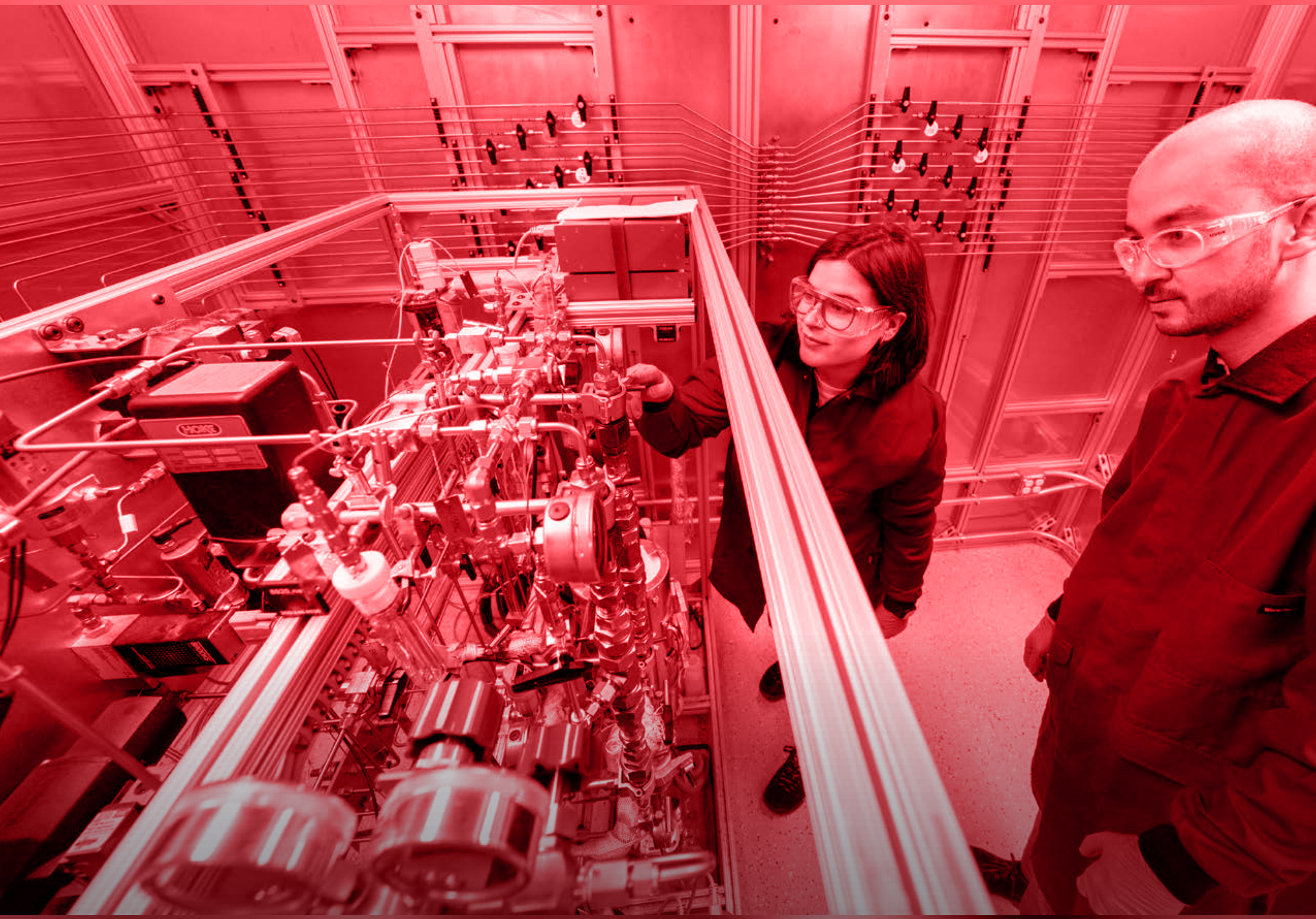


SYSTEMS DEVELOPMENT AND INTEGRATION: EMERGING AND SUPPORTING TECHNOLOGIES

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

The Systems Development and Integration – Emerging and Supporting Technologies (SDI-EAST) Technology Area is one of 12 technology areas reviewed during the 2023 Bioenergy Technologies Office (BETO) Project Peer Review, which took place April 3–7, 2023, in Denver, Colorado. A total of 26 presentations were reviewed in the SDI-EAST session by five external experts from industry and academia. For information about the structure, strategy, and implementation of the SDI-EAST Technology Area and its relation to BETO's overall mission, please refer to the corresponding Program and Technology Area Overview presentation slide decks (energy.gov/eere/bioenergy/systems-development-integration-emerging-and-supporting-technologies).

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $57.8 million, which represents approximately 10% of the BETO portfolio reviewed during the 2023 Peer Review. During the Project Peer Review meeting, the presenter for each project was given 30 minutes to deliver a presentation and respond to questions from the review panel.

Projects were evaluated and scored for their approach, impact, and progress and outcomes. This section of the report contains the Review Panel Summary Report, the Technology Area Programmatic Response, and the full results of the Project Peer Review, including scoring information for each project, comments from each reviewer, and the response provided by the project team.

BETO designated Robert Natelson as the SDI-EAST Technology Area review lead, with contractor support from Remy Biron of Boston Government Services. In this capacity, Robert Natelson was responsible for all aspects of review planning and implementation.

SYSTEMS DEVELOPMENT AND INTEGRATION – EMERGING AND SUPPORTING TECHNOLOGIES REVIEW PANEL

Name	Affiliation
Gene Petersen*	Retired
Corey Leclerc	New Mexico Institute of Mining and Technology
Marie-Odile Fortier	University of Nevada, Las Vegas
Rishi Shukla	Archer Daniels Midland Company
Amit Goyal	DNV

* Lead Reviewer

SYSTEMS DEVELOPMENT AND INTEGRATION – EMERGING AND SUPPORTING TECHNOLOGIES REVIEW PANEL SUMMARY REPORT

Prepared by the Systems Development and Integration – Emerging and Supporting Technologies Review Panel

INTRODUCTION

The SDI component of the BETO program deals with technologies that are on track to evolve into demonstration-level systems or are involved in supporting demonstration or commercialization efforts. As such, they have developed a strategy that looks at this process from an industry point of view. The SDI component is addressing the potential for taking technology beyond the R&D stage into actual implementation and readiness for commercialization. Its span of projects and focus on catalyzing the development and commercialization of promising bioenergy technologies are pivotal to the continued growth of the bioenergy sector.

Their mission is well defined, including their contribution to the Sustainable Aviation Fuel (SAF) Grand Challenge, which, along with other federal agencies, is to enable industry to produce 35 billion gallons/year by 2050 with a near-term milestone of 3 billion gallons by 2030. As part of this larger effort, BETO has a target goal of having four projects undertake a demonstration-level effort in producing SAF. To get there, they have included several projects in their portfolio that have the potential to achieve this. In addition, they have kept the door open to newer technologies through funding some emerging technologies that have promise. In SDI-EAST, the program has sought industry and stakeholders via workshops and the inclusion of industry participants in funding opportunity announcement (FOA) reviews. The critical paths have changed over the years, and the SDI program has sought to fill these gaps with opportunities for the R&D community to participate via FOAs. The latest FOAs are getting more precise, so the mission, goals, and targets are getting clearer. To develop the program, almost every project had industry or stakeholder input. In addition, they have filled gaps with annual operating plan (AOP) efforts for crosscutting and enabling technologies. Another strategy tool that was employed was the use of road maps that outline the technology development needed and opportunities for public-private partnerships. The current emphasis in the new Multi-Year Program Plan focuses on reducing carbon intensity and increasing carbon dioxide (CO_2) reduction in areas beyond light-duty fuels. These have driven some program priorities that are reflected in the selection of projects.

The program includes a diverse set of projects, including all pathways—pyrolysis, hydrothermal liquefaction (HTL), upgrading of waste greases and oils, gasification/Fischer-Tropsch, blending, syngas/landfill gas upgrading, aqueous phase, and ethanol conversion unique approaches. Feedstock handling, modeling efforts, and bioproducts reflect the breadth and depth of the program. More importantly, these programs have also mandated high greenhouse gas (GHG) reduction potential and lower cost targets. Stakeholder input in feedstock selection (ethanol, pyrolysis, greases, bio-based solid feedstock handling), market readiness levels, specifications for product/testing, and validation is well documented. Industry-led efforts and participation with academia and nonprofits are good indicators of a well-balanced program. AOP crosscutting and enabling programs have made significant progress. The modeling efforts, the study of marine fuels, and developing coprocessing with refinery streams have all achieved desired results and, more importantly, shared information/tools with the larger community. DOE's initiative to determine how biomass can play a role in marine/rail fuels is new and well directed.

The transportation sector produces significant levels of GHGs. Although BETO has previously looked at light-duty vehicle fuels, they have now broadened their efforts to other very important impact areas that are hard to decarbonize, such as SAF, marine fuels, rail fuels, and other heavy-duty-use fuels. The focus on reducing carbon emissions has put a different spin on some priorities and emphases of R&D within the SDI program.

The current market for light-duty fuels continues to be impacted by electrification, so the SDI program's efforts at finding new directions for bio-based fuels is appropriate.

The effects of the recent pandemic became a bit apparent in some projects. Staffing became an issue for some. BETO may need to be sensitive to deadlines and milestones where this situation occurs and consider extending deliverables as appropriate.

STRATEGY IMPLEMENTATION AND PROGRESS

The industrial-like approach involves increasingly more efforts at due diligence for achieving technology readiness levels (TRLs) and the validation of each step in the progression toward the completion of milestones within each project. Independent analyses of progress along a project's timeline are being effectively implemented. The granularity of technology development in production or system development is much more aligned with industrial technology development and the road to implementation and possibly commercialization. Not all technology development is a linear or smooth path. The requirements for projects in this SDI area include the identification of risks and mitigation strategies, clear performance objectives, and where the system development has an impact on meeting BETO's strategic goals and intermediate performance milestones. These areas are all actively managed by BETO staff through quarterly reports and site visits, where possible and feasible. The program is to be lauded for bringing in expertise beyond their program capabilities to help evaluate progress on projects such as ICF as an independent engineer.

One other salient point of the SDI program is the participation of national laboratories in appropriate areas. These include independent analyses of the potential development of fuel decarbonization efforts in areas such as marine and rail fuels, as well as helping develop tools for enabling system development or establishing analytical criteria that can be used to compare competing technologies.

While yield is very important, a process that is stable and reproducible may allow for a little loss in yield. This is particularly true for commodity products such as fuels; hence, figures of merit or minimum benchmarks should be used to assess the integration of unit operations and allow for the development of proof of the overall system. Then improvements in individual unit operations can be addressed as needed. Some projects hit targets by changing reactor conditions, but that comes at a cost and should be reflected in techno-economic analysis (TEA). But as long as there is more value in the product than the cost of producing it with some margin for profit, the technology can be successfully developed.

The TEA/life cycle analysis (LCA) modeling for each project is appropriate, though there could be a better correlation between LCA related to reducing carbon intensity and emissions and the components of LCA. How the SDI programs supports and pushes the role of LCA in a project will be important to the overall success of the BETO efforts. In this vein, it is a concern that Fischer-Tropsch has not worked in the past and whether it will work with current efforts.

When assessing impacts, the projects should probably address only the market penetration potential of their technology, not the whole market as is typically shown. Process viability and stability is more important than achieving maximum yields or optimum performance. Several projects used technologies that are typically not economically viable. It would be great to see this addressed early on. An example is the use of supercritical anything for a fuel-producing process.

Greases as a source of fuel have long been envisioned. It is worthwhile to see some efforts in assessing this potential. There are existing commercial facilities that produce biodiesel from oils, and if greases can be brought into the supply mix, it would be good for meeting BETO's goals and help deal with an existing waste management issue.

The program has funded three projects on high-value bioproducts under the SDI-EAST portfolio that enable SAF economics. This aligns with most BETO SDI FOAs that allow using up to 50% of carbon for valuable product production other than SAF. The projects showcased the production of different bioproducts using waste streams and have made significant progress in terms of better understating the process conditions and underlying science. One important feature for bioproducts, however, is to meet the required product specifications that are generally more stringent in terms of purity compared to a fuel. On this, the projects seem to lack clear identification of the minimum specifications required to qualify as bioproducts. One initiative that presented on graphite products for battery applications has recently started and made good progress with clear plans for testing, scale-up, and stakeholder engagement. There are some specific comments on a couple of projects. One involves the recovery of methoxyphenol and other compounds from fast pyrolysis waste streams; it is a derivative of a past DOE-funded program (MEGABIO), and, so far, it has demonstrated a mixture of products, with several distillation cuts with no effective separation, and no clear strategy on the future separation of products to meet required specifications. Even the names of compounds have not been identified. Second, lignin-to-carbon-fiber and/or asphalt additive projects also require a fair benchmark for comparison. These projects may also be better suited under the conversion or bioproducts portfolio wherein the product specification criterion is more rigorous.

Several projects do not look economically feasible, so it would be good to discuss that aspect early on or throughout the project. The TEA/LCA modeling for each project is appropriate, though there could be a better emphasis on early-stage TEA/LCA work to guide the project outcomes. Several projects lacked results on LCA or TEA and had it scheduled for the last budget periods. The wood-heating projects do not seem to address the social justice aspects that were highlighted in the introduction of this part of the program and that give more credence to these efforts to be included in BETO.

For the woodstove projects, the idea that people from lower socioeconomic backgrounds use wood heat most often was important, but several solutions seemed to be for high-end heaters that those people could not afford. One presenter mentioned that high end was how you get it on the market, and that you can then sell it to lower-income people, which was reasonable but not obvious. It is almost like a diversity, equity, and inclusion (DEI) component specific to wood heaters. Another issue involved in these efforts is the availability of electricity and internet, which low-income people may not have, especially internet.

RECOMMENDATIONS

The following recommendations are not listed in any sort of prioritized order and represent items that should provide increased viability of the SDI component of BETO.

Recommendation 1: The SDI program should interact more with the Conversion Technologies and Renewable Carbon Resources programs to enable more acceleration of technologies across the BETO portfolio of projects.

Similar to the previous 2021 Peer Review recommendations, a recommendation to the program is to foster greater interaction between BETO programs. One example can be drawn from the CO_2 utilization area. A task was described in this BETO technology area about how to tie TEA and LCA together. It is evident that some emerging technologies do both, but they have not really done the effort to tie them together, as was done in the CO_2 utilization area. This may be a future direction the SDI program could take to enhance the viability of demonstrating that a process system is viable. The interface with the Feedstock-Conversion Interface Consortium (FCIC) and technology developed there should be a resource all system development projects should follow or be exposed to if it is not already ongoing. Also, the SDI program could look to pluck some projects from the bioconversion and thermochemical areas into further development in SDI. A question is whether the SDI program should invest in more emerging technologies or focus on using the portfolio they have to scale up to demonstration projects to achieve their strategic goal.

Recommendation 2: BETO should consider increasing resources for the marine fuels effort.

Marine fuels projects have progressed really well. BETO should consider a higher level of support for the testing and implementation of marine biofuel technologies. The level of support divided between four national labs really limits the availability of resources for progress in the time committed. Marine biofuels should have a higher level of support than currently provided to deliver on the goals for carbon intensity reduction and GHG reduction.

Recommendation 3: The SDI program should encourage projects to have even more transparency with TEA/LCA efforts.

Projects were sometimes loath to show the estimates drawn from TEAs relative to costs, etc. Some LCAs were a bit spotty in providing meaningful data. Some projects cannot seem to get out of the TRL 3–4 stages, where they feel they need to maximize performance. They just need to define a figure of merit that allows them to proceed with process integration, and they can come back to the individual process steps to improve them, if needed. The lack of a requirement of preliminary, and, later in the projects, complete LCA and TEA is a missed opportunity for quantitative checkpoints in the decarbonization and commercialization potential of the technologies and pathways studied by program-funded projects. Some projects showed sensitivity analyses based on their TEAs. Such analyses should be part of any emerging technology system to show directions for reducing operating expenditures (OpEx).

Recommendation 4: BETO should have greater interaction with the DOE Hydrogen and Fuel Cell Technologies Office due to the importance of hydrogen use in reducing biofuel carbon intensities.

Several emerging projects employ hydrogen, and greater interaction with the DOE hydrogen (H_2) program may be warranted, particularly with regard to reducing the carbon intensity of processes using steam methane reforming.

Recommendation 5: DEI efforts may be better strengthened through better inclusion of DEI tasks with overall project tasks.

Not all the projects that require a DEI component have truly incorporated these values into their approach and could benefit from clearer expectations in the FOAs to meet these goals. This could be guidance for project teams to include budget items dedicated to these efforts in their proposals, to weave inclusion and equity into key components of their projects like their approach to industry involvement, and to include diversity and equity in their discussions of risk management.

Another example of this are the projects supporting wood-burning stoves and associated technologies. Clarity with the U.S. Environmental Protection Agency (EPA) on regulations would help the industry progress and meet the strong social justice aspect of the projects. The majority of the focus on achieved improvements should be on households living at or below the poverty line. A higher degree of support on projects with a strong social or environmental justice clause would benefit society and deliver on air quality improvements. A discussion of how their solution will be attractive to lower-income groups would be helpful. It would also be helpful to better understand the validation process. This could be done project-by-project or just more generally. Some groups spend more than a year validating, which seems like a long time. Resources for efforts in improving wood-burning stove technology are beneficial.

Recommendation 6: BETO needs to listen to industry more to understand the metrics needed to off-ramp a technology to industry.

The program may benefit from having criteria that lead to the termination of a project and when industry can take over. BETO is not in the business of picking winners, and it may be that BETO believes industry can determine what they want to pursue, but there may be value in defining criteria when BETO support is no longer warranted.

SYSTEMS DEVELOPMENT AND INTEGRATION – EMERGING AND SUPPORTING TECHNOLOGIES PROGRAMMATIC RESPONSE

INTRODUCTION

The SDI-EAST team would like to thank the review panel for providing their time and expertise throughout the 2023 Project Peer Review process, including the critical and helpful interaction with the presenters, the Review Panel Summary Report, and the valuable project comments. We appreciate the review panel's comments noting the clear strategy for supporting near-term, demonstration-scale projects (around 50 dry metric tons of biomass per day; corresponding to around 1 million gallons of biofuel per year) of integrated technologies while also supporting novel unit operations at the pilot scale (around 1 dry metric ton biomass per day; corresponding to around 20,000 gallons of biofuel per year). We appreciate that the review panel observed the emphasis on reducing GHG emissions. The review panel noted that the portfolio includes industry-led projects but also national laboratory-led enabling activities. The SDI program strives for technology demonstration but also appreciates the expertise at the national laboratories to reduce universal technical uncertainties.

The review panel commented that the SDI program should be cognizant that sometimes maximizing a certain parameter may not be the best target for a pilot/demonstration project, but rather at this stage it is important to demonstrate process stability. Without minimizing this important comment, some additional background may place this in better context. Typically, a scope for a project, as written on the negotiated statement of project objectives, will include ambitious metrics for the project to reach at the end of the intermediate budget periods. For an active project presenting at the Project Peer Review, these ambitious metrics are often presented in detail. But, also, most FOAs include requirements for continuous operational runs (100–500 hours continuous for the pilot scale; 500–1,000 hours continuous for the demonstration scale). These continuous runs usually occur at the end of a project and thus may not have been discussed for many projects at the Project Peer Review unless they are sunsetting. The SDI program will keep in mind the importance of these continuous tests to demonstrate process stability.

Following are the SDI program's responses to the review panel's recommendations. Again, we appreciate the effort and are listening and responding.

Recommendation 1: The SDI program should interact more with the Conversion Technologies and Renewable Carbon Resources programs to enable more acceleration of technologies across the BETO portfolio of projects.

BETO, including the SDI program area, has recently instituted efforts to create more engagement between the various BETO programs, including with the Carbon Conversion and Renewable Carbon Resources programs. A recent adjustment in BETO's personnel activities is assigning liaisons where a technology manager from a separate program joins another program's regular weekly update meetings. We are also instituting quarterly meetings for more interfacing to share program highlights. One potential impact of these more frequent interactions is better recognition of project progress across different TRLs and across the pathway from feedstock logistics and preprocessing to conversion, scale-up, and integration.

The SDI program is also working with the FCIC to facilitate conversations between the FCIC and the pilot and demonstration projects in SDI's portfolio. The FCIC is jointly managed by the Renewable Carbon Resources, Carbon Conversion, and SDI programs. The FCIC is actively conducting R&D in feedstock variability, materials handling, preprocessing, materials of construction, and feedstock impacts for both low-temperature (biochemical) conversion and high-temperature (thermochemical) conversion. SDI's pilot and demonstration projects benefit from hearing the latest research on the impact of feedstock variability on preprocessing and conversion. Sometimes pilot or demonstration projects make simplifications about feedstock quality, or dismiss potential challenges at the feedstock-conversion interface, or, at least, do not have the bandwidth or resources to consider these challenges; thus, more communication sooner, across the BETO platforms, is critical.

Recommendation 2: BETO should consider increasing resources for the marine fuels effort.

BETO's second-highest fuel priority is marine fuels. The SDI program funds some laboratory and private recipient R&D in the marine fuels space and plans to increase marine funding in the future. The SDI program also supports DOE's role as a co-lead of Mission Innovation's Zero-Emission Shipping mission, which seeks to introduce commercially viable zero-emissions fuels for oceangoing vessels by 2030.

Recommendation 3: The SDI program should encourage projects to have even more transparency with TEA/LCA efforts.

The SDI program will work to include more language in future FOAs, pending appropriations, requiring transparency of TEA assumptions. The SDI-EAST review panel did not see many projects selected under FOAs where LCA was required. The SDI's Fiscal Year (FY) 2016 FOA required LCA to ensure that the projects were developing pathways producing advanced or cellulosic biofuels with more than 50% or 60% GHG reductions, respectively, that would meet the requirements of the Renewable Fuel Standard. On the other hand, the SDI's FY 2017, FY 2018, and FY 2019 FOAs did not have strict requirements for LCA. For example, the SDI's FY 2017 FOA only required applicants to report the GHG estimate in the application, but no LCA work was required as part of the project scope. The SDI's FY 2018 FOA required applicants to report the GHG estimate in the application, and the GHG reduction had to be at least 50%, but no further LCA work was required in the project scope. The SDI's FY 2019 FOA required applicants to report the GHG estimate in the application and conduct LCA in the project scope, but the FOA did not require any quantifiable metric for GHG reduction. The SDI's FY 2020 FOA had a requirement for LCA to show that the project was developing a pathway producing fuel with at least 60% GHG reductions. The SDI's FY 2021 FOA then reverted to more transparent efforts, requiring projects to develop pathways producing fuels with at least 70% GHG reduction, and moreover requiring projects to include special deliverables in the project scope whereby the project will release a public final technical report describing how the technology would contribute to BETO's 2030 goal of $2.50/gallon gasoline equivalent (GGE) minimum fuel selling price (MFSP) with at least a 70% reduction in GHG relative to petroleum-derived fuels.

Recommendation 4: BETO should have greater interaction with the DOE Hydrogen and Fuel Cell Technologies Office due to the importance of hydrogen use in reducing biofuel carbon intensities.

The SDI program acknowledges that, thanks in part to DOE leadership, massive improvements are underway in the hydrogen sector. These activities include the Hydrogen Shot to reduce the cost of clean hydrogen by 80% to $1/kg by 2031; the H2@Scale initiative to convene stakeholders across the hydrogen production and use supply chain; and the development of Regional Clean Hydrogen Hubs, led by the DOE Office of Clean Energy Demonstrations with $7 billion in funding. Because these activities are still nascent, it is difficult to identify the right interfaces where SDI projects would have meaningful interaction. It is noted that BETO has historically shared expertise around the bioenergy state of industry with H2@Scale to ensure that the hydrogen community is aware of the need for clean hydrogen utilization in biofuels production. The SDI program will seek to maintain communication with the DOE Hydrogen and Fuel Cell Technologies Office. Coincidentally, a BETO program manager has recently started a temporary detail as the deputy director of the DOE Hydrogen and Fuel Cell Technologies Office. Closer interaction among the offices is anticipated.

Recommendation 5: DEI efforts may be better strengthened through better inclusion of DEI tasks with overall project tasks.

The inclusion of DEI considerations is relatively new for DOE and BETO/SDI. Only one year of FOA awards, from FY 2021, were required to include DEI tasks in their projects. The SDI-EAST review panel saw only the start of efforts for DEI incorporation into SDI projects. As the projects from the FY 2021 FOA progress, DEI activities should become clearer and targeted. There have also been ongoing working groups at the DOE Office of Energy Efficiency and Renewable Energy level to ensure better integration of DEI efforts into FOAs.

Recommendation 6: BETO needs to listen to industry more to understand the metrics needed to off-ramp a technology to industry.

This is an excellent recommendation, especially considering the need to accelerate scale-up efforts to meet the goals of the SAF Grand Challenge and the Zero-Emission Shipping mission. Recently, BETO announced a request for information to understand the maritime industry's current alternative fuels trajectory, the driving forces behind it, and key barriers to achieving the transition to zero-emissions fuels. The SDI program will continue to consider opportunities where requests for information or workshops would be a reasonable approach.

On another note, the SDI program is supporting a new AOP led by the Data, Modeling, and Analysis Technology Area team to develop a SAF state-of-the-industry report. Better understanding of the metrics of the current SAF industry, which uses hydroprocessed esters and fatty acids (HEFA) technology, is one way that the SDI can understand the paths for commercializing SAF and other fuels.

IMPROVED BIOMASS FEEDSTOCK MATERIALS HANDLING AND FEEDING ENGINEERING DATA SETS, DESIGN METHODS, AND MODELING/SIMULATION TOOLS

Forest Concepts LLC

PROJECT DESCRIPTION

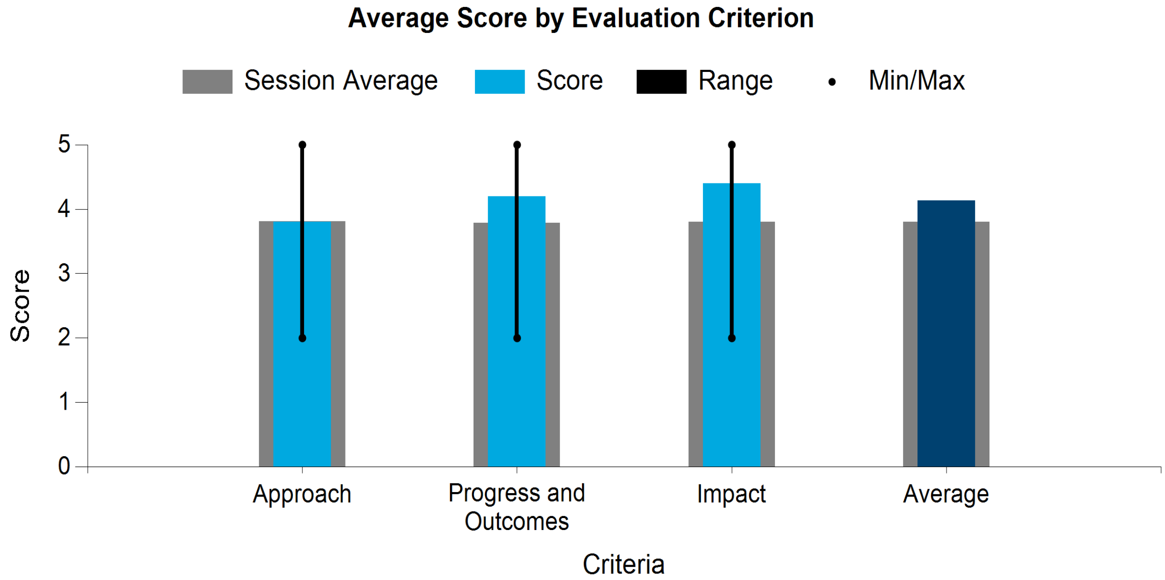
WBS:	3.1.1.002
Presenter(s):	Christopher Lanning
Project Start Date:	06/01/2018
Planned Project End Date:	04/30/2023
Total Funding:	$1,849,411

The overarching objective of this project is to contribute to the design and operation of reliable, cost-effective, continuous feeding of biomass feedstocks into a reactor of an integrated biorefinery.

The overarching goal comprises two subgoals: (1) develop and validate a comprehensive computational model to predict the mechanical and rheological behavior of biomass flow to enable the systematic and reliable design of biomass handling/conveying system, and (2) engineer and improve laboratory protocols and equipment to generate property-driven response curves for specific biomass feedstock species and formats accounting for their dependence on biomass physical properties including particle size distribution, true density, bulk density, and moisture content and external mechanical properties including temperature and pressure.

The project team includes Forest Concepts and Pennsylvania State University. Forest Concepts leads the design and construction of new laboratory methods and equipment. Penn State leads the development and adaptation of bulk flow models to the problem of biomass materials and equipment.

New equipment developed include a 250-mm cubical triaxial tester (CTT) to provide biomass mechanical property data and a large gas pycnometer to quantify biomass particle density to ensure that simulations are populated with biomass-specific data. New analysis software developed include an application for CTT and pycnometer data reduction and analysis, a biomass materials database, and finite element method-based simulations. Biomass materials used in the project include milled wood chips and corn stover.



COMMENTS

- Approach: The project's approach aligns with the metrics defined under Topic Area 4, DE-FOA-0001689. Particle sizes from 1 mm to 6 mm for two different types of biomass were tested. The focus is on tool development, repeatability, and the move from conventional materials (such as soil); limited pilot-scale testing; and an improved modeling tool. The project leverages other projects for data that are under DOE's purview. The team has worked closely with Purdue and Idaho National Laboratory. Stakeholder engagement is by a variety of sample testing for industry clients.

- Progress and outcomes: A new CTT tool scale-up allowing for the measurement of material behavior in three orthogonal directions, adopted for biomass materials; and a gas pycnometer to measure solid densities (true particle density) using air as the pressure medium for larger particle sizes up to 30 mm. Data were presented for two biomass types; the experiment versus simulation difference was less than 15% for two hopper wall angles. Budget Period 3 added a new task—integrated biorefinery projects were also modeled.

- Impact: One key piece for all biomass technologies is understanding biomass feeding processes. This is not well understood. The project has provided new tools to study the physical and mechanical properties of wood chips for applications in hoppers, valves, and conveyors. Results: five potential licenses for new lab equipment; six additional materials studies for others using tools built during this program; and workshop and knowledge sharing. This is a 5-year project with nondestructive testing under 10 minutes for low temperature, a significant achievement in tool development.

- The project has developed a modeling approach using data from newly purchased equipment to improve the prediction of biomass flow in industrial equipment. Anyone who has used biomass knows that it is a much different solid than many others that have been an issue previously in industry.

- The team has used mechanical measurements from new equipment to inform a model on how biomass will flow. They demonstrated some successful examples of how their technology can be used with a thorough discussion of why the method they are using is needed and what the shortcomings are of using physical properties.

- The technology can either be used as a user facility-type opportunity for those in need of understanding their handling systems or the company can sell units for companies to use in-house. This project fills a hole that will greatly help solve a tough problem with solids handling. They have presented at trade meetings and put considerable effort into contacting potential stakeholders.
- This is a project that has great relevance to the processing of biomass. The success of the project is evident by the interest from potential users and stakeholders.
- The need for new equipment and analytics was proven to be valuable. The effort will be proven at TRL 6 and up by others. This proof of concept is a valuable addition to the overall processing of biomass for fuels and chemicals. They have been partners with several other BETO projects, which attests to the value of their efforts. It was not made clear the costs for using their unique technology and what bearing that has on the overall TEA of processes.
- The project team is developing new equipment and modeling tools to determine the bulk flow properties of biomass feedstock handling and feeding, with pilot-scale validation, to fill this data gap in the biomass industry. The project team has presented their progress at an industry forum and presented webinars for major test plants as well, thus keeping industry informed. Patenting and peer-reviewed publications are in progress; however, it is unclear how the model tool itself will be disseminated, such as whether it will be open source, and how the team is ensuring that its design will be compatible with the needs and expectations of operators and other users. The approach is thorough, and the outcomes of the project have the potential to be widely adopted by various types of biomass processing plants. The project team has made timely progress in all R&D efforts of the grant, with a budget extension that is primarily to leverage this project's data collection to benefit other ongoing DOE-funded projects.
- The project would have applicability in coproducts as well. The model has very large error bars (Slide 17), so there are concerns about the applicability of the model to real-world situations; all work done so far is on lab and pilot equipment. Even after the model output, however, the changes in finished equipment are limited, and the sample application is very limited in the study.

PI RESPONSE TO REVIEWER COMMENTS

- Thanks to each reviewer for the countless hours devoted to assimilating and evaluating the various projects. We highly value your thorough review and thoughtful comments. A first-of-its-kind biomass-scale CTT and associated gas pycnometer were wholly designed and built by the project team under this project to provide data sets for existing bulk materials flowability models used in other industries. The driving need for the improved flow modeling and equipment is widely recognized throughout the industry, as pointed out by the reviewers and confirmed in our extensive industry interactions. While the current design of the equipment is now available to academia and industry customers, we will continue to revise and streamline the entire data collection, reduction, and modeling process based on industry feedback and ongoing in-house use of the technology. We are working on a standard format for the dissemination of various model coefficients and related material characteristics so that the data sets generated by the project team and other users of the equipment may be comparable. Once a material is fully characterized, the resulting mathematical material model is applicable to all scales of equipment. One reviewer expressed concern about the large spread of material property data around the mean values. The presented data sets have large statistical error bars, but experience with biomass materials suggests that variance is more a confirmation of the natural range of variance of the material rather than experimental error; thus, (1) mean values are useful to understand relative differences between different species, sizes, etc., but (2) the range is vital to engineering robust handling systems because the span must be accommodated for reliable flow. Simulations need to be conducted with high, median, and low values to predict the effect of natural variance on the variance of instantaneous flow or nonflow. Mean values are rarely used for engineering design with biological materials in other industries. For example, the structural wood industry uses strength ratings at the second standard deviation such that roughly 95% of the beams will have actual bearing capacity larger than the design capacity. Similar techniques should be applied to the results and applications from these tests.

VIRTUAL ENGINEERING OF LOW-TEMPERATURE CONVERSION

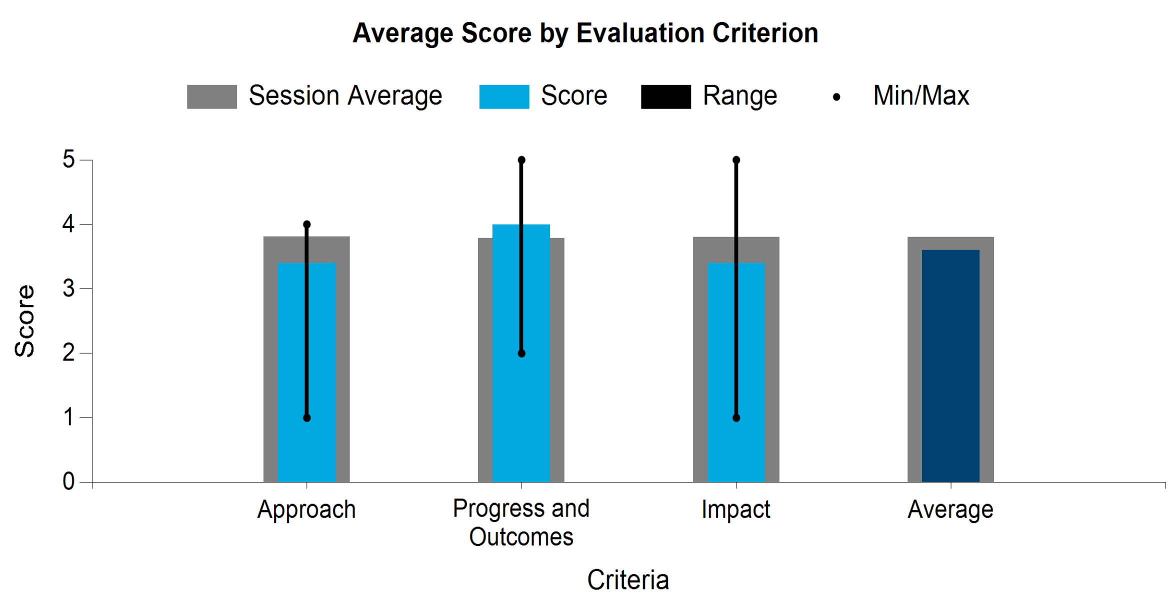
National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.1.1.010
Presenter(s):	Ethan Young
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2023
Total Funding:	$835,000

In this work, we present the development of an overarching software framework and supporting multiphysics models to simulate the end-to-end process of biomass conversion. This virtual engineering software is designed with the goal of accelerating R&D and reducing risk for market-relevant biomass conversion processes. We currently support multiple models, computing paradigms, and fidelities representing the steps of feedstock pretreatment, enzymatic hydrolysis, and bioconversion. Although this virtual engineering approach was developed to support a biomass workflow, we have designed each component in a way that allows us to easily support new domains, unit models, and feedstocks.

We begin by presenting the user-facing aspects of the virtual engineering software and highlight how simulated elements are defined and linked by virtual engineering functions. We then present an overview of the high-fidelity computational fluid dynamics (CFD) models developed to support our target domain before segueing into our efforts to develop accurate and fast surrogate models, capturing the salient outcomes from the CFD simulations in a significantly less computationally demanding manner. We then present how virtual engineering calculations interface with a commercial TEA software, Aspen Plus. We conclude by presenting virtual engineering case studies that leverage these methods and discuss how our methods can be extended to support a wide variety of accelerated biofuel commercialization pathways in the future.



COMMENTS

- Approach: The project is funded under AOP lab call Advanced Development and Optimization; it focuses on modeling/hardware co-development to improve biomass processing/handling inside the plant. The approach is to validate, using parallel models on each identified step, and showcase integrated results. The project team and level of engagement from each subject matter expert seems appropriate. The project management team roles are well defined in the presentation and explained during the presentation.

- The project's goal is to incorporate detailed unit operation simulations into plant-wide simulations to give more accurate process simulations. They have used cellulose extraction, conversion to sugar, and sugar conversion as an example. Because many of the more detailed unit operations take days to simulate, a model reduction process that uses artificial intelligence will be used to incorporate detailed simulation data into a simpler-to-run model.

- The team has put together a model that incorporates unit operation simulations into plant-wide simulations. They have determined improved ways to reduce the model that takes less time than a Monte Carlo simulation.

- The resulting simulations work for a very narrow set of inputs even for a narrow set of unit operations. This project holds so much potential if another layer of programming could be used to either make the results more general or to speed up the reduction of the model. This project could automate what we already do in designing chemical plants. It is just not there yet.

- This project meets one of the strategies for BETO to meet their goals. They have gone beyond the normal use of Aspen to make a more robust virtual engineering package with CFD. Results show relatively low error compared to experimental data.

- As a whole, this effort is the kind of work a national laboratory can do because it is more of an unbiased entity. The national lab effort avoids the purely academic side of such modeling because they are joined at the hip with the experimental side of the business. The proof of value will be in those who will attempt to use it. The team did not address this issue other than to say that it is an open-source software.

- This capability could benefit several projects in the SDI portfolio in undertaking their work, and that potential should be pursued.

- The project is developing proof-of-concept virtual engineering software that is domain-agnostic and connects mathematical models of unit operations to predict the outcomes of biomass pretreatment, hydrolysis, and bioconversion, with a focus on reducing computational time for users while providing reliable modeling results through surrogate modeling components. The users would need to enter three to five inputs for each of the three steps, which are based on the most sensitive or driving variables that are mostly within an operator's control. The model includes input parameter limits so that it will only perform within the ranges that have been validated through the software. Validation against published data shows an acceptable error percentage. Optimization capabilities are also incorporated. The approach appears solid and considers the needs of the industry, but it is unclear how the model will be disseminated or promoted to users beyond being accessible on GitHub or whether future user needs are being solicited via an advisory board, survey instrument, or otherwise to further improve the implementation potential. Because the goal is to provide accelerated development and reduce risk for market-relevant biomass conversion processes, the development of this open-source model has high potential for impact to industry if it genuinely fits the needs of operators (and if operators are aware of its existence). The project is now within its last year and has met its goals at this stage within the scope of the software development, and it could now benefit from considering outreach and feedback with industry.

- The model is only as good as the input provided to it for development. It seems the model is not continuously updated based on feedstock variability, etc. How applicable would this model be to different sources of feedstock and affected by operating conditions? I am concerned that they have simplified a set of computational models to satisfy the Python solver. The model's connection with Aspen is unclear to this reviewer. It seems the model is stand-alone, without the interplay with Aspen, and several key parameters (particle size, biomass type, etc.) are hard-coded and not available for the user to change. No confidence of the model prediction is provided.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you to the reviewers for their detailed analysis; it was a pleasure discussing the virtual engineering project with you, and we were pleased to see that the merits of a computational, system-wide approach were well received. The reviewers generally identified two critical areas for future work: the dissemination and adoption of the methods we have developed and the generalization of these tools to new pathways, models, and inputs, which we will elaborate on here. We agree that this cross-platform enabling software is only as useful as our ability to get it in front of end users to see how they interact with the tools and what missing features we could collaborate on to provide. In FY 2022, we wrote and successfully delivered a milestone demonstrating an overview of the virtual engineering capability to groups from both academia and industry. These sessions were helpful in terms of informing us which directions we should pursue more heavily (e.g., more development of Aspen techno-economic integration) but fell short of providing us with real-world users and future developers. To remedy this, we have proposed to host webinars and training sessions as part of the work during this project's continuation. Enabling new users to download, install, and run our methods would significantly reduce the barrier to entry for creating Notebooks tailored to the unique needs of their workflows and models. With regard to any perceived narrowness of our allowable inputs and models, we understand that demonstrating virtual engineering tools using explicit case studies risks giving the impression that only the chosen variables are mutable and/or that only a single, rigid workflow is supported. Generally speaking, the virtual engineering elements that link different unit operations do not presuppose any programming framework, data structure, or computational complexity and make it very easy to construct collections of widgets to solicit user input for new values, e.g., the particle size in the pretreatment model. Adjusting the value of a variable outside the confidence interval of a model or simulation may lead to unpredictable results, but we attempt to preempt this by enforcing conservative limits during input validation. Further, we have proposed integrating the initial training of surrogate models and adding the ability to augment those training sets with subsequent high-fidelity simulation evaluations as part of this project's continuation. The ability to automatically inject an Aspen model with calculations from an external physics model is the focus of our end-of-project milestone, which will be described in a manuscript in the near future.

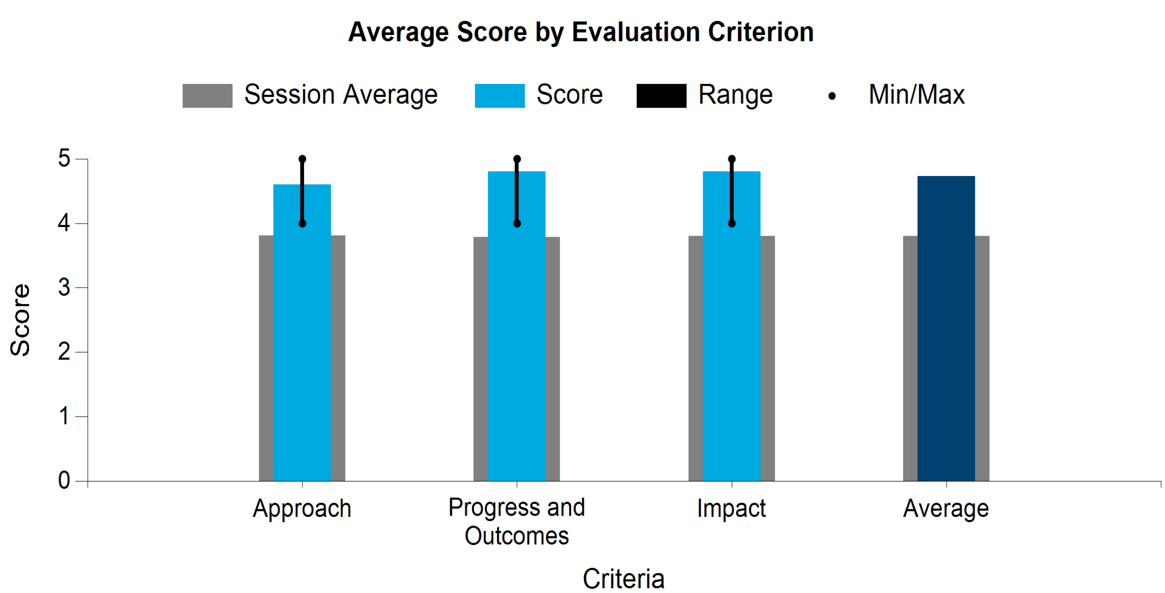
ADVANCING THE DEVELOPMENT OF BIOFUELS FOR THE MARITIME SECTOR—ORNL, NREL, PNNL, ANL

Oak Ridge National Laboratory

PROJECT DESCRIPTION

WBS:	3.1.4.014
Presenter(s):	Michael Kass
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$5,216,787.45

This project seeks to understand the efficacy of biofuel use in the marine sector as a means to reduce carbon intensity and GHG emissions. The research team includes Oak Ridge National Laboratory (ORNL), Argonne National Laboratory (ANL), the National Renewable Energy Laboratory (NREL), and Pacific Northwest National Laboratory (PNNL), and it is year 2 of a 3-year study. The major research thrusts are to conduct a techno-economic feasibility study/LCA and gage the technical feasibility of biofuels. Promising pathways include the use of bio-intermediates (pyrolysis oils and HTL oils). These efforts demonstrate solid pathways toward GHG reduction in the maritime sector. Challenges exist in the forms of resource competition and lack of information, especially engine test results. Progress can be summarized as (1) the team has established a framework and methodology for TEA studies based on feedstock type and production pathways, (2) GHG emissions reduction potential has been determined for many biofuels and production pathways, (3) HTL oils have demonstrated stable blends with heavy fuel oil, and (4) the compatibility and combustion quality of bio-intermediates is suitable for blends up to 15%. The research team periodically disseminates information to the stakeholder community via a number of channels. One measure of interest is the expanding membership in the project advisory committee and industry requests for information and participation from team members.



COMMENTS

- Approach: The project approach aligns with metrics defined under the lab call. Technical: Identify pathways that can meet marine fuel blending requirements; several pyrolysis and HTL pathways are considered. A ranking of schemes was conducted to downselect or find suitability of blends, especially with regard to spot ASTM tests. Project management: Elaborate national lab participation on blends, TEA, and LCA, with feedback from several industry partners. Opportunity lies in two-stroke engines. Key goal: Blends with very-low-sulfur fuel oil.

- Progress and outcomes: The team has made significant progress on identifying catalytic fast pyrolysis (CFP) and HTL oils with mitigating strategies for upgrade and blending. The TEA/LCA results clearly show that most HTL routes and a few CFP routes show promise. There is a lack of clarity in the industry for decarbonization or adoption/selection of fuels. In this regard, the consortium has definitely engaged the right partners from industry, regulatory, adoption/standards, and guidance.

- Impact: The project has not only achieved results, it has also advanced the cumulative knowledge for the fragmented approach due to the variety of biocrudes and risks involved in adoption. The TEA/LCA results serve as guidance for GHG impacts, costs, and the stability/reliability of fuel oil blends. Further, all major pathways (except a few Fischer-Tropsch diesel results are sparse) have been considered and included. Fuel properties have not been neglected, resulting in a narrow band of biofuels that might be acceptable. The consortium is led by national labs and can leverage (benefit from) some other projects that have looked at upgrading biocrudes for refinery processing. It seems the budget is sparse relative to the achievements and potential impact this project can make. I hope this study will continue and find the required support.

- A collection of national labs have combined their capabilities to address problems with marine fuels. They have received buy-in from a range of companies, including some shipping companies that can help inform them of the nuances of fueling maritime vessels and the role biofuels can play.

- The presentation described an analysis of asphaltene precipitation and how they were able to determine which biofuels would cause asphaltenes to precipitate.

- A significant amount of LCA and TEA were completed for various fuels, showing that some are competitive.

- This seems like an excellent hole for the labs to fill. The labs have a lot of the necessary equipment to test biofuels for maritime applications, which is likely not common for a university consortium or independent testing lab. The labs are an excellent fit here and have made excellent progress.

- This is an appropriate project for DOE laboratories. They can provide an unbiased assessment of the potential for processed biomass fuels to impact the maritime market. They have made significant progress and have addressed many concerns from the 2021 review comments. A question that probably needs to be addressed is when is there a logical point at which to let industry take it over? This group may want to define their desired ideal outcome, so they can plan toward that. There should be some measures of performance that would encourage shipping companies to start contracting out fuel supplies from companies like Ensyn or others.

- This project involves four national labs and funding at $2 million annually. The expertise at each lab is being used toward investigating the potential opportunities for marine biofuels. The project appropriately incorporates LCA and TEA throughout the tasks instead of using these analyses as one-time checkpoints at the very end of a project. There is active engagement of industry and related stakeholders; 20 entities are represented across energy companies, shipping and engine companies, industry experts, biofuel companies, shipping terminals, nonprofit organizations, and governmental organizations, while new partnerships and initiatives are still being generated. The results of this project are being disseminated on a timely basis, across peer-reviewed publications and industry presentations, and detailed parametric LCA models have already been incorporated into the latest release of ANL's respected Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET) platform. The project has also identified challenges such as the precipitation of asphaltenes, which will require mild hydrotreatment of heavy oils, and studied the stability of fuel blends at the laboratory scale. This is a well-designed project that has made commendable progress and shows high potential for a significant impact to the marine biofuels industry.

- The project is quite well formulated with relevant industry stakeholders. The presentation covered all relevant FOA goals, and the reviewer did not find any technical concerns with the project. The reviewer suggests looking at longer-term stability testing for asphaltene precipitation in the blends.

PI RESPONSE TO REVIEWER COMMENTS

- Response to Reviewer 1: Thank you for the positive and encouraging comments. The specific lab roles related to blend testing, TEA, and LCA are as follows: ORNL has acquired and has access to several residual fuel oils. These fuels have served as the basis for blend stability testing. ORNL, along with PNNL and NREL, perform blend stability experiments; PNNL is focused on HTL oils, NREL is focused on pyrolysis oils, while ORNL evaluates blend stability from the PNNL and NREL oils as well as commercial oils. ORNL is also planning on conducting aging studies with industry input. All LCA work is conducted by ANL. TEA work is conducted by both PNNL and NREL. PNNL has primarily focused on HTL oil pathways, while NREL is looking into pyrolysis oil pathways and other biofuels (methanol, lignin ethanol oil, biodiesel, etc.). With regard to the concern on the budget level, the research team is actively looking at opportunities to leverage with the U.S. Department of Transportation, U.S. Department of State, and industry.

- Response to Reviewer 2: Thank you for the encouraging comments.

- Response to Reviewer 3: We have had several internal discussions regarding industry transfer. Based on the feedback and input from our external advisory board, there are several fuel-specific metrics that include successfully demonstrating long-term (4 months) blend stability aging studies. The other key metric is successful operation in engine performance studies before realistically considering industry adoption. Our ideal outcome would be to identify and confirm an economic, sustainable, and scalable pathway toward biofuel use as a blend with residual fuel oil (in the near term), with the eventual implementation of a zero-carbon fuel option.

- Response to Reviewer 4: Thank you for the positive comments.

- Response to Reviewer 5: Based on this reviewer's comment along with input from our external advisory board, the research team is pursuing long-term stability tests based on standard sedimentation tests and gel permeation chromatography. Another planned set of experiments includes operating selected blends in a closed-loop circulation system where the fuel is periodically sampled to determine blend stability and potential degradation over an extended period of continuous operation.

INTEGRATED SEPARATIONS TO IMPROVE BIOCRUDE RECOVERY FOR BIOFUELS AND BIOPRODUCTS

Research Triangle Institute

PROJECT DESCRIPTION

WBS:	3.4.3.305
Presenter(s):	Dave Dayton
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2025
Total Funding:	$4,612,503

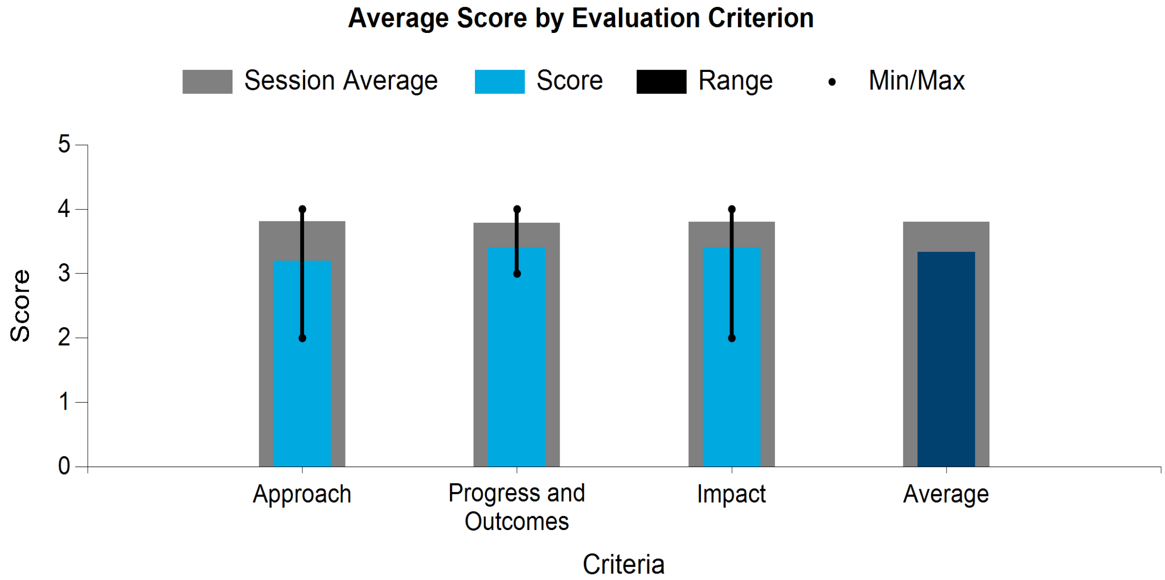
Research Triangle Institute (RTI) International has been developing an advanced biofuels technology that integrates catalytic biomass pyrolysis and hydrotreating to produce advanced hydrocarbon biofuels and high-value chemicals. Current efforts are geared toward key technical challenges, such as improving the carbon efficiency of the integrated process by optimizing the biomass thermochemical conversion step to simultaneously maximize both biocrude intermediate yield and quality. Other efforts include developing strategies for bioproduct recovery and efficient upgrading of biocrude to bio-blendstocks.

RTI continues to focus on optimizing the operation of our 1-ton-per-day (1-TPD) catalytic biomass pyrolysis unit and process conditions (temperature, flow rates, catalyst-to-biomass ratio, and feedstock properties) to increase biocrude yields. Capturing biomass pyrolysis vapors requires separating solids at pyrolysis temperatures, quenching the pyrolysis products that have a broad molecular weight distribution and boiling range, capturing the condensation aerosols, and separating biocrude from water.

Cost-competitive advanced biofuel technology strongly depends on yield, but recovering bioproducts before upgrading intermediates to biofuel provides a higher-value revenue stream to improve the overall process economics in an integrated biorefinery approach. The inherent functionalized nature of biomass offers a unique opportunity for the production of bio-based oxygen-containing chemicals that are not easily synthesized from petroleum feedstocks; therefore, the deoxygenation of catalytic biomass pyrolysis vapors to produce a low-oxygen-content biocrude may be a missed opportunity for bioproducts.

Technical issues across the entire value chain—from feedstock, through conversion, to biofuels and bioproducts—are being addressed with the goal of demonstrating the integration of separations with CFP to enhance biomass conversion efficiency. Ecostrat, with more than 20 years of experience sourcing and supplying more than 5 million tons of wood fiber and organic feedstock in markets across North America, is evaluating biomass supply chain logistics to optimize biorefinery size and location as a function of sustainable, cost-competitive feedstock resource availability, market dynamics, and regional infrastructure.

RTI will focus on the scale-up and integration of separation processes in the 1-TPD biomass pyrolysis unit to (1) improve the separation of solids from the vapor product stream, (2) enhance the rapid quenching and collection of pyrolysis vapors, (3) separate highly oxygenated bioproducts from the liquid intermediates, and (4) recover the remainder for upgrading into advanced biofuel. Coprocessing strategies for upgrading biocrude fractions with petroleum intermediates into finished fuels that meet ASTM specifications will be explored, while biocrude fractionation will support recovering high-value market-compatible bioproducts.



COMMENTS

- Approach: The project approach aligns with the metrics defined under Topic Area 1, DE-FOA-0002203.
  - Technical: Integrated separations to showcase methoxyphenol and other products, recovery, and its impact on the economics of biofuels as byproduct credits.
  - Project management: No slides on management approach. Partner list provided on Slide 16 with roles.
- Progress and outcomes:
  - Builds on several other projects for CFP awarded to this organization.
  - Verification completed.
  - Budget Period 2 work biomass resourcing and procurement.
  - A market study on methoxy phenols and their uses.
  - A 7-gallon-per-day laboratory-scale separation unit.
  - Claims 75% recovery, 90% purity (to what?), no residual losses.
  - What was the yield of methoxyphenols in prior work? What is the required purity? How does it compare with commercial products in terms of acceptable level of trace impurities? Seven different distillation cuts are shown on Slide 8—each has five different components. Even highly concentrated/purified cuts have 5% to 20% individual concentration of molecules. Unfortunately, such product mixtures do not qualify as bioproducts. Are there any precedents cited for such a product mix/sales, or has anyone shown interest in further purifying it? What are the plans to improve this to the desired >90% or commercial benchmark? What is the basis of assuming cost/price for such a fraction for TEA?

- Impact:
  - The project builds on several funded programs on CFP. The organization has high capabilities and partners to support the program; however, the presented results do not reflect that a particular set of bioproduct/s with desired properties is produced even at lab quantities. Anticipated yields with this degree of separation seem too low to make an impact on economics, and rather can be detrimental due to the number of separation steps needed. No clear benchmarks for product specification or approaches to improve purity have been identified.
  - As a reviewer, I felt a bit lost in the number of funded programs at this institute. It was not clear if the intended goals of this particular project are being achieved, even with a great deal of experience and benefit of data from other programs. I am also not sure if this project has different results from past funded programs, such as MEGABIO, and I request a comparison of past versus new results for bioproducts. A more careful go/no-go review is recommended.
- This process aims to include pilot-scale separation for a fast pyrolysis system. A goal is to remove some stream to act as a chemical building block. This builds on previous work by the principal investigator (PI). The initial verification has been completed.
- A significant amount of supply chain analysis was completed. It is not clear why this is the place for supply chain analysis. If it does fit in, it was never stated how it does so at this point, given the number of projects the PI is working on.
- The unit operations are operational. It is not clear what the value of the supply chain analysis was to this project. It is also not clear that the methoxyphenols are the best chemical building block to extract from the process. The actual separation design seems like the most valuable accomplishment for this project, though it was not discussed as in depth as the supply chain or methoxy phenols.
- It is not clear why the results of the verification Step 1 were not included in the original presentation instead of in the additional slides. Those results showed the project was on track. Otherwise, this project is on schedule, and preliminary results demonstrate that it will be possible to coproduce a product stream and fuels. The selection of one type of coproduction stream is sensible, and focusing on that one stream will be good. The team probably needs to see what value that stream has. Good partner with Ecostrat. They are targeting the appropriate TRLs. There is an old saying that “there is a world of difference between a valuable mix of chemicals and a mix of valuable chemicals.” They need to continue to address this issue.
- This project aims to improve solids separation from the gaseous stream for the rapid collection of pyrolysis vapors and to assess the potential for the collection of coproducts along the pathway. Methoxyphenols, which are precursors to flame retardants, can be recovered through separation from the biocrude generated via pyrolysis. This increases the commercialization potential for the system. The project team is investigating approaches to improve (nearly double) the carbon routed to biofuels from the same input amount of biomass. The project is in its second budget period and involves a multitude of industry partners.
- Challenges with their scheme will limit the purification of methoxyphenols. The process team should consider molecular distillation as opposed to distillation on the recovery step.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for taking the time to evaluate our project and providing constructive suggestions for improvement as the project continues into the next phase. Over the past 15 years, we have been developing catalytic biomass pyrolysis technology to produce biofuels and bioproducts with support from DOE/BETO in several different projects. Throughout these projects, we have installed and commissioned a 1-TPD catalytic biomass pyrolysis unit (April 2013), a pilot-scale hydroprocessing unit (January 2015), and a laboratory-scale separation unit (January 2019). Only minor process modifications have been made since the commissioning of the 1-TPD unit; however, after years of operation, issues with biocrude recovery have been identified, and the scale of the laboratory separations does not match well with the 1-TPD unit. Therefore, the primary goal of this project is to scale up the separation unit operations and integrate them into the 1-TPD unit. This will improve biocrude recovery, reduce the effort to effectively fractionate biocrude for upgrading, and facilitate the recovery of bioproducts. Catalyst fines and char often carry over past the primary cyclone and condense with higher-molecular-weight pyrolysis products, resulting in a loss of 15%–25% biocrude unless the solids can be separated after condensation (which is impractical). Therefore, one separation unit operation being considered is a hot gas filter for particulate removal prior to biocrude condensation. Downstream of the primary quench, we are also considering liquid-liquid extraction units that were proven in the laboratory-scale separation unit to fractionate biocrude into low-oxygen-content organic feedstock for more efficient hydrotreating and high-oxygen-content liquids with potential for isolating bioproducts. The basis for the separation unit operations in this project are the results from our previous projects, and the methoxyphenol recovery from biocrude is specifically based on the laboratory-scale separation unit developed in our MEGABIO project (DE-EE0007730). The results collected during our previous projects will be reproduced in this second budget period to inform the intermediate verification and define the basis for the go/no-go decision point to move ahead with the design modifications in the 1-TPD unit. The purpose of scaling up the separation unit operations and integrating them into the 1-TPD unit is to increase the yield of the collected biocrude and separate it into fractions to facilitate methoxyphenol recovery and cohydroprocessing with refinery intermediates. Biocrude yield has the largest impact on the modeled process economics, but the recovery of higher-value bioproducts also has a significant impact, as demonstrated in our previous projects. The experimental results from this project will be input into the process model that forms the basis of the TEA; however, the commercial potential of this proposed pathway is directly related to the scale of the modeled integrated biorefinery. Clearly, the economics are favored by economies of scale, but there is a practical limit to the size of the integrated biorefinery defined by the cost and availability of the biomass feedstock that can be delivered to the plant. Consequently, we are partnering with Ecostrat to perform a supply chain analysis at selected sites in the southeast and the northwest to determine the optimum scale of an integrated biorefinery while considering the existing demand for regional biomass resources and existing infrastructure.

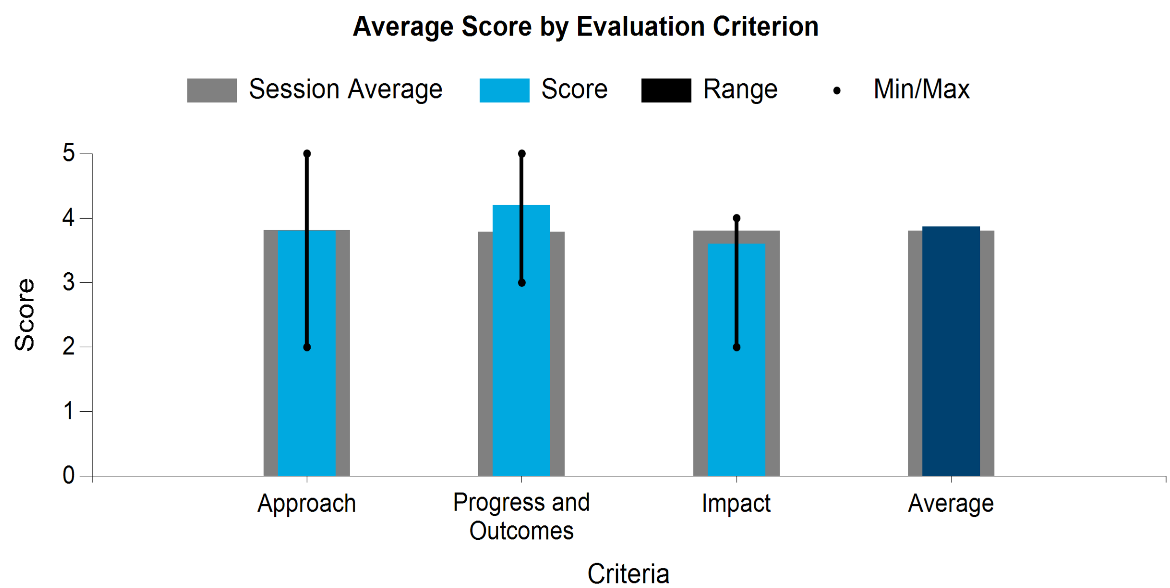
BIO-OIL COPROCESSING WITH REFINERY STREAMS—PNNL, NREL, LANL

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.4.3.306
Presenter(s):	Asanga Padmaperuma; Huamin Wang; Karthikeyan Ramasamy; Katarina Younkin; Michele R Jensen; Reinhard Seiser
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2023
Total Funding:	$5,056,000

The objective of this three-laboratory project is to accelerate the adoption of coprocessing biomass-derived feedstocks with petroleum streams in current refineries by developing and broadly disseminating foundational data for processing renewable intermediates and offering coprocessing strategies. It will enable using U.S. refineries that in 2020 had a capacity of 8.8 million barrels/day for hydrotreating and a capacity of 5.6 million barrels/day for fluid catalytic cracking (FCC). Three critical challenges were identified by the project's industry advisory board: (1) a critical operability risk comprising process stability around catalyst deactivation; (2) a regulatory risk comprising the need to rapidly measure biogenic carbon and oxygenates in processed streams; and (3) a significant knowledge risk centered on the lack of coprocessing data, including feedstock compositions and contaminants, product compositions, the reaction kinetics of unique biocompounds, and associated TEA/LCA. The outcomes of addressing the three challenges are: (1) preventing catalyst deactivation by reducing alkali species through hot gas filtering (FCC) and reducing nitrogen compounds by pretreatment (hydrotreating/hydrocracking); (2) developed methods for inexpensive/rapid biocarbon analysis through 14C and delta 13C analysis methods; and (3) provided detailed compositions on bio-oil feeds and coprocessing products, including contaminants, operational data including biocarbon yields, an improved kinetic reactor model for hydrotreating, and associated TEA/LCA.



COMMENTS

- Approach: The project approach aligns with the metrics defined under the lab call.

- Technical: This is a multipronged approach to increase the use of bio-derived crudes for processing in existing refineries: FCC; hydrotreating/hydrocracking; and fats, oils, and greases (FOGs)—biocrudes from different sources. Track contaminants and biogenic carbon.
- Project management: The project includes elaborate national lab participation on blends, upgrading, and the analysis and tracking process. It includes several industry partners/feedback and a few prominent catalyst suppliers/advisors.

- Progress and outcomes:
  - The coprocessing goals expanded new catalysts, feeds, and improved models.
  - The CFP oil coprocessing *in situ* and *ex situ* showed the impact of O on storage and stability.
  - Yields for coprocessed bio-oils with vacuum gas oil (VGO) in FCC were comparable, with a 5% blend.
  - The product has 1%–2.5% O_2.
  - Catalyst deactivation was observed with all bio-oils; the mitigation strategy is a guard bed in addition to upgrading bio-oil.
  - Liquid scintillation counter C14 tracking was improved for several types of colored or raw bio-oils.
- Impact: The project has made considerable progress and showcased the tracking of biogenic carbon using multiple methods—5% blends for all approaches, mitigation strategies for catalyst deactivation, or modifications to reactor models. This directly enables the integration of large quantities of bio-derived feedstocks in current refinery operations. It is unclear how much the quantities were processed—what statistical data, quality control has been done so far? Any insights on this might be helpful for adoption and reliability. The program has clearly achieved its goals per the timeline. The complex network of task owners has been effectively managed to attain the desired outcomes. There is interaction with a lot of minority groups via workshops, webinars, and sharing knowledge.
- The goal of this project is to fill in missing information in which petroleum refiners need to have more confidence, including biofuels in their processes as a first step at bringing biofuels to market. The group of several labs is able to do varied studies on the effects of adding biofuels to refinery-type applications.
- The presentation mentions a few success stories, including a study on adding bio-oils to VGO. The group has also received a significant amount of input from industry partners.
- It is good to see the labs take a role in this important function, though I would expect that the refiners would have a consortium to study different related problems to integrating biofuels. It seems that industry stakeholders would be careful to tell the labs what they truly need to avoid giving away trade secrets. It would be interesting to hear how open and specific the refiners are in describing problems they need addressed.
- The project has made appropriate progress toward the project's goals. The project has provided BETO with information that can be used to justify the incorporation of processed biomass into refinery streams. There are several projects in BETO's portfolio that address the incorporation of processed biomass into refinery streams. The program probably should do a bit more to integrate these projects into something oil refineries can look at. The one reviewer comment on 75% incorporation into oil refinery streams is

ambitious, but changing 100-year-old technology would require shutdown economics, and that is not feasible right now. The team has good partnerships in industry. The project does a good job with DEI.

- This project is assessing how existing petroleum refineries could integrate drop-in bio-intermediates, like biocrude from the HTL of biomass, for coprocessing into finished fuels. This has the potential to reduce the scale-up needs of the biofuels industry through sharing the existing infrastructure, and it might possibly reduce the carbon footprint of petroleum-based fuels; however, depending on whether the fraction of biocrude to petroleum crude ultimately coprocessed at scale is relatively small, this may provide greater assistance to the petroleum industry than to the bioenergy industry, or regardless of the fraction, both industries may overlap in their separate accounting of the biogenic carbon throughout processing and in finished fuels. The project team has been tracking biogenic carbon in products, though, to ensure a process that incorporates a high proportion of biogenic carbon in the fuel products. It would be interesting to simultaneously track or model the reductions in fossil fuels going through a refinery. The project's DEI efforts uniquely include an energy justice analysis, which is commendable for a 3-year project that involves shared infrastructure with fossil fuels. Still, it is unclear how this analysis is performed and how the results may be used in future implementation decisions. Since the last DOE Project Peer Review, 2 years ago, the project team has published 14 papers in peer-reviewed journals. Because the DEI efforts also involve the recruitment of underrepresented students, it would be useful to report the number of papers that involved these students as coauthors and other metrics to assess the success of these efforts.
- The project is quite well presented, however, not all refineries are the same, and the differences in processing ability will impact the incorporation of bio-oil. The method developed to track the incorporation of biogenic oil is significant and novel.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for highlighting some strengths of our program, such as the multipronged approach and the wide national lab and industry participation. This program at the national laboratories has evaluated various effects of introducing biomass-derived liquid feedstocks into refinery streams by coprocessing. We have collaborations with large and small refiners, learning about each of their needs and the types of available processing equipment. This has encouraged the study of different next-generation feeds (CFP, fast pyrolysis, and HTL bio-oils) in different coprocessing units (FCC, hydrotreaters, and hydrocrackers). Industry partners have also provided valuable feedback and have expressed appreciation for receiving fundamental data, such as experimental and modeling results, and compositional data of feeds and products. According to refiners' remarks, there exists a collective interest within the industry to integrate bio-derived feedstocks into refineries, aiming for the efficient production of sustainable fuels. To de-risk the adoption, both emerging feedstocks and refinery capabilities will need to adjust, with support from the foundational study. We agree that the future bio-economy will both involve building new biorefineries as well as transitioning petroleum refineries to increase the biofuel portion of their operations. Even fuels produced at biorefineries are often sent to existing large-scale refineries for upgrading and blending. Therefore, the tracking of biocarbon throughout both processes is an important component of evaluating the progress toward incorporating biogenic fuels, which is one of the major objectives of our program. We will continue to provide innovative opportunities to increase DEI through multiple internship opportunities and collaborations with minority-serving institutions. Regarding the stability of various CFP oils, we find good repeatability of pressure-drop increase in our heated nozzle as an indication of bio-oil instability, and we provide this feedback to suppliers and refiners. While various measurement methods show some oxygen content in the product, speciation by gas chromatography-mass spectrometry shows that the expected oxygenates in the product from FCC coprocessing might be less than 1%, mainly consisting of phenols, furans, and ketones. Catalyst mitigation is an important topic for coprocessing in hydrotreaters, employing fixed-bed catalysts, while the catalysts in FCC coprocessing are less impacted due to their continuous replacement during operation. In our laboratory studies, we have coprocessed liter quantities of CFP oils and HTL biocrudes with tens of liters of petroleum feeds. At present, industrial refineries have been coprocessing FOGs, whereas for the above-mentioned next-generation bio-oils, they are currently assessing data regarding their impacts on refinery operation and performance, such as from our program, as well as their availability through large-scale production.

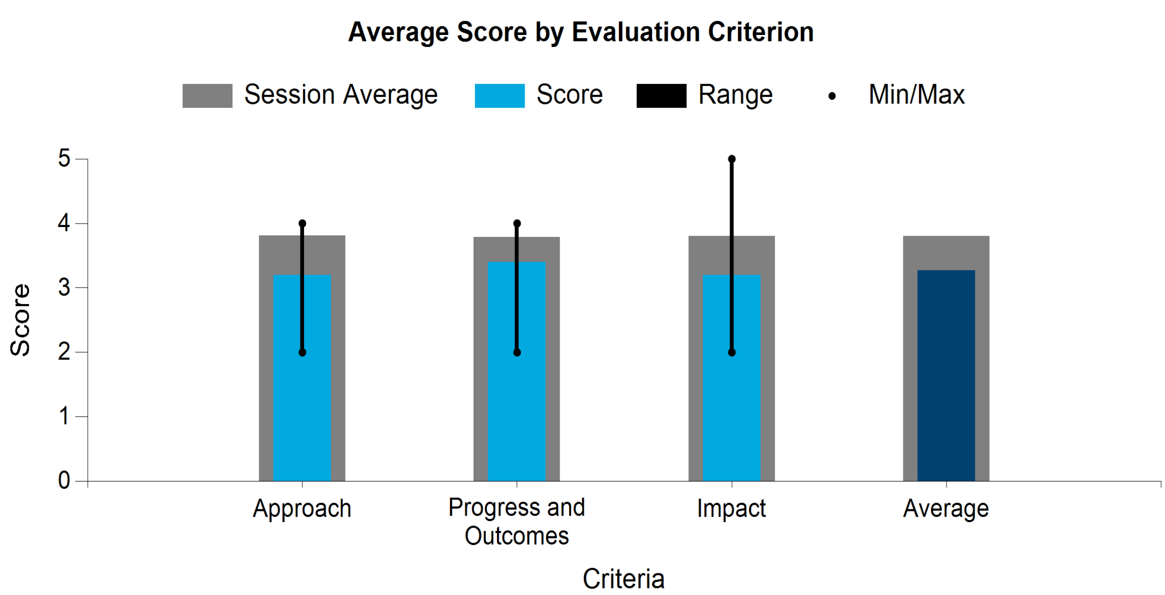
MICROCHANNEL REACTOR FOR ETHANOL TO N-BUTENE CONVERSION

Oregon State University

PROJECT DESCRIPTION

WBS:	3.4.3.504
Presenter(s):	Brian Paul
Project Start Date:	10/01/2020
Planned Project End Date:	06/30/2024
Total Funding:	$5,000,000

Oregon State University (OSU) is partnering with PNNL and LanzaTech to develop a new process technology with the potential for reduced capital and operating costs for an alcohol-to-jet (ATJ) process technology that is currently being commercialized by LanzaTech. Employing new catalyst technology developed at PNNL, ethanol is first converted into n-butene-rich olefins with >90% conversion and >80% selectivity. Olefins are then oligomerized, hydrotreated, and fractionated into jet blendstock. Energy savings are realized by coupling the severely endothermic ethanol dehydration with exothermic C-C bond formation. Further process intensification and modularity is achieved by integration into a microchannel reactor platform. Advances in additive manufacturing methods enable catalyst scaffolds to be integrated directly within reactor channels during fabrication, further reducing capital expenditures (CapEx). The project is now working to demonstrate a one-eighth-scale system prior to a full-scale demonstration of 0.15 ml/min. Single-channel reactors have been demonstrated, and a kinetics model has been developed and used to design "numbered-up" reactors for demonstration-scale evaluation. Three reactor design and manufacturing strategies have been developed that are capable of supporting system-level cost targets set by TEA, two of which have the potential to reduce reactor equipment cost by as much as 50% using advanced additive manufacturing methods.



COMMENTS

- Approach: The project approach aligns with the metrics defined under Topic Area 1, DE-FOA-0002203.

- Technical: This project focuses on ethanol conversion to olefins with an emphasis on butene using microchannel reactors. It showcases advantages in rapid scale-up, leveraging additive manufacturing as the low-cost fabrication process.
- Project management: Although there were no clear slides on this, PNNL and OSU seem to have managed the project progress well.

Progress and outcomes:

- Validation with 90% conversion and >55% selectivity to C3 and above olefins.
- Single-channel reactor 80% ethanol conversion and 80% selectivity to butene-rich olefins with required productivity/yield to meet TEA requirements.
- Clear approaches on catalyst reactor scale-up, cost estimates, and methodology have been presented.
- Details of single-channel reactor show, Slide 7, approximately 60% butene and overall olefins as 80%. Propene and ethylene are not C4 compounds; what other compounds are claimed as C4?
- Advance reactor single-channel performance initial results are presented and look promising but need improvement.

Impact: If successful (the project has 2 more years), at a small scale, the project has shown considerable progress, but it lacks performance criterion. The rate of production, selectivity, and conversion results are promising and can certainly make a meaningful impact if reactor scale-up costs can be managed by improved manufacturing methods. Past work on microchannel results have shown scale-up challenges. It is unclear what the catalyst deactivation rate is at low space velocities. Some decline can be observed at 100 hours time on stream (TOS) (Slide 7); more data are required to estimate regeneration process, downtime, and costs.

- The proposal is going to use microchannel reactors to convert ethanol to butane due to their scalability. This is the first step in an ethanol-to-jet fuel process. The team consists of OSU, PNNL, and LanzaTech.

  The process has been scaled up from a bench-scale reactor to a large version using Fecralloy foam with a catalyst wash-coated on it. In this system, the butane selectivity is less than 65%, but the total olefin selectivity is 80%. A modular design for a microchannel reactor has been proposed.

  The initial run converted 10 g of ethanol per hour with a space velocity on the order of a few reciprocal hours. The microchannel reactor will operate at a similar space velocity. This is slow given the advantage of microchannel reactors is the higher output. It would be great to see what the pressure drop in the microchannel reactor is, though at such a low flow rate, it may be small. Also, it is not clear how the reactor will be maintained at 350°C–450°C. It will be difficult to keep all the channels at these temperatures uniformly as well as to start the reactor.

- Microchannel reactors have been looked at for many years. There have always been limitations in what they can achieve. This project has demonstrated at the single-channel level sufficient performance to look at scaling opportunities. The catalytic process is relatively straightforward and appears to be adaptable to scaling. The project needs to continue to look at interface issues and particularly in continuous operation. There is concern about the multichannel reactor—not that it will not work, but first-of-a-kind units usually have some hiccups. They should be mindful of quality control on the manufacture. The team is very well poised to establish whether this can or will work in an actual operational environment. They will either know it works, or they will find it is too challenging. They should be able to get an answer.

- This project investigates a pathway from ethanol to butene-rich olefins to jet-/diesel-fuel-range hydrocarbon chains in a microchannel reactor. Although the modularity of the microchannel reactors serves a useful purpose in scale-up, it is unclear how (1) removing deposits of solids, (2) clearing channels clogged by heavy oils, (3) regular maintenance on the reactors, or (4) troubleshooting problems occurring in one or more of a large set of microchannel reactors would be handled in reactors with these dimensions; however, bench-scale reactor evaluation results are favorable from the experiments performed thus far. The design of the catalyst as a coating on a removable foam insert into a microchannel reactor mitigates my initial concerns about catalyst recovery for regeneration; however, for adaptation of this design to continuous-flow conditions, this system appears to greatly increase the friction and may require more pumping energy, which would increase the carbon footprint and costs of the produced fuel. The model validation using experimental results appears insufficient for a conclusive fit because each condition has only three data points to fit. Additional experimental testing would be required to more robustly assess the ability of the model to predict conversion or selectivity based on input rates of ethanol. The cost analysis performed is also incomplete at this time because it covers only CapEx; it is unknown whether operational costs completely dwarf the costs of the raw materials, for instance. The results of an energy balance at both the bench scale and the projected commercial scale would be particularly interesting given the unique geometry of the reactors. This could answer a research question about the optimal point in balancing between increasing the surface-to-volume ratio for higher catalytic conversion and decreasing the surface-to-volume ratio to decrease pumping energy needs against frictional forces or higher energy use in maintenance steps. The project is close to its midpoint and will be exploring scalability, life cycle costs, and life cycle GHG emissions within the next 2 years. This will provide more clarity on whether these concerns are valid or would be overcome through continued process design.

- The best results are obtained at very low weight hourly space velocities. I wonder what the advantage is of microchannel versus packed bed at this low velocity. The CapEx of foam are still quite high.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their insightful comments, and we appreciate the acknowledgement of the merits of this BETO program. In response to questions about what compounds are claimed for selectivity calculations, the "olefins" include the selectivity to all the olefins produced, including ethylene, propylene, and butylene. The selectivity to the predominant olefin produced, n-butene, is separately indicated.

- Regarding the questions related to performance criterion and the need for continuous operation, the performance criteria are (1) achieve >80% total olefins and >80% conversion for a single-channel reactor; (2) demonstrate a scaled microchannel system to convert 0.15 standard liter per minute of ethanol for 500 hours TOS for full-scale demonstration; (3) within capital and operating cost targets.

- On the comment relative to scale-up challenges associated with microchannel reactors, we agree that the scale-up of microchannels is challenging, but we contend that the scale-up of any system can be challenging. First, we note that two companies have successfully deployed microchannel process technology as spinoffs of PNNL (Velocys and STARS Technology Corporation). Further, in this project, we are concerned with only gas phase conversion; thus, there are no solids or liquids reacting or being produced when in the microchannel reactors (liquids will condense out downstream after gas-liquid separation). Beyond this, we have demonstrated that the catalyst can be regenerated *in situ* upon mild oxidation and that separate catalyst inserts can be removed and replaced where necessary. Therefore, even if there are byproduct issues, we expect that many of the same approaches that work, for example, in a 10,000-tube shell-and-tube reactor, having 1-inch-diameter tubes with 1/16-inch extrudates, will apply here, including (1) heating under inert gas to remove heavy oils, (2) hydrogen stripping to remove heavy oils and deposits, and (3) regenerating in air to burn out deposits. In extreme cases, an appropriate solvent or washing solution can be pumped through the reactor. Finally, these units are modular, so different units can be replaced when necessary without affecting the whole reactor system.

- Relative to the comments on catalyst deactivation, the reviewer is correct to point out how there is a small amount of deactivation observed over 100 hours; however, the catalyst has been shown to be fully regenerable, so the processing system will be designed and operated in a manner to periodically regenerate the catalyst. Recently, PNNL successfully performed an 800-hour TOS catalyst test with the catalyst being regenerated every 100 hours. We did not have time to discuss these details regarding the catalyst within the review.

- Regarding the comments relative to the reactor design, we have run numerical simulations with approximately 100% increased throughput (weight hourly space velocity 3.0) and were still able to reach the target conversion and selectivity, suggesting higher throughput is possible. Further, the pressure drop through the reactor is only partially related to the flow through the porous catalyst layer, which is small (with simulations estimating it as approximately 20 Pa). Significant pressure drop is associated with the "feed-nozzles," to ensure even flow distribution between plates, which is a design variable that can be adjusted. Also, simulations show that the overall heat balance of the reactor is sufficiently maintained by transferring heat from exothermic reactions at the end of the reactor bed upstream to endothermic reactions via partition walls (plates) between catalyst inserts. Therefore, the entire reactor energy balance is maintained by the inlet temperature of the reaction mixture, which will be maintained via preheat. Detailed protocols will be developed for startup and shutdown of the reactor, depending on several parameters, with heat distribution being only one of the several phenomena.

- Regarding the questions related to model validation, we are confident that model validation using experimental results is robust and meaningful because the "fit" is not a blind polynomial fit but rather a fit to an extensive mathematical model (set of partial and ordinary equations encompassing all transport phenomena and reaction kinetics). Therefore, the model is based on first principles with no empirical correlations or factorial parameters. The accuracy of the reaction rate constants estimated from the least-square optimization hinges on the number of experiment points used in the modeling. Every point on the graph represents an average of three independent measurements, enabling us to calculate the estimated parameters' variances. We are confident that experimental points on the graph are assuming a monotonous rise without unexpected excursions between recorded points.

- Regarding the comments on finding the optimal surface-to-volume point to balance catalytic conversion, pumping energy, and maintenance cost, this is an interesting comment. We agree. Our mathematical model represents a design tool that is helpful in informing an independent cost model built around the full reactor scale, connecting the technical details mentioned and the overall net present value of the business.

- In response to the comments on the need for quality control in reactor manufacturing, we agree that the precision in manufacturing is critical for successful reactor operations overall, including even flow distribution between reactor beds and layers. To address this, test articles have been fabricated by the reactor vendor to evaluate the effect of tolerances on reactor design. Further, fluidic testing will be performed to verify fluid flow distribution across multiple channels of reactor shells prior to catalyst loading.

- Regarding the comments on the cost of the reactor inserts, this is why we are pursuing two alternative advanced reactor designs that are leveraging the ability for additive manufacturing to deliver more complex structures at lower overall cost.
- Regarding the factors driving economic evaluations, raw material costs have been found to dominate production costs as follows: 87% ethanol; 13% catalysts and chemicals, energy, and other utilities, and fixed costs.
- Regarding questions on the advantages of microchannel reactors over packed-bed reactors, microchannel reactors provide the potential to reduce business risk for scale-up over packed-bed reactors. Significantly less precommercial investment is required to demonstrate scaling by piloting a single module. By numbering up, the first prototype module can be used for production, reducing the time needed for return on investment. With conventional scaling, greater time and investment are required across the conventional bench, pilot, demo, and commercial development pipelines. These advantages are enabled in part by the intensification of microchannel reactors over conventional packed-bed reactors. In a practical (not ideal) packed-bed reactor, the catalyst carrier particles are randomly packed throughout the packed-bed volume, resulting in slight variations of voidage space (especially along the reactor walls). These variations of voidage space (even if small) quickly give rise to significant variations in temperature and flow distribution. In contrast, microchannel reactors contain an engineered porous catalyst carrier media, providing better flow conditions and thermal uniformity, enabling intensification.

INTEGRATED REACTIVE CATALYTIC FAST PYROLYSIS SYSTEM FOR ADVANCED HYDROCARBON BIOFUELS

Research Triangle Institute

PROJECT DESCRIPTION

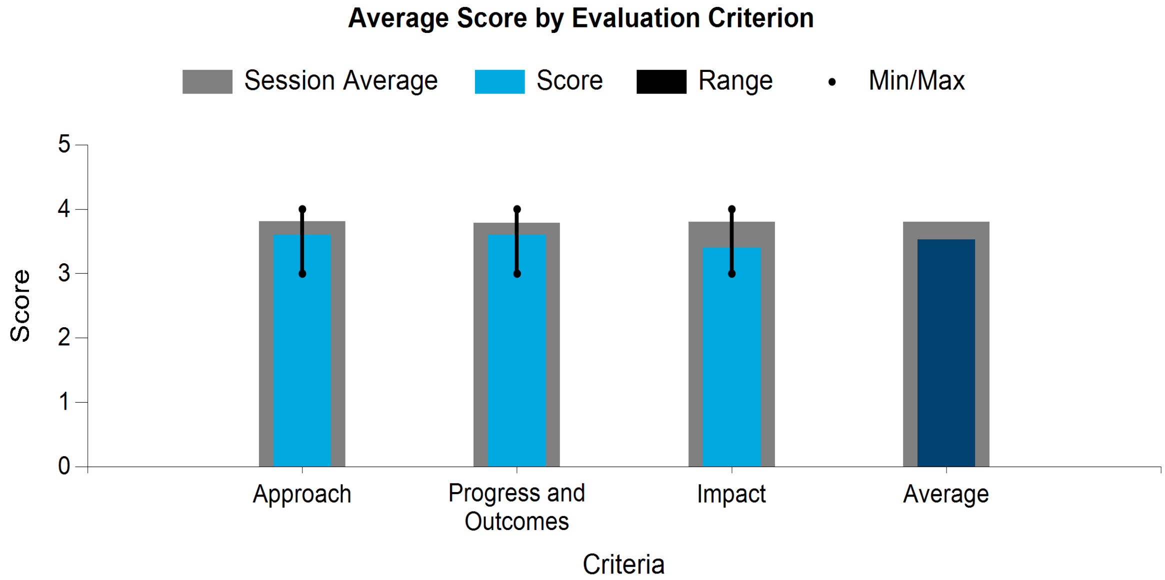
WBS:	3.5.1.204
Presenter(s):	Dave Dayton
Project Start Date:	10/01/2019
Planned Project End Date:	03/31/2024
Total Funding:	$2,945,831

The development of a cost-competitive technology for advanced biofuel is largely dependent on product yields. The key technical challenge associated with direct biomass liquefaction technologies is maximizing the carbon efficiency of the integrated process by optimizing the biomass thermochemical conversion step to simultaneously maximize biocrude intermediate yield and quality. Biocrude quality is often simply defined by the oxygen content of the liquid intermediate. Catalysts in the thermochemical conversion step are applied to enhance the deoxygenation of the pyrolysis vapors to produce a low-oxygen-content, thermally stable biocrude intermediate that can be effectively and efficiently upgraded into advanced hydrocarbon biofuels. Unfortunately, the oxygen content in biocrude is inversely proportional to yield in catalytic biomass pyrolysis, so, ideally, the catalyst should promote deoxygenation of the pyrolysis vapors while minimizing carbon loss to light gases, char, and coke.

RTI International has been developing a novel direct biomass liquefaction technology, referred to as reactive catalytic fast pyrolysis (RCFP), and incorporates atmospheric pressure hydrogen and an *in situ* catalyst provided by our partners at Haldor Topsoe. Hydrogen in the pyrolysis reactor improves biocrude yield by reducing char and coke formation and improves biocrude quality by eliminating reactive oxygenates. Catalyst screening in a lab-scale bubbling fluidized-bed reactor system was used to identify a suitable RCFP catalyst for enhanced hydrodeoxygenation (HDO) while optimizing process conditions (H_2 partial pressure, temperature, and space time) and improving carbon efficiency.

A focus of this project is to design, fabricate, and operate a reactor system that can continuously regenerate and reduce the RCFP catalyst to maintain steady-state HDO activity while meeting the hydrogen demand of the RCFP process. With this scaled-up system, enough low-oxygen-content RCFP biocrude can be produced to support extensive upgrading studies.

The outcome of the project is to improve the technical feasibility of the integrated RCFP/upgrading process by producing 100 gallons of a renewable blendstock that meets ASTM D975 specifications. The project goal is to scale up the RCFP technology and meet or exceed the carbon efficiencies measured in laboratory experiments. TEA, based on experimental results, will substantiate the economic viability of a fully integrated process design to produce a finished diesel blendstock that can sell for $3/GGE with 50% GHG emissions reduction potential through robust system optimization and integration.



COMMENTS

- Approach: The project approach aligns with metrics defined under Topic Area 4, DE-FOA-0002029.
  - Technical: Reactive fast pyrolysis in a fluidized-bed reactor with catalyst regeneration and recycling.
  - Project management: No specific slides, but it is listed on Slide 17 with roles. The presenter also verbally elaborated on their roles.

  Progress and outcomes:
  - Details of biomass to be used, catalyst to be used.
  - The lab-scale fluidized-bed reactor used for the study with smaller-scale particles and product collection is well described.
  - Design work and 3D image for proposed fluidized system, to be completed by a subcontractor.
  - A summary of the RCFP catalyst testing with all phase yields was presented; however, the expected/desired outcomes (based on preliminary TEA estimates for yields) and comparison with it are not clear.
  - The biocrude upgrading results show an increase in O_2 content (0.86% to 6% from 10 hours to 140 hours TOS) and a corresponding decrease in H_2 content? This is indicative of rapid deactivation; during the presentation, the PI confirmed this. What are the mitigation plans? if the catalyst does not meet the criterion for short durations, what is the reason to move to scaled-up work? The process hazard analysis is by a consultant, Saltegra Consulting.
- Impact:
  - The project has limited time left to fabricate and demonstrate a very challenging fluidized-bed reactor with various recycle streams. This requires pressure balancing and observing the catalyst attrition and loss/makeup. There are difficulties in regenerating and feeding the catalyst, along with

product recovery and characterization. Given the remaining time, approximately 1 year, meeting the target goals is at high risk. The presenter mentioned that they have requested an extension for the project and will not use project time during the waiting period for receiving the fluidized-bed reactor unit. Also, the results shown for the hydrotreating catalyst are not encouraging for scale-up.

- The goal is to design, fabricate, and operate an HDO reactor that processes kilograms per hour. The process will use multiple condensers and an electrostatic precipitator to purify the biocrude. The process will require a catalyst regeneration step as the catalyst cokes and is oxidized during decoking, thus requiring a subsequent reduction. The process has been previously verified.
- A process hazard analysis was conducted due to the use of hydrogen.
- Hydrotreating was included to ensure proper oxygen removal, resulting in a more stable biocrude.
- The catalyst was tested for multiple regeneration cycles with no loss in activity.
- It seems that there is still quite a bit of work to be done. There was no risk assessment, though it seems that some problems have arisen, and some may be on the horizon.
- On the surface, it seems like a bad idea to have hydrogen pass through an electrostatic precipitator. In this case, the fuel and ignition source are present. Only an oxygen source is required for an explosion.
- This project has been subjected to extensive independent engineering review and has met the goals and recommendations. It is in the throes of finishing up, with the goal of producing a 100-L product, and the team seems on their way. I would like to have seen what they consider to be the figure-of-merit values to justify proceeding to the next TRL. Every step does not need to be at max performance but enough so that justification for further effort is warranted. This is a good team, and there is good interplay among them. They did a hazard and operability study at the engineering scale, which is very good. Their aqueous phase recycling is a plus. It is a worthy thing for BETO to have a project that provides the information and technology to allow for drop-in refinery products. This avoids a lot of the issues with fuel compatibility.
- This project appears to have been accounting for the carbon balance in a way that does not smoothly lend itself to subsequently performing an LCA of the system. The carbon reported for char and coke includes the carbon that is burned off from the coke. This carbon is not accounted for in the gas emissions, and the "gas" is pyrolysis gas; however, the division of carbon between the fraction that will remain in the char and the fraction that is burned off will make a difference in the calculations of potential carbon sequestration in the produced char (from the components that do not combust and that remain fixed in this material). Although the project team is well positioned for industry engagement, the project team might benefit from involving academics with LCA expertise or LCA professional consultants in these tasks to accurately determine the fate of carbon and the overall life cycle GHG emissions of the produced fuel. The project is in its last budget period, and the carbon footprint of the generated biofuels will affect its commercialization potential.
- The reviewer is concerned about the ability of the PI to deliver on the multiple BETO projects they have with competing priorities, especially as they noted challenges with hiring post pandemic. It is clear that they would not be able to make 100 gallons by the end of the project, and they are probably looking at an extension.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for taking the time to evaluate our project and providing constructive suggestions for improvement as the project continues into its final phase. As pointed out by the reviewers, we have quite a bit of scope remaining in the project and not much time to complete it. As a result, we anticipate requesting a 12-month no-cost time extension to complete the biocrude production and upgrading that is planned. The fabrication of the scaled-up unit continues, and we expect to take delivery of the completed system in November 2023. We expect that installation and commissioning will be completed in spring 2024, followed by 12 months of operation. The experimental results will be used to update existing process models that are the basis for the TEA. An LCA is also part of the final project deliverables. In the interim, we continue to work with our catalyst development partner, Topsoe, to finalize the procedure for producing a catalyst in a spray-dried format that has similar performance (45% carbon efficiency in the C4+ products with less than 15 wt % oxygen in the biocrude product) compared to the extrudates that were used to achieve the technical targets for the intermediate verification. Additional small batches will be produced by Topsoe and tested in RTI's two-fluidized-bed reactor system, the same reactor that has been used for all process development to date. Large batches for testing in the new unit will be produced once the catalyst formulation and synthesis have been finalized. We do not anticipate any delays in meeting that deliverable. The operation of the scaled-up unit will be invaluable in advancing the state of the RCFP technology. Two key objectives remain to be investigated during the final phase of this project: (1) optimizing process conditions to maximize biocrude yield and (2) producing enough RCFP biocrude to perform long-term hydrotreating to improve upgrading performance. To maximize biocrude, there are two design features in the scaled-up unit that need to be tested during the process optimization. First, the catalyst addition rate needs to be determined and balanced with the bed removal rate in an attempt to maintain steady-state RCFP catalyst performance. Catalyst samples can be collected to determine the extent of regeneration (carbon content on catalyst) because the catalyst regeneration is decoupled from the RCFP process. Second, the impact of recycling the hydrogen-rich tail gas on biocrude yield needs to be verified. Preliminary RCFP biocrude hydrotreating and coprocessing has been very promising. Deactivation of the hydrotreating catalyst is evident, but increasing pressure drop and reactor plugging has not been observed. This provides an opportunity to conduct long-term (greater than 150-hours TOS) hydrotreating experiments to understand catalyst deactivation mechanisms and establish process conditions to maximize TOS. Hydrotreating process conditions have historically not been changed to facilitate comparison with previous studies; however, results from select biocrude upgrading studies have indicated that hydrotreating catalyst activity can be recovered by increasing temperature. Therefore, increasing the initial hydrotreating temperature is one strategy for maintaining longer-term catalyst activity. There is also room for investigating different catalysts, catalyst dilution ratios, and catalyst dilution strategies.

BIOCRUDE PRODUCTION AND UPGRADING TO RENEWABLE DIESEL

Research Triangle Institute

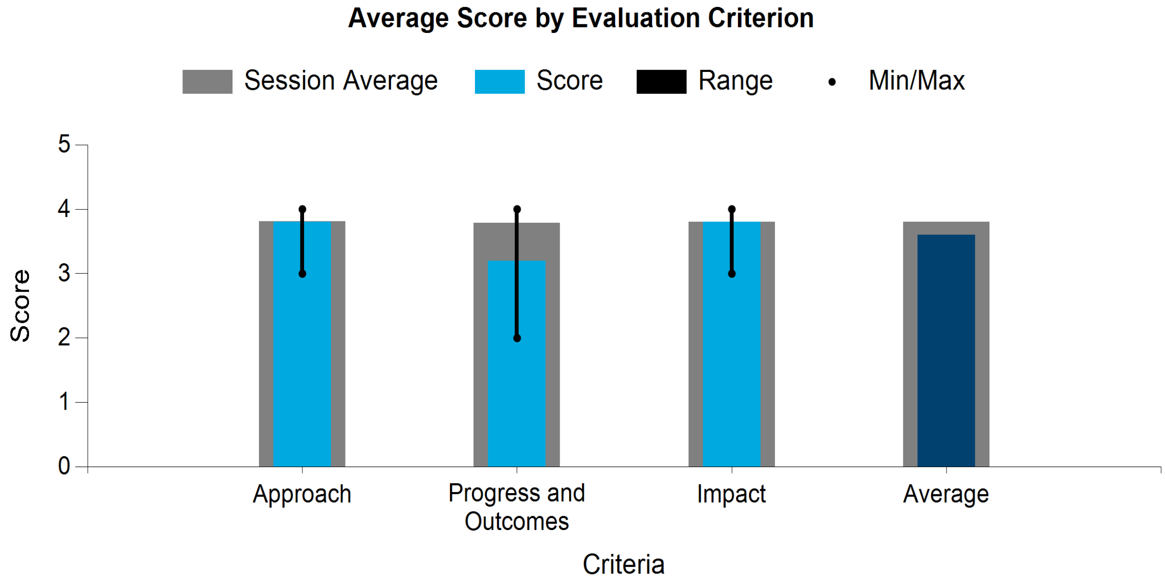
PROJECT DESCRIPTION

WBS:	3.5.1.301
Presenter(s):	Dave Dayton
Project Start Date:	10/01/2018
Planned Project End Date:	08/31/2023
Total Funding:	$3,192,405

A lot of activity in catalytic pyrolysis and hydroprocessing has occurred in the past 15–20 years with notable successes and failures; however, very little technical information is available in the open literature from continuous, integrated, pilot-scale studies. The next step along the technology commercialization pathway is to scale up the catalytic biomass pyrolysis process, integrate this technology with a hydroprocessing unit, and demonstrate the long-term operation and performance of the integrated process. RTI International is developing an advanced biofuels technology that integrates catalytic biomass pyrolysis and hydrotreating to produce hydrocarbon-based biofuels. Additional separation technology is being developed to recover valuable products from biocrude or fractionate biocrude prior to upgrading.

The goal of this project is to maximize the yield of biocrude from a catalytic biomass pyrolysis process and effectively and efficiently upgrade the biocrude intermediate into a renewable diesel blendstock. This goal is not unique; however, innovative approaches will be investigated to achieve the technical targets for an economically feasible, integrated, advanced biofuels process. The focus of the proposed project is to (1) optimize the physical and chemical characteristics of biomass feedstock, in a commercially viable manner, to maximize biocrude yields (independent of oxygen content) in catalytic biomass pyrolysis; and 2) improve biocrude upgrading efficiency by fractionating the liquid intermediate and independently hydroprocessing each fraction to maximize biofuel production.

The proposed project team builds on years of experience to seek innovative solutions that address technical challenges across the value chain—from feedstock preparation to biomass conversion, intermediate upgrading, and biofuel production. Idaho National Laboratory, in collaboration with Forest Concepts LLC, is evaluating physical property requirements for selected feedstocks to develop correlations that reduce the risk of feeding upsets in RTI’s 1-TPD catalytic biomass pyrolysis unit. RTI and NREL collaborated on reactor modeling to optimize conversion process performance. RTI and Haldor Topsoe are developing a new strategy to upgrade biocrude that will minimize process severity while maximizing TOS. A systems approach will be taken to maximize the efficiency of biofuel production by fractionating biocrude, determining the most efficient way to process each fraction (hydrocracking or hydrotreating), or how best to recombine the fraction for ultimate biofuel production. Instead of trying to maximize deoxygenation during the catalytic biomass pyrolysis step, the goal is to optimize biocrude yields in the conversion step while managing downstream HDO by pretreating, fractionating, or coprocessing biocrude fractions to maximize biofuels carbon efficiency to improve the technical feasibility of renewable diesel production from cellulosic biomass. TEA, based on experimental results collected in the proposed project, will substantiate the economic viability of a fully integrated process design.



COMMENTS

- Approach: Technical—catalytic pyrolysis, with solvent extraction, aqueous phase recycling, and upgrading of various product intermediates via hydrotreating separately.
- There are two approaches for biocrude fractionation, solvent followed by water and vice versa, with the second approach showing less use of the solvent. Hydrotreating of various streams is analyzed separately.
- Progress and outcomes:
  - Four different sizes/biomass are tested to produce a total of close to 100 gallons of biocrude.
  - Biocrude, solvent extract and raffinate are well characterized, with up to 10%–15% unknowns.
  - The makeup solvent rate is not stated in the presentation. This could have a major impact on the overall cost. The reviewers request this information with run time data using actual feedstocks and loss rates.
  - Aqueous phase recycling is claimed to show major improvement in terms of reduction in the use of the water requirement, which is a significant achievement; however, for this stream level of impurities recycled, it has not been measured, verified, or addressed.
  - Three product intermediates are hydrotreated separately; it is a good approach to understand the impact on catalyst stability and identify the source. The results indicate that the hydrotreating catalyst is not stable for all three streams, and the lack of feed required to achieve steady state has been shown as the reason for the incomplete work.
  - The TEA case is well documented, with sensitivity analyses for two cases, where in one case aqueous organics are rejected with wastewater.
- Impact:

  - If successful (the project is in its last extended budget period), the project claims a reactor-ready feedstock and has well-defined approaches for product separations and impact on economics. If successful, the project can make a significant impact and aligns with various DOE programs.
  - What is not clear is the impact of intermediate quality on the hydrotreating catalyst. This has been the case for many years and a stumbling block for most fast pyrolysis technologies. What deactivation rates were observed, and how different are these from past data? The remaining time in the program and ability to generate enough quantities of intermediates required to do reasonable hydrotreating studies for various streams, as well as to come up with an overall commercial embodiment, and hence effective TEA to meet cost goals is quite limited. Overall, the project lacks the level of performance expected in last budget period.

- The project will produce upgraded biocrude from biomass using catalytic pyrolysis. Biomass of different sizes were investigated.
- The project compared the order of separations that use toluene or water as a solvent and found that the water separation should occur first. They have found significant catalyst deactivation issues that they are still trying to figure out.
- A TEA was carried out that found a fuel selling price of $3.33 and identified the most important factors that affect the price.
- The project has progressed, but the catalyst deactivation issues are an issue. The team has not yet produced the required amount of fuel, but they will have an extension to do so.
- This project has received considerable attention and analyses by the independent engineer. The comments from the previous review were direct, and some were not complimentary. The project team worked to address some of them, but they spent more time addressing the original goals of the project. Those goals were largely achieved, although some remain to be completed. The project progression is achieving TRL 6. The potential to go to higher TRLs is possible, and the sensitivity analyses were the right step in possibly going forward. Perhaps other industry partners will be needed to further this work. I am not sure if the project has defined the performance metrics it needs to complete the validation of the work.
- This project investigates and tests a pathway for biocrude production and upgrading to renewable diesel. A strength of this project is its analysis of the ability to recycle the aqueous coproduct so that water use and subsequent wastewater treatment needs can be reduced. The results of the hydrotreatment experiments also provide critical data to ultimately calculate the carbon footprint of the renewable diesel through this production process. With the data already collected by the project, an LCA could be performed in addition to the TEA that has been continuously developed during this project. It is part of the remaining tasks within the scope of the project, but the research would benefit from LCAs being performed at various stages to identify opportunities for improvement as the design develops. The project has received an extension.
- The yield is lower than expected. The characterization of the finished renewable diesel (cloud point/wax content/density, etc.) is required. The use of agricultural residue will result in a higher renewable identification number (RIN) value. Light cycle oils should be considered for use as a solvent. I am unsure if they will make 100 gallons by the end of the project. Likely a no-cost extension would be required.

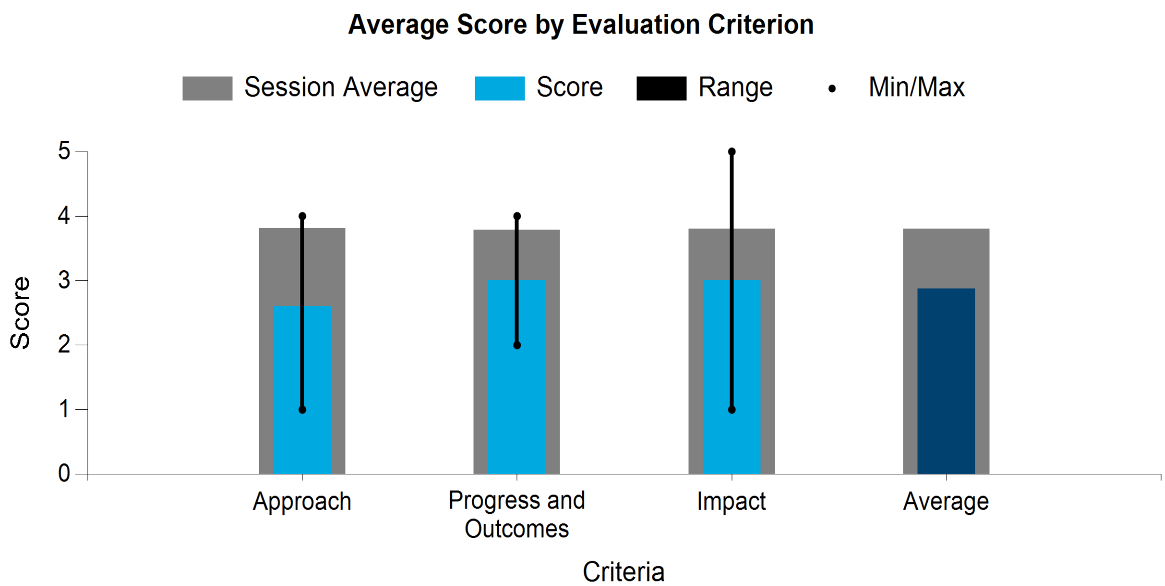
PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for taking the time to evaluate our project and providing constructive suggestions for improvement as the project continues into its final phase. We would like to acknowledge the technical and contractual challenges encountered during this project. Lower-than-expected biocrude yields continue to be a dilemma that needs to be understood, and plugging hydrotreating reactors during biocrude upgrading is still quite common, though progress is being made to correlate the feed composition to hydrotreating performance. In addition, initial and intermediate verifications during the project took longer than planned, leading to significant delays in the technical work plan. Superimposed with the departure of key personnel and extensive pilot plant maintenance that has been required, we have requested a no-cost extension to complete the remaining scope of work. During the past 15 years, we have been conducting laboratory and pilot-scale R&D to advance the state of catalytic biomass pyrolysis technology to produce biofuels and bioproducts. The focus of these efforts has been to improve the CFP biocrude yield and the upgrading process at the pilot scale to demonstrate the techno-economic potential of an integrated biomass pyrolysis/hydrotreating pathway for renewable diesel production. This study builds on past projects that led to the design, fabrication, installation, and operation of pilot-scale unit operations for (1) CFP in a 1-TPD unit, (2) biocrude upgrading in a hydroprocessing reactor system, and (3) biocrude separation strategies to support bioproducts recovery and improved upgrading performance. The main objectives in this project address the key technical challenges associated with biomass conversion and separation and upgrading of intermediates. Preparing and feeding biomass has been a challenge for successfully scaling up and demonstrating thermochemical conversion technologies. One objective of this project is to evaluate the impact of feedstock preparation on cost and catalytic pyrolysis performance, particularly biocrude yields. Our partners at Forest Concepts are doing a detailed economic assessment of their technology for biomass preparation (drying and size reduction) as a function of particle size. We are then processing that feedstock in our 1-TPD catalytic biomass pyrolysis unit to evaluate the effect of particle size and feedstock type on biocrude yield and chemical composition. Recognizing that the absolute results may be reactor- or scale-specific, we expect the correlations to be relevant at a larger scale. In this final phase of the project, we will repeat the 1-mm and 2-mm Douglas fir CFP experiments for comparison to 1-mm and 2-mm alder CFP. Ten additional forest residual feedstocks will also be processed in the 1-TPD biomass unit. We will continue to explore optimized process conditions to maximize biocrude yields. Aqueous phase recycling not only reduces freshwater consumption (by 80%) in the process but also recycles organics back into the process, providing an opportunity to increase carbon efficiency. Continued sampling and analysis of the recycled aqueous stream will be used to follow the accumulation of specific biocrude components and help identify any impurities (alkali salts or nitrogen and sulfur-containing species) that may cause catalyst deactivation in downstream upgrading processes. The biocrude produced from the remaining biomass feedstock will subsequently be upgraded to renewable diesel. We have been exploring biocrude fractionation as a strategy to improve upgrading efficiency. Selected separation techniques are being used to segregate biocrude into fractions that are more easily upgraded and fractions that contain known components that cause fouling and plugging in the hydrotreating reactor. Fractionating the biocrude also puts less emphasis on HDO during CFP while putting a greater focus on increasing biocrude yield. In the final phase of this project, the second separations strategy (water washing followed by solvent extraction) will be demonstrated at the 7-gallon-batch laboratory scale to determine the relative separations efficiency, solvent use, and solvent recovery compared to the first strategy, where solvent extraction was followed by water washing. All hydrotreating products will be distilled to recover the renewable diesel fraction and characterized to determine if the fuel properties meet the ASTM D975 standard. The existing process model of the integrated catalytic biomass pyrolysis (CFP)/biocrude hydrotreating process will be updated with the experimental results collected during the final phase of this project. This model will form the basis of the final TEA for the integrated process to document the impact of the feedstock preparation on biocrude yield and quality as separations are used to achieve commercially relevant upgrading to biofuel. An LCA of the CFP/hydrotreating pathway will also be completed using the pilot-scale experimental results to evaluate the carbon intensity of the pathway for scenarios using the different feedstocks.

AGRICULTURAL AND WOODY BIOMASS TO DIESEL FUEL WITH FT INTERMEDIATE

West Biofuels LLC

WBS:	3.5.1.304
Presenter(s):	Matthew Summers
Project Start Date:	10/01/2018
Planned Project End Date:	12/31/2024
Total Funding:	$2,933,000



COMMENTS

- Approach: The project approach aligns with the metrics defined under Topic Area 2, DE-FOA-0001926.
  - Drop-in renewable diesel/jet fuel with >50% biogenic material, large-scale unit operations with commercial feedstock, mass/energy balance, TEA work, and minimum of 100 gallons final product. TEA/LCA with breakeven point; 1-dry TPD feedstock.
  - Gasification units, two Fischer-Tropsch units (slurry and fixed bed), and a combined Fischer-Tropsch wax, VGO upgrading at three different organizations.
  - Project management: Focus toward construction, commissioning, product transfer, and trials alignment.
- Progress and outcomes:
  - Gasification units commissioned and overhauled.
  - Fischer-Tropsch units commissioned but have not yet been tested.

    - Fischer-Tropsch wax (product was obtained from other research groups/industry) and VGO upgrading/distillation. Product specification compared with ASTM requirements.
    - 20%–40% coprocessed Fischer-Tropsch wax at the lab and pilot scale.
    - The project is conducting similar work at two locations to better understand the type of gasifier, Fischer-Tropsch, and coprocessing results; however, it seems to be repeating a lot of work that has been conducted in this area (funded by DOE NETL/BETO) offices on past projects. The goals of the project in terms of the desired Fischer-Tropsch product distribution were not clear from this presentation. Is the goal to increase Fischer-Tropsch diesel cut or heavily rely on upgrading Fischer-Tropsch wax?

- Impact:
    - If successful (the project started in April 2021 and has completed two budget periods), the project will allow distributed intermediate product generation to be blended with existing refineries. The project is run at a scale that is representative for quality checks to meet the statistical requirements for blending/risk reduction. Fischer-Tropsch reactors are highly impacted by syngas quality; both chosen gasifiers show varying H_2/CO ratios and CO_2 concentration. Fischer-Tropsch data provided on Slide 7 show >50%–60 wt % wax (if that is the desired Fischer-Tropsch product distribution), and hence the project highly depends on wax recovery and upgrade. The work on the Fischer-Tropsch wax upgrade has not yet started. The project can highly benefit from past data and work in the choice of the Fischer-Tropsch reactor.

- The goal of this project is to produce diesel fuel using Fischer-Tropsch technology. The Fischer-Tropsch process is being carried out by West Biofuels using a fixed-bed catalyst as well as Best using a slurry bed reactor.

- The project has produced wax that can be used in a fluidized catalytic cracker resulting in acceptable fuel properties. A gasifier has been commissioned in Austria for Best, while West already has a gasifier on-site.

- There is no economic analysis that is important for this project. Fischer-Tropsch is a mature technology that has not had much, if any, sustained commercial success. The presentation did not include anything about the process that makes one believe that this one will be different. It certainly works, but it is not clear that it is cost-effective to do this.

- The project is on track to meet objectives. It is clear that this project addresses BETO's strategies to produce drop-in fuels. There are some novel approaches with VGO and Fischer-Tropsch technology. These kinds of projects bolster the opportunities to look at the thermochemical processing of biomass for the production of oil refinery-type fuels. The project has a good risk analysis and mitigation strategies. The project needs to take a closer look at interface risks because that is always a hurdle to successful integration. This is a good team. Their long-term goal is to design and build their own operations, and they have a long way to go, but they are on track. They need to continue to assess local permitting and environmental issues to ensure they do not run into any snags that will delay their progress. Anticipate the worst, hope for the best.

- The project is investigating and developing a renewable diesel fuel production pathway through gasification, Fischer-Tropsch, coprocessing of the produced wax with VGO via FCC, and separation of produced diesel from other products, which could also be hydrotreated to generate diesel fuel. The project was originally funded in 2021, but it was affected by the pandemic; still, the initial verification has been completed, and industry involvement is well developed. The project team aims to quantify the biogenic versus fossil carbon flows through the system, which is necessary to identify the extent to which the produced diesel can be considered a renewable fuel due to the added fossil carbon inputs during FCC. This analysis would benefit from being extended into a full LCA to quantify the life cycle GHG emissions of the fuel, including emissions associated with its processing energy needs, VGO production, and hydrogen inputs, among other components. It is unknown whether this process generates a lower-carbon footprint diesel than conventional diesel without this analysis. This may also enable optimization toward lower GHG emissions as the project is analyzing the effects of different ratios of wax to VGO experimentally.

- The work is focused on replicating work done in Austria with feedstock from the United States and in the United States; however, no technical updates or modifications to the Austrian work appear to be planned. So, it is questionable if they are just replicating previous work done elsewhere and just reporting those results. The reviewer struggles to see the novelty of the approach or value of replicating work done elsewhere.

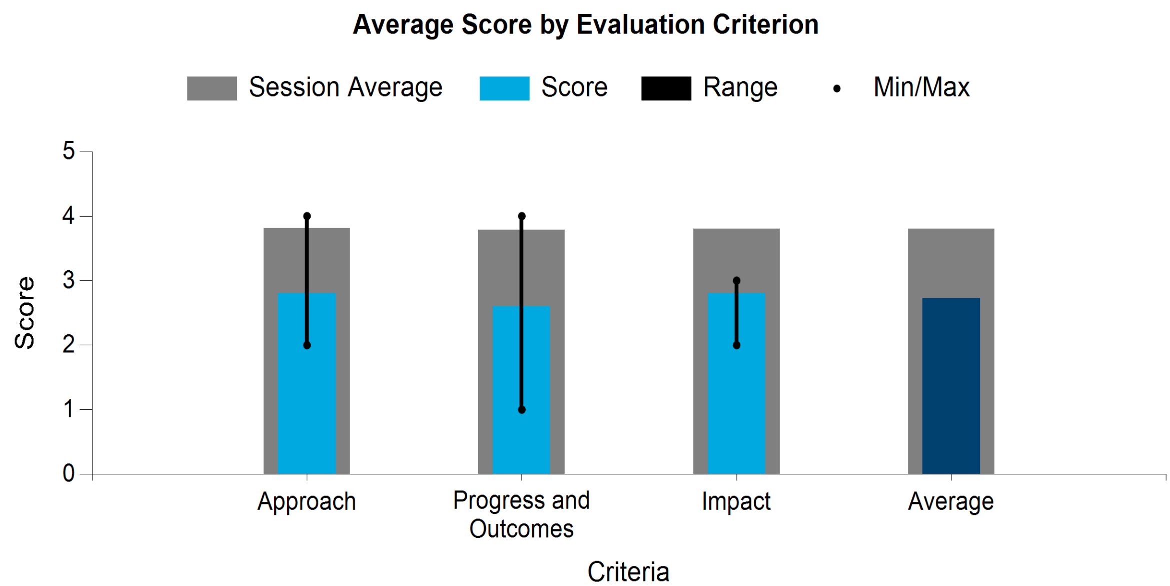
NOVEL METHOD FOR BIOMASS CONVERSION TO RENEWABLE JET FUEL BLEND

Technology Holding LLC

PROJECT DESCRIPTION

The overall objective of the proposed innovation is to demonstrate the techno-economic feasibility of an integrated process to produce drop-in jet fuel blend and isoprene as a coproduct from biomass hydrolysate such that private funding can be obtained after the initial governmental funded period. The technology will be matured from TRL 3 to TRL 4.

WBS:	3.5.1.401
Presenter(s):	Mukund Karanjikar
Project Start Date:	10/01/2018
Planned Project End Date:	03/31/2023
Total Funding:	$3,125,000



COMMENTS

- Approach: The project approach aligns with metrics defined under AOI-1 DE-FOA-0001926 in terms of gallons of product, selectivity toward cycloalkanes, improvement of required properties, and lower aromatic content. It is not clear if the level of GHG reduction has been met or included thus far in the project. The technical approach is to showcase a catalytic reaction to produce a cycloalkane/isoalkane mixture as a substitute for jet fuel without blending requirements. The project builds on past work for isoprene production via fermentation.

- Progress and outcomes: The verification stage and several other tasks have been successfully completed with up to 4 liters of dimethyl cyclooctanes (DMCO) production. The blends were tested with two HEFA and Jet A, showcasing meeting property requirements. The current focus is on pilot plant design. The team has made significant progress on all aspects. Some key questions that remain are TEA and justification for converting isoprene (a high-value/low-volume chemical) to SAF. Differences in the rate of productivity via fermentation (and hence scales) followed by Zeigler Natta-type chemistry.

- Impact: The project demonstrates (1) a shift toward cycloalkanes/isoalkane product with low or no aromatic content; (2) a unique approach using isoprene as an intermediate precursor; and (3) most importantly, showcasing that the property metrics requirement has been met at a greater detail.
- Questions: What is the rate of reaction for fermentation? What are the comparative sizes for fermentation versus catalysis? Was a model compound used for the catalysis reaction thus far and/or for pilot studies? What is the cost of the production of isoprene?
- The overall process consists of a fermentation to make isoprene, then isoprene is converted to cyclic alkanes using a catalyst. The fuel has been blended to make jet fuel, but it has the properties to be a stand-alone drop-in fuel. There was no discussion of the team (though it may just be Technology Holdings), and the discussion of risks are not specific enough, i.e., first-of-a-kind capital plant, to understand the technological advancement of the project.
- Most tasks have been accomplished with a pilot plant to be designed. The very different timescales for the fermentation and the catalytic process were not addressed. The catalytic process uses a homogeneous catalyst, but that was not described to know if it can be recovered. The production of impurities in the fermentation was not addressed. The idea that only the isoprene would leave the fermentation as a vapor does not seem reasonable.
- This is an interesting and novel route to cycloalkanes. Several important issues were not covered in the presentation, making it difficult to know what impact this process will have and the likelihood it will be possible as a fully integrated system.
- The project has achieved a measurable proof of concept. The results are noteworthy. There remains a long path ahead for fuel certification and the demonstration of an integrated system ready for piloting. The project should focus on how to put the pieces together with risk factors not on the global level but on the engineering-scale level. The potential of this approach is good for BETO's strategic goals; however, the presenter mostly spoke of future potential. The presentation would have been more meaningful if it had included some details of the process and how they were being conducted. I found this to be a major weakness of the presentation.
- This project focuses on assessing the feasibility of a processing pathway including fermentation that selects for isoprene and conversion of the isoprene to a jet fuel blend with DMCO. The project, which began in October 2018 and ended in March 2023, has met its goals of blend tests and partial fuel characterization, but not full characterization to assess the potential of the blend to meet ASTM standards, its fuel production goal of 10 gallons (although it has produced 4 liters of DMCO and started pilot plant design), LCA of the environmental impacts, or TEA. Without these data, it is unclear whether the project has commercialization potential despite the project team being in discussions with industry and the U.S. Department of Defense about the pathway.
- This project is addressing an unmet need in the space. The project is still not approved and needs to go through the ASTM approval process. The bigger challenge is the production of isoprene itself, with challenges in anaerobic fermentation. The project TRL is still partially unmet with FOA goals.

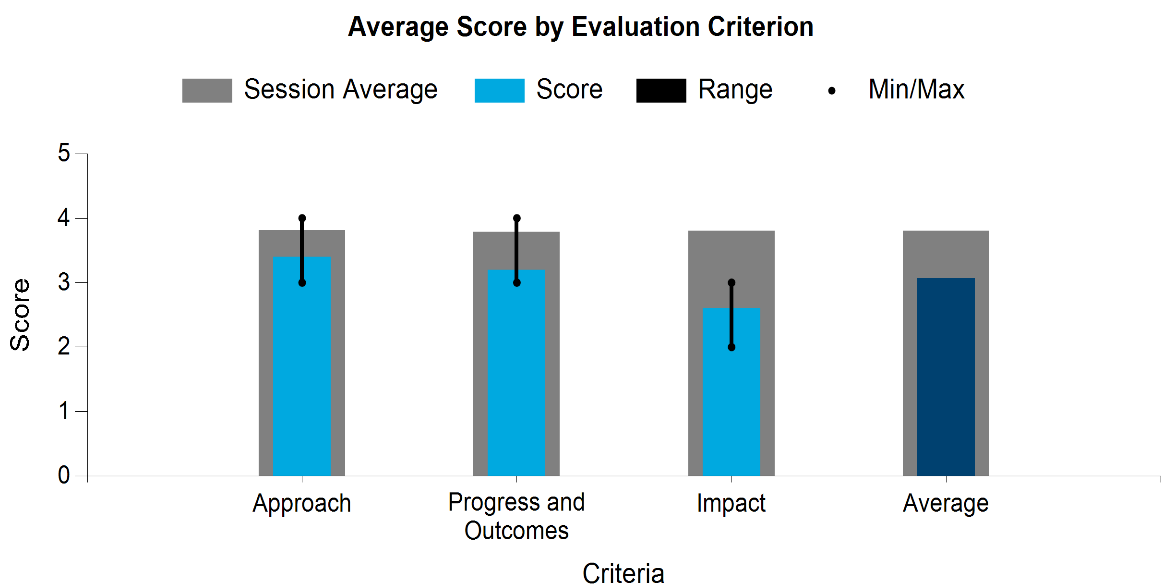
HYBRID HEFA-HDCJ PROCESS FOR THE PRODUCTION OF JET FUEL BLENDSTOCKS

Washington State University

PROJECT DESCRIPTION

WBS:	3.5.1.402
Presenter(s):	Manuel Garcia-Perez
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2023
Total Funding:	$3,472,904

The production of HEFA is the best current option for jet fuel production. HDO of bio-oils derived from pyrolysis and HTL of lignocellulosic materials produces jet fuel rich in aromatics, also known as hydrotreated depolymerized cellulosic jet (HDCJ). Relevance: Although HEFA is the most promising technology for jet fuel production, the construction of new units is limited by the availability of triglycerides. Pyrolysis and HTL bio-oils produced today are not accepted in any existing industrial facilities for further refining. Coprocessing triglycerides (yellow greases) with the phenolic-rich fraction of pyrolysis oils could help to increase feedstock availability for HEFA plants and create a path for bio-oil refining. Challenges: Our goal is to evaluate the technical and economic feasibility of using HEFA facilities to coprocess pyrolysis or HTL oils with yellow greases. Currently, our main challenge is to steadily operate the 400-mL continuous hydrotreatment reactor to produce larger quantities of jet fuel for tier beta and alpha tests. Accomplishments: We completed the oils collection, characterization, and emulsion stability studies. We have identified suitable conditions for coprocessing in a batch (250-mL) reactor and in a continuous 40-mL reactor. The fuel properties of the different cuts have been studied. The information collected is being used to conduct mass and energy balances and TEA and LCA of the hybrid HEFA-HDCJ technology. We are designing and evaluating a supply chain for the hybrid HEFA-HDCJ concept for the conditions of the state of Washington.



COMMENTS

- Approach: The project approach aligns with the metrics defined under AOI-1 DE-FOA-0001926 in terms of gallons of product, choice of feedstock, and scalability potential (merging with an existing process).

The technical approach is to increase the availability of feedstocks required for the HEFA process, which is currently limited by using yellow grease. The team has worked in tandem and showcased a large volume/amount of processing at each step. A major technical barrier was and still is coke formation and reactor clogging.

- Progress and outcomes: The verification stage and several other tasks at the laboratory scale—including product collection, product characterization, TEA, and LCA—have been successfully completed, with a long list of publications. The group has openly shared knowledge and made significant progress. TEA/LCA data are constantly updated. Only an area of concern is the limited product generation, and, as such, the project did not meet the FOA goal of a minimum 100 gallons of product and is less likely to achieve it in the remaining time. Higher hydrogen pressure with commercial catalysts that have a highly prescriptive catalyst presulfidation process might help reduce the coke and increase the life/TOS between regenerations. The main technical hurdle is the thermal coking of the pyrolysis oils prior to the catalyst bed or upper zones of the reactor bed.

- Impact: If the claims are realized, the project will demonstrate (1) an approach to reduce risk by combining hydrothermal and pyrolysis technology to advance the scalability of the HEFA process, (2) verification of the miscibility and product mix to generate feed for cohydrotreatment, and (3) reduction of experiments via TEA/LCA and lab results are well documented and help other technologists. Recommendation: The project can make a significant impact if more time/funds become available to do cohydrotreating work with industrial catalyst participation. Coke reduction for mixed-feed hydrotreating is at a more advanced stage than showcased here.

- The project cotreats bio-oils from liquefaction or pyrolysis with yellow greases. The management of the project with all task leads and progress in each task are presented very nicely. A major issue is coking of the catalyst, to be described next. It might be good to have a partner that can help with this issue.

- Coking in the scaled-up unit is a major issue that will require major reengineering of the process to avoid. The coking causes plugging of the system and shutdown, limiting the amount of continuous operation.

- Most tasks are not yet completed. The TEA and LCA are 90% complete, but they were not presented. Given the problems with plugging, the TEA or a modified TEA for a redesign could help determine whether to continue down this path.

- It seems that the plugging issues due to coking are severe issues that require much more time than is available to address. The results have been published in several papers, so much of the work is clearly important despite this major issue.

- This is a promising technology that has been evaluated in actuality at TRL 4–5. The encountered problems limited the team's ability to meet the performance goals; however, these are not insurmountable, and the team is working to address them. They are using the right tools to assess the performance needs, but they probably need more time to scope all the potential risks. The team has made a good number of academic analyses that helped the project, and they made an honest assessment of the project's progress; however, this process seems a long way from the finish line, and there is still a lot to prove that it has commercial potential. They have done a reasonably good job of assessing the feedstock sources. They may want to look to the Port of Umatilla, which was involved in gathering and collecting yellow-type greases for processing a few years back, to see if they have any avenues that would serve as suppliers for a process like this one.

- The project involves the development of a hybrid coprocessing pathway for pyrolysis oils and HTL oils with yellow greases to ultimately generate jet fuel. The project team has worked on supply chain analysis, LCA, and TEA in addition to performing bench-scale studies of cohydrotreatment of the oil and grease feedstocks. They have been able to test at small scales, but continuous coprocessing has faced issues at the lab and bench scales. Because the project is in its last year, the team shared that the original target of 100 gallons of jet fuel will not be reached. Additionally, there are biomass feedstock and yellow grease supply difficulties in the region (northwest United States), with a high likelihood of limiting commercialization potential. The lab-scale and bench-scale studies and modeling studies have provided some useful results that may assist in identifying future R&D directions; even the challenges experienced may inform new approaches that can overcome them in the future. As it stands however,, there is a relatively low likelihood of significant impact and commercialization potential, and new risk management strategies may need to be employed in any further study of this pathway.

- Challenges with coke formation and catalyst fouling continue to present barriers. The team has successfully demonstrated less than 1% coke formation.

PI RESPONSE TO REVIEWER COMMENTS

- The PIs thank the reviewers for the very constructive comments. Our main challenge today is to overcome the coke formation issues that are limiting our capacity to continuously operate our HDO unit. We were able to operate our 40-mL continuous unit for 255 hours in coprocessing (340 hours total run); however, when scaling to 400 mL, plugging happened at 26 hours of coprocessing (125 hours total run). Although we need more time to overcome these issues, we do not agree with Reviewer 2 regarding the low likelihood of a significant impact and commercialization potential. The encountered plugging issue is mainly due to the poor coke tolerance of trickle bed reactors and the fact that we cannot use very active precious metal hydrogenation catalysts due to the presence of sulfur in the feedstock. The coke levels achieved are low and tolerable by other reactors. In our opinion, the issue can be solved with the use a different type of reactor for the stabilization step (e.g., a slurry reactor) and by conducting a deeper stabilization of the oil before cohydrotreatment (perhaps using esterification strategies with alcohols, which are well described in the literature).

DROP-IN RENEWABLE JET FUEL FROM BROWN GREASE VIA THE BIOFUELS ISOCONVERSION PROCESS

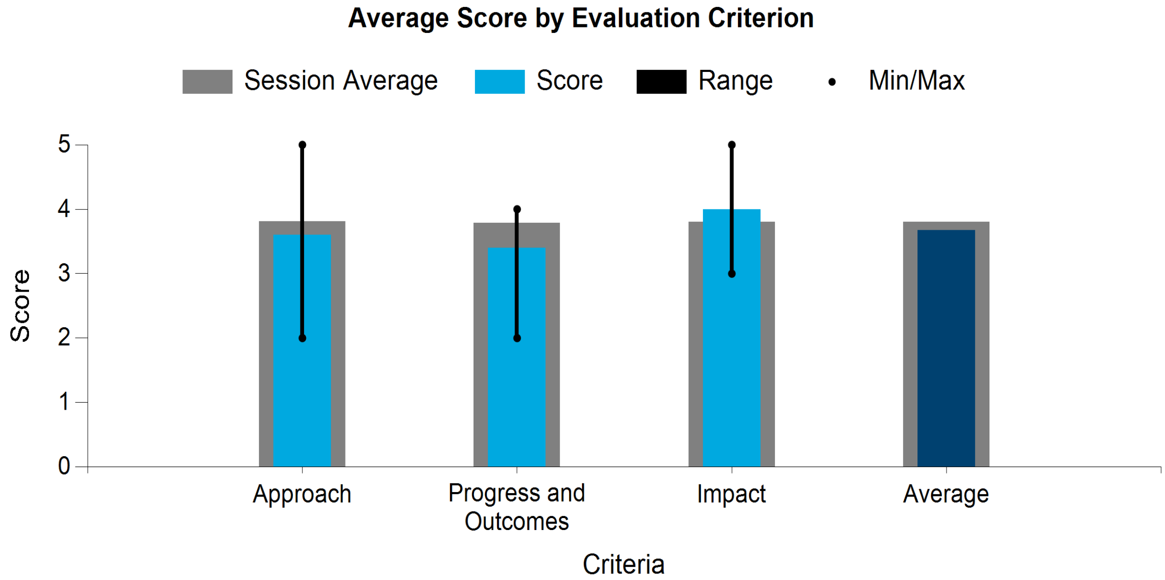
Applied Research Associates

PROJECT DESCRIPTION

WBS:	3.5.1.404
Presenter(s):	Jeff Rine
Project Start Date:	10/01/2018
Planned Project End Date:	03/31/2023
Total Funding:	$2,951,431

The Biofuels ISOCONVERSION process is a patented technology for converting lipids into naphtha, jet, and diesel fuels. The Biofuels ISOCONVERSION process consists of a hydrothermal cleanup (HCU) operation; a conversion operation, called catalytic hydrothermolysis; hydrotreating; and distillation into jet and diesel fuels. Catalytic hydrothermolysis jet (CHJ) from the Biofuels ISOCONVERSION process is an approved pathway under ASTM D7566 Annex 6 to produce commercial jet fuel. Brown grease is an acceptable feedstock for the Biofuels ISOCONVERSION process under Annex 6 and was the target feedstock for this DOE project. CHJ is a candidate for use as an unblended, 100% SAF because its chemical and physical properties are nearly identical to jet fuel derived from petroleum. Valuable coproducts from the Biofuels ISOCONVERSION process include diesel fuel that meets the ASTM D975 specification and naphtha that can be used as a gasoline or an E-85 blending component.

A goal of this DOE project is to demonstrate a “mature price goal” of less than $3/GGE. A key to meeting this goal is to demonstrate that the Biofuels ISOCONVERSION process can use highly contaminated, low-cost feedstocks, such as brown grease, to make jet fuel. Historically, brown grease costs approximately $0.10/lb ($0.75/gal), which is a small fraction of the cost of edible plant oils, such as soybean or canola oil. The Applied Research Associates (ARA) HCU process (U.S. Patent #10,071,322) removes metals, soaps, phospholipids, and other contaminants, producing a clean lipid feedstock for conversion into jet fuel via the Biofuels ISOCONVERSION process or other approved conversion processes. Pilot-scale testing during this project demonstrated that the HCU process reduces metals and phosphorus in highly contaminated brown grease to less than 5 ppm in a single step. Because HCU is a single-step, hydrothermal process that does not rely on conventional degumming and clay bleaching processes, solid wastes are eliminated, and the yield of clean oil is greater than 99%. Work performed during this project optimized HCU operating parameters to successfully reduce contaminants in brown grease. Brown grease cleanup and conversion was demonstrated in pilot systems with throughput capacities up to 3 barrels/day. Approximately 600 gallons of renewable crude from brown grease was produced for hydrotreating and distillation into 100 gallons of jet fuel meeting ASTM D7566 Annex 6. Initial pilot distillation of the hydrotreated product into CHJ demonstrated that all key specification requirements were met. Larger pilot distillation operations are underway, with an estimated completion date during FY 2023 Q2. Preliminary engineering is also underway for a commercial-scale facility capable of using brown grease as a feedstock to produce liquid fuels at less than $3/GGE. An estimated completion date for preliminary engineering is also FY 2023 Q2. The Biofuels ISOCONVERSION process is currently at TRL 7 for clean feedstocks. This project will increase the TRL for the HCU of brown grease from TRL 4 to TRL 7.



COMMENTS

- Approach: The project approach aligns with the metrics defined under AOI-1 DE-FOA-0001926 in terms of gallons of product, choice of feedstock, scalability, and hence cost. It is not clear if the level of GHG reduction has been met or is included thus far in the project.
- The technical approach is to showcase the removal of metals/impurities from brown grease and upgrade it to a blendstock for hydrotreating and distillation. The team has worked in tandem and has showcased a large volume/amount of processing at each step.
- Progress and outcomes: The verification stage and several other tasks have been successfully completed, with >400 gallons of intermediates. The hydrotreated crude and distillates were compared with jet fuel and diesel fuels, showcasing major agreement with desired properties. The current focus is on distillation and TEA. The team has made significant progress on all aspects; the ASTM 7566 Annex 6 criteria have been met. For the supercritical reaction step hazard and operability analysis, the team is working with a licensee. The project has one limitation of collecting the required amount of untreated brown grease. The team has made great technical progress. The water/gallon fuel used or recycled is to be confirmed. The project has been extended to Sept. 30, 2023.
- Impact: If the claims are realized, the project will demonstrate (1) a shift toward a new waste feedstock; (2) a unique approach using mixed feedstock with variability (a key risk of collection and homogenization); and (3) most importantly, showcasing that the property metrics requirement is met in greater detail for jet and diesel fuel. The next step to review the TEA results. The HCU and Biofuels ISOCONVERSION integrated process have already shown commercial traction. The low feedstock cost is advantageous. This project has clearly demonstrated the use of an underused feedstock to a fuel with great agreement with required properties. The work has been conducted at the pilot scale with good reproducibility. The project shows excellent process.
- The process uses HCU to clean brown grease, then catalytic thermolysis to make syncrude, which can be treated in a conventional hydrotreater and distillation column. The team comprises ARA, and they are using a tested method that they have developed. They have addressed a major risk involving the addition

of lime to brown grease, which causes serious problems for their process. The Southwest Research Institute performed their hydrotreating and distillation.

- They have performed many milestones, with the TEA left. Their process is definitely possible using properly treated brown grease as a feedstock.
- Water is used in multiple steps in their process with little to no discussion of how much is lost in the different steps. The cost of generating supercritical water is expected to be quite large, yet there was no discussion of how much water was needed in the catalytic hydrothermolysis reactor. The cost of brown grease is going to change once it is used to create a fuel. This should be considered in the TEA report.
- The brown grease resource has needed a more thorough look to assess its potential. This project seems to be able to show that. The clean HCU product needs to meet the performance requirements, and it seems to have done that. The issue in all FOG systems is the efficient and cost-effective collection of the feedstock. Normally, people are glad to give it away, but if the value can be imputed to the product of processing, the suppliers may demand a cost for supplying the brown grease. It is not clear how they managed the waste streams.
- This project has very good potential to be demonstrated at a larger scale. There has always been potential in brown greases, and this project may be the right route to meeting that potential.
- The project is developing a Biofuels ISOCONVERSION (trademarked) process for drop-in renewable jet fuel production from brown grease, which is a low-cost wet waste feedstock generated from a variety of sources. With the high volumes of brown grease generated in the United States, there is potential for this process to convert a waste into a higher-value fuel product. Currently, however, collectors treat the brown grease with lime, which affects the conversion and “cleanup” processes by scaling the reactor. The project team is advised to test the solids generated in the reactor because previous studies of the HTL of calcium-rich feedstocks have generated hydroxyapatite (another higher-value product) along with a biocrude oil. Although these solids currently serve as an impediment to scale-up and commercialization in terms of their effects on the current reactors, they may provide additional economic benefits from the conversion process at the commercial scale if they are confirmed to be a high-value product like hydroxyapatite; however, the process still faces a challenge with the high volumes of oil-contaminated wastewater that would require treatment after separation. The wastewater has not been characterized, and the effects of changing the water-to-grease ratio have not been studied. The possible trade-offs in costs and environmental impacts from process to process along the life cycle of this fuel production pathway indicate the need for an LCA and TEA to better project the potential of this pathway. Despite this, industry partners are planning and constructing unit processes from the Biofuels ISOCONVERSION system. This 5-year project ended in March 2023, having met multiple goals but not the goal of producing 100 gallons of jet fuel through this process.
- The availability of brown grease is approximately 1.5 MM MT. Also, the supply chain is not segregated. The presence of calcium and other polymers will affect the reactor. D3 RIN credits for the diesel fraction should be explored.

HIGHER-ENERGY-CONTENT JET BLENDING COMPONENTS DERIVED FROM ETHANOL

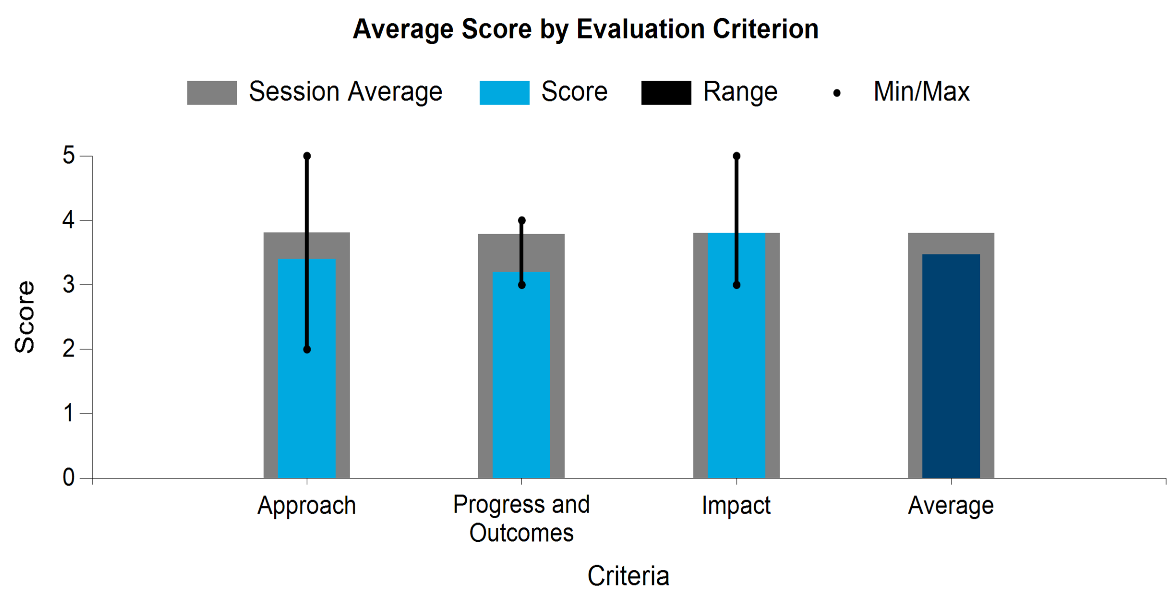
Purdue University

PROJECT DESCRIPTION

WBS:	3.5.1.408
Presenter(s):	Gozdem Kilaz
Project Start Date:	10/01/2019
Planned Project End Date:	07/31/2024
Total Funding:	$2,217,768

BETO's efforts in generating SAF have helped establish the production of isoparaffinic synthetic jet fuels with favorable properties, such as high energy density, excellent thermal stability, and favorable cold-flow performance. Combined with isoparaffins, cycloalkanes carry the potential of further fuel performance improvement with at least a 4% net increase in energy content. PNNL has already demonstrated a sustainable, nonpetroleum route to isoalkanes; however, the production of cycloalkanes from waste and biomass is challenged by hydrogen requirements, preferential selectivity to aromatic compounds, and low yields to jet-fuel-range components. Purdue University has partnered with PNNL and LanzaTech to create a strong team with the fuels, catalysis, process development, and scale-up expertise needed to successfully address these challenges.

Olefin intermediates will be produced from ethanol using existing technologies from the Chemical Catalysis for Bioenergy Consortium (ChemCatBio) and from PNNL/LanzaTech. In this project, we will leverage experience in converting a variety of olefins to jet- and diesel-range hydrocarbons to develop a new process with high selectivity to cycloalkanes. Processes such as hydroforming can convert alkanes and alkenes to cyclic alkanes (e.g., naphthalene from n-decane), and PNNL has demonstrated the production of cyclic alkanes from butene with 25% selectivity. The team will build on this established proof of concept in developing a process ready for scale-up using PNNL facilities to produce a minimum of 2 gallons of fuel blendstock. The project makes use of Purdue's extensive analytical capabilities to measure fuel properties that are indicative of the product's "drop-in" potential. Further experiments and analyses are currently executed to evaluate the end product's optimum blend proportions with conventional jet fuel.



COMMENTS

- Approach: The project approach aligns with the metrics defined under AOI-5 DE-FOA-0002029 in terms of gallons of product, selectivity toward cycloalkanes, improvement of required properties, lower aromatic content, scalability, and hence cost. It is not clear if the level of GHG reduction has been met or included thus far in the project. The approach is to showcase a catalytic reaction to produce >60 wt % cycloalkanes (using knowledge from isoalkane catalysis) as a substitute to jet blends to meet the high energy content and low swelling of O-ring materials requirements. The project builds on past work for feedstock generation for this reaction using industrial waste gases to olefins.

- Progress and outcomes: The verification stage has been successfully completed. The initial go/no-go was passed for the development of the analytical methods by April 30, 2022. Budget Period 2 work has focused on catalyst studies to improve cycloalkane yields and TOS. Results: 30 mol C% cycloalkanes, TOS 34 hours. The team has identified key cycloalkanes that maximize energy density (it is not clear how much of those are produced). The results on Slide 14 show a catalyst for alcohol dehydration to olefins (not the current focus of the study) and a literature citation for olefin to cycloalkane (up to 90% selectivity); it is not clear if this has been reproduced. The team has made significant progress on analytical methods in conjunction with identifying the impacts of what can potentially swell the seals, which is well documented with an understanding of the reasons behind it. The team has completed the key compound identification (cycloalkane trans- and cis-decalin) and the TEA/LCA model.

- Impact: If the claims are realized, the project will demonstrate (1) a shift toward cycloalkanes; (2) lower aromatic content and high energy density, and (3) improvement in lower swell properties. The project is geared toward meeting the required milestones and can advance the state of the art (SOA) by advancing new analytical methods and the impact of a new chemistry on O-ring swelling.

- The team comprises Purdue University, PNNL, and LanzaTech, giving a well-rounded team. Their goal is to convert alcohol to cycloalkanes to blend with jet fuel. They give specific goals for cycloalkane composition, with reasonable steps to take should they have problems meeting these goals.

- They completed the initial verification and have put a significant amount of effort into product identification. They have also identified target cycloalkanes that maximize energy density. They have also performed LCA and ring swelling analysis.

- The project has the potential to deliver high-cycloalkane-content jet fuel blending components. The identification of optimal cycloalkanes seems a bit too specific, and it is unreasonable to target those three cycloalkanes. It seems that the beginning and the end of the process have seen good progress, but the middle is lacking, and it is really needed to tie it all together.

- The project is designed to improve an existing process to produce a better SAF. Their approach is appropriate and addresses critical requirements for the LanzaTech process to be more relevant to producing jet fuel. Their approach is comprehensive, and they have a good risk management plan. They are a bit overambitious in planning for commercial-scale operation when they need to validate the findings at TRL 6 or TRL 7. They are not ready for TRL 8 because they are still in the system development stage. Overall, this is a well-managed project with an industry partner that has had success in commercializing technology.

- The project aims to develop and model a process for generating higher-energy-content jet blending components from ethanol to produce a jet fuel that has favorable fuel properties and that requires less hydrotreatment. The objectives include LCA and TEA of a 50-million-gallons/year commercial-scale process, catalyst development, analytical method development, process optimization through lab experiments, and the production of 2 gallons of cycloalkane fuel blendstock. The project has met its first two first milestones, but it has also adjusted its schedule to a no-cost time extension. The project team includes industry and aims to improve upon an existing PNNL/LanzaTech process. The potential for a significant impact is unclear; the data on selective catalytic formation of cycloalkanes and lab analysis methods emergent from the project could be useful to industry, but the approach appears to be a set of adjustments to a specific existing process used by one company. The preliminary LCA focuses more on the type of feedstock than on the conversion approach and comparing that to the impacts of other pathways; such results would be helpful in further optimizing the studied processing pathway.

- The project is limited by the pathway approval for SAF; however, it is important work toward addressing unmet questions in the development of SAF. The project is asking for a no-cost extension, and the reviewer wonders if the project team has adequate resources for the same.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the positive comments from the reviewers highlighting our innovative approach for producing cycloalkanes that maximizes energy density for jet blendstock; builds on past work for feedstock generation using industrial waste gases to make olefins; improves upon an existing PNNL/LanzaTech process; can advance the SOA for new analytical methods; demonstrates the impact of new chemistry on O-ring swelling; has strong teaming, with an industry partner with success in commercial technology; and shows a comprehensive approach, has good risk management, and is well managed.

- Regarding the question of whether GHG reductions have already been met, a >70% reduction in GHG has already been met by producing jet blendstock from renewably sourced ethanol. PNNL/LanzaTech already developed the ATJ processing for producing an isoparaffinic jet blendstock from ethanol. Here, we are working to improve this processing by shifting the product slate to cycloalkanes, which are more energy dense than isoparaffins. One reviewer mentioned that key cycloalkanes that maximize energy density were identified, but it was not clear how many of these have been produced experimentally. The target cycloalkanes were identified by researchers at Purdue separate from the conversion work being done at PNNL. The goal of the Purdue team was to identify the most promising molecules for maximizing energy density to (1) inform the PNNL experimental team and (2) provide this insight in a journal manuscript that is about to be submitted for publication. The Purdue team picked molecules to evaluate with guidance from PNNL on what products and mixtures might be possible to produce using the chemistry being developed. Details for how the degree of branching and other features affect energy density were discovered. This information will inform the research community as well as our own work moving forward.

- There was a question whether the results shown for olefin to cycloalkane selectively up to 90% had been reproduced by our team. We apologize for the confusion. No, this was from data reported from the literature. Thus far, we have had limited success in obtaining high cycloalkane selectivity with single-step processing; therefore, we showed the results from this paper as a proof of concept for producing high cycloalkane selectivity when using a two-step approach. Here, jet-range olefins are first produced followed by ring closure to produce a jet-range cycloalkane. We have recently pivoted our approach to this two-step processing, and we are working to reproduce results from this paper as part of this effort. We are also evaluating another two-step approach that also appears promising. We look forward to reporting on these results in the next review.

- There was a comment that we are ambitious in planning for commercial-scale operation. First, we point out that the TEA and LCA performed were assuming commercial-scale operation, as is typically done. Second, we made the point that, if successful, we could take advantage of the commercial platform already being built out by LanzaTech. Here, we use the same olefin intermediate for producing cycloalkanes as the current PNNL/LanzaTech process for producing isoparaffins as jet blendstock; thus, there would be the leverage of an ongoing commercial deployment activity already underway.

- There was a question whether this work could be useful to industry where our approach leverages a specific existing process. We point out that the olefin feedstock used here could be produced from a variety of sources, and thus we believe that this catalysis could be broadly impactful. The processes for producing aromatics from olefins are widely used in industry today. But commercial technology for producing cycloalkanes do not exist; thus, the new processing being develop here could lead the way for new cyclization chemistry.
- Finally, there was a comment that the project has asked for a no-cost extension (actually two), and the reviewer wonders if the project team has the resources to do so. The team is, indeed, running out of resources, but, fortunately, the team believes it will soon have the data required to meet the very challenging go/no-go criteria to move into the final budget period.

CELLULOSIC-DERIVED ADVANTAGE JET FUEL

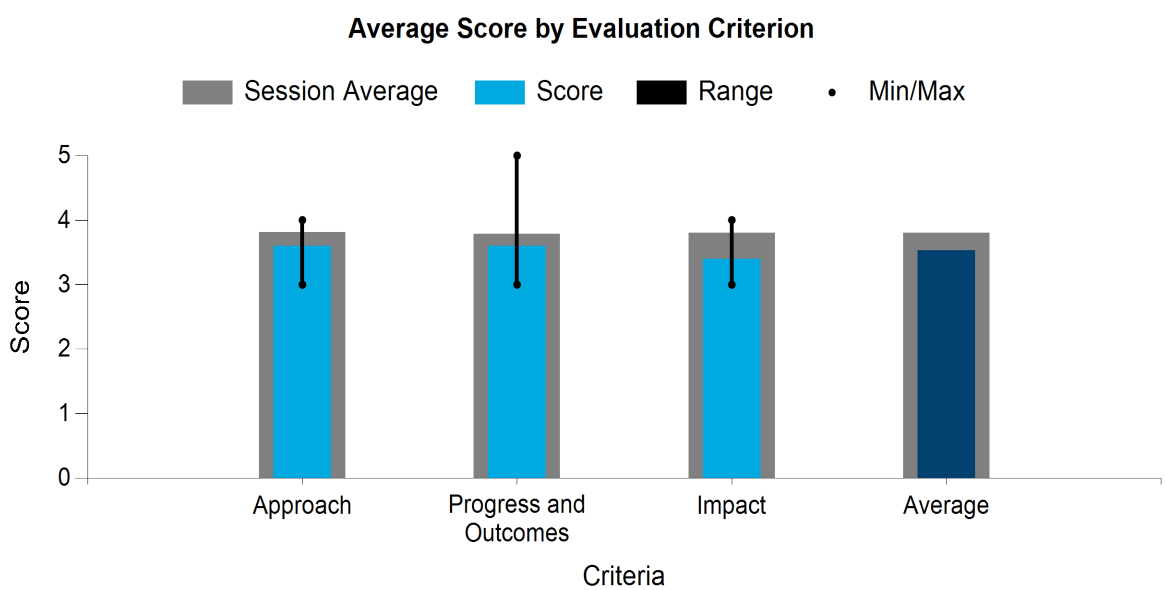
The Regents of the University of Colorado

PROJECT DESCRIPTION

WBS:	3.5.1.410
Presenter(s):	J. Will Medlin
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2024
Total Funding:	$2,705,048

This project will produce a jet fuel from cellulosic-derived sugars using a novel catalytic processing technology. The produced liquid fuel will have high content of cyclo-paraffins and dicyclo-paraffins, compounds that have high energy density, thermal stability, and a low freeze point, all of which are desirable properties for jet fuel. The process of generating jet fuel from cellulosic feedstocks provides a route for generating a large volume of product (7–14 billion gallons) from corn stover at a competitive price. This project will provide the necessary evidence for improved yields and operability to allow this technology to move toward commercialization.

The project is led by the University of Colorado Boulder in partnership with NREL, Shell, and Virent. This project combines the deacetylation and mechanical refining (DMR) deconstruction technology developed by NREL with a novel catalytic conversion technology discovered by Virent. NREL is working with Virent to design and commission a catalytic process unit to produce 2 gallons of on-specification jet fuel. Shell, one of the leading providers of jet fuel to the aviation industry, will provide analytical support by conducting analysis for ASTM approval as well as conducting blending studies of the generated jet fuel. The University of Colorado Boulder will lead the project and conduct fundamental studies of the required condensation chemistry to guide improvements of the catalytic process.



COMMENTS

- The project approach aligns with the metrics defined under AOI-5 DE-FOA-0002029 in terms of gallons of product, product stability/compatibility, and MFSP. It is not clear if the level of GHG reduction and aromatic content (8%) metrics have been included thus far in the project. The approach is to reduce ash content using NREL's DMR technology and improve the condensation catalyst stability and the process optimization. Key innovations are high-yield/low-ash-content sugars and an improved condensation catalyst, minimizing competing reactions. The verification stage has been successfully completed. Budget Period 2 work has been completed for one quarter on the condensation catalyst as a bench-scale test using model compounds. A schematic for the reaction paths and setup is shown, but no data are provided for the conversion/selectivity or the stability of the catalyst (the presenter verbally mentioned 3–4 weeks). Similarly, the benefits of the DMR technology are listed, and a product profile with an ash profile and sugar yield is required to determine the impact of its benefit on the process and if sugar meets the specifications required for downstream catalysis. Overall, the four-step proposed process has three hydrogenation steps, and as such quite high hydrogen demand, and this needs to be reported and accounted for in the TEA.

- The project has a good mix of university, national lab, and industry participation. That the national lab contributor is the founder of one of the industry partners seems to be a major strength. A technical problem that deals with the relative rates of the different potential reactions is being handled well by looking at the model compounds and model reactions. This kinetic information should be helpful in predicting the potential range of products. The metrics for the catalyst stability were not clear. Typically, catalysts deactivate over time, so giving a performance benchmark for a particular amount of time would be a better description.

- Despite how recently the project started, it seems that the lab experiments are up and running. It is of interest to the project that smaller molecules react faster and should be considered for the kinetics. A process flow diagram of the overall system was presented, which is encouraging. A phase separator between the first and second reactor showed that everything went to the second reactor.

- It seems that Virent is working on variations of this. Without a TEA or LCA, it is truly difficult to assess the overall impact. It does seem that a more stable condensation catalyst was the main goal of the work. More information on how this would be scaled up from the lab reactor would be helpful because this is going to be an important piece. Though Virent has done this in the past, more information could be shared.

- This project is on track and has met the first critical decision requirements to continue. The project is at TRL 6 of evaluation and seems to have the pieces necessary to complete this level. The project team should focus less on improving each step and more on how integrating the unit operations work together. Interface issues may be a risk they need to address. Whole-system issues are more important to look at than the efficiency of each unit operation. DMR is still a process; the team is working on delivering adequate quantities of clean sugars, so that area will need to be eventually addressed. Virent has been working on this technology for a long time, and I expected a bit more advancement than what has been shown.

- This project involves the development of a novel pathway to produce jet fuel involving catalytic hydrogenation, HDO, and condensation. The start of the 3-year project was January 2022, and the team has spent less than 2% of their budget; they passed the initial verification in 2022 and are on track toward their June 2024 go/no-go decision point. In this first phase of the project, they have involved industry in the unit process design (one PIs is the founder of the company) and made progress on the bench-scale testing of possible catalysts for the steps toward producing jet fuel. The project has the potential to improve yields from the conversion of sugars to jet fuel, and it is considering the risks involved with catalyst stability. There is the potential for the coproduction of other fuels besides jet fuel, providing greater commercialization potential; however, there are sustainability considerations that should be investigated as the project develops, particularly because of the separate steps involving catalysts and the reliance on hydrogen throughout conversion and upgrading: (1) the hydrogen demand per gallon of jet fuel, (2) the treatment of waste streams such as the 1 gallon of wastewater produced per gallon of jet fuel, (3) the materials and energy involved in catalyst production and regeneration (also affected by catalyst lifetime, which is already within the team's scope of study), and (4) the proportions of jet fuel versus other fuels that would result from the pathway (would this process ultimately be best commercialized toward a different end product that may be generated in greater quantities?). Some of these aspects might be quantified as the team assesses the economics of the pathway in the future as planned, but some might weigh more heavily toward the carbon footprint of the jet fuel than its costs. If the carbon footprint of this biomass-derived jet fuel is higher than that of conventional jet fuel due to high energy, hydrogen, wastewater treatment, and the carbon footprint of the catalyst production, this could substantially affect the scale-up success of the NREL DMR with Virent processing pathway.

- The level of blending that can be accomplished and the yield per ton of biomass are unclear, though I am not penalizing the project for that because it was not part of the original FOA. The key concerns are around using the DMR process and the cleanup required around DMR to meet the feedstock specifications for making SAF using the Virent process. The ion-exclusion technology is not sufficient to meet the feedstock specifications they desire. Also, finally, the SAF pathway meets all the specifications but is not necessarily tied to the stover feedstock.

PI RESPONSE TO REVIEWER COMMENTS

- Comments: The project approach aligns with the metrics defined under AOI-5 DE-FOA-0002029 in terms of gallons of product, product stability/compatibility, and MFSP. It is not clear if the level of GHG reduction and aromatic content (8%) metrics have been included thus far in the project. The approach is to reduce ash content using NREL's DMR technology and improve the condensation catalyst stability and the process optimization. Key innovations are high-yield/low-ash-content sugars and an improved condensation catalyst, minimizing competing reactions. The verification stage has been successfully completed. Budget Period 2 work has been completed for one quarter on the condensation catalyst as a bench-scale test using model compounds. A schematic for the reaction paths and setup is shown, but no data are provided for the conversion/selectivity or the stability of the catalyst (the presenter verbally mentioned 3–4 weeks). Similarly, the benefits of the DMR technology are listed, and a product profile with an ash profile and sugar yield is required to determine the impact of its benefit on the process and if sugar meets the specifications required for downstream catalysis. Overall, the four-step proposed process has three hydrogenation steps, and as such quite high hydrogen demand, and this needs to be reported and accounted for in the TEA.

- Response: We appreciate the comments. The TOS profiles are being collected as part of the ongoing work to enable quantitative comparisons of catalyst stability across different materials and operating conditions. The suggested analysis of the DMR technology, as well as the impact of hydrogen demand for the total process, will be included in the TEA. Validation data provided to the validation team from previous work at Virent is included here, which shows that the hydrogen consumption for the overall process was 0.16 kg of hydrogen per kilogram of final hydrocarbon products (includes gases and liquid organic products): "Table C.2.4. Hydrogen input rates and consumption data. Benchmark. Intermediate Final H_2 Input Rate (mol H_2/mol C) 2.12 1.24 0.96 H_2 Consumption (kg/kg liquid fuel product) 0.3 0.17 0.16."

- Comments: The project has a good mix of university, national lab, and industry participation. That the national lab contributor is the founder of one of the industry partners seems to be a major strength. A technical problem that deals with the relative rates of the different potential reactions is being handled well by looking at the model compounds and model reactions. This kinetic information should be helpful in predicting the potential range of products. The metrics for the catalyst stability were not clear. Typically, catalysts deactivate over time, so giving a performance benchmark for a particular amount of time would be a better description. Despite how recently the project started, it seems that the lab experiments are up and running. It is of interest to the project that smaller molecules react faster and should be considered for the kinetics. A process flow diagram of the overall system was presented, which is encouraging. A phase separator between the first and second reactor showed that everything went to the second reactor. It seems that Virent is working on variations of this. Without a TEA or LCA, it is truly difficult to assess the overall impact. It does seem that a more stable condensation catalyst was the main goal of the work. More information on how this would be scaled up from the lab reactor would be helpful because this is going to be an important piece. Though Virent has done this in the past, more information could be shared.

- Response: Thanks for the helpful suggestions. We agree about the importance of a TEA for elucidating the overall impact, and we acknowledge that scale-up issues may be significant. These will both be addressed during the coming months of the grant.
- Comments: This project is on track and has met the first critical decision requirements to continue. The project is at TRL 6 of evaluation and seems to have the pieces necessary to complete this level. The project team should focus less on improving each step and more on how integrating the unit operations work together. Interface issues may be a risk they need to address. Whole-system issues are more important to look at than the efficiency of each unit operation. DMR is still a process; the team is working on delivering adequate quantities of clean sugars, so that area will need to be eventually addressed. Virent has been working on this technology for a long time, and I expected a bit more advancement than what has been shown.
- Response: We appreciate this comment. The reason for the major focus on the condensation step is related to a point made in this comment. Virent (and others) have developed relatively advanced technology for many key steps in the reaction process, particularly related to hydrogenation and HDO. Condensation, on the other hand, is much less developed, and technology improvements are needed to advance the overall process. Nevertheless, we acknowledge that the integration of all process units is critical for the success of the project, and that will be the major focus of our upcoming work (and is the key step for our go/no-go decision). This work must also include the analysis of the DMR process that is suggested in this comment.
- Comments: This project involves the development of a novel pathway to produce jet fuel involving catalytic hydrogenation, HDO, and condensation. The start of the 3-year project was January 2022, and the team has spent less than 2% of their budget; they passed the initial verification in 2022 and are on track toward their June 2024 go/no-go decision point. In this first phase of the project, they have involved industry in the unit process design (one PIs is the founder of the company) and made progress on the bench-scale testing of possible catalysts for the steps toward producing jet fuel. The project has the potential to improve yields from the conversion of sugars to jet fuel, and it is considering the risks involved with catalyst stability. There is the potential for the coproduction of other fuels besides jet fuel, providing greater commercialization potential; however, there are sustainability considerations that should be investigated as the project develops, particularly because of the separate steps involving catalysts and the reliance on hydrogen throughout conversion and upgrading: (1) the hydrogen demand per gallon of jet fuel, (2) the treatment of waste streams such as the 1 gallon of wastewater produced per gallon of jet fuel, (3) the materials and energy involved in catalyst production and regeneration (also affected by catalyst lifetime, which is already within the team's scope of study), and (4) the proportions of jet fuel versus other fuels that would result from the pathway (would this process ultimately be best commercialized toward a different end product that may be generated in greater quantities?). Some of these aspects might be quantified as the team assesses the economics of the pathway in the future as planned, but some might weigh more heavily toward the carbon footprint of the jet fuel than its costs. If the carbon footprint of this biomass-derived jet fuel is higher than that of conventional jet fuel due to high energy, hydrogen, wastewater treatment, and the carbon footprint of the catalyst production, this could substantially affect the scale-up success of the NREL DMR with Virent processing pathway.

- Response: As noted, the hydrogen demand for this process is potentially a significant limitation, and this aspect will be investigated via TEA as the project proceeds. This comment raises an excellent point about the appropriate analysis of waste streams, such as the water produced from the HDO and condensation reactions, which will be significant due to the high oxygen content of the original biomass; we will attempt to incorporate such analysis in our future work. As the comment mentions, the energy and materials inputs for the catalysts are a key motivation for this project; the primary negative impact of having a catalyst with low stability is the inputs required to regenerate the catalyst (and corresponding efficiency losses). We also acknowledge the point about the process potentially generating product fractions that may best fit outside the jet fuel (blend) range, although it is worth mentioning that the process has been specifically designed to produce high yields of cycloparaffins in the appropriate molecular weight range for jet fuel. Finally, we agree that, ultimately, it will be important to demonstrate the carbon footprint of jet fuel generated from this process.
- Comments: The level of blending that can be accomplished and the yield per ton of biomass are unclear, though I am not penalizing the project for that because it was not part of the original FOA. The key concerns are around using the DMR process and the cleanup required around DMR to meet the feedstock specifications for making SAF using the Virent process. The ion-exclusion technology is not sufficient to meet the feedstock specifications they desire. Also, finally, the SAF pathway meets all the specifications but is not necessarily tied to the stover feedstock.
- Response: Thanks for the comments. The level of blending that can be obtained will be a focus of studies after the generation of jet fuel by the integrated process. Yield information was not directly presented in the presentation, but our goal is to produce 70 gallons of jet fuel per ton of corn stover. Ion exclusion by itself will not meet the final feedstock specification because a finishing ion exchange step will be required to remove the small amount of contaminates that remain after ion exclusion. The advantage of ion-exclusion technology is that it eliminates the necessity of using ion exchange to remove all the contaminates, which would be more expensive.

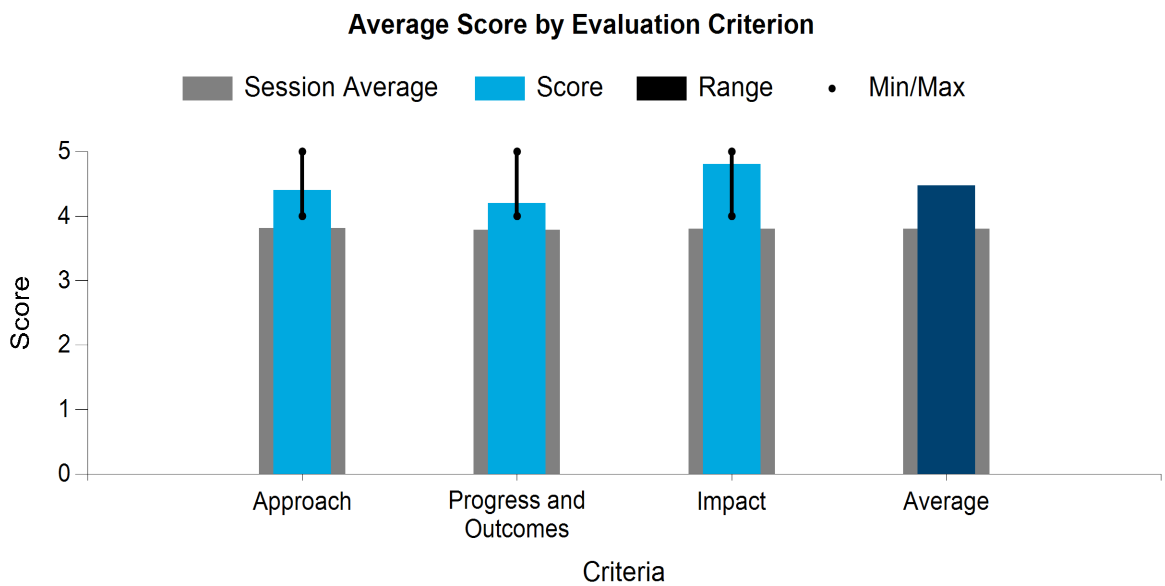
PRODUCTION OF RENEWABLE CYCLOALKANES FROM ETHANOL FOR BLENDING WITH JET FUEL TO ENHANCE ENERGY DENSITY AND MATERIAL COMPATIBILITY AND REDUCE PARTICULATE EMISSIONS

Vertimass LLC

PROJECT DESCRIPTION

WBS:	3.5.1.412
Presenter(s):	John Hannon
Project Start Date:	10/01/2019
Planned Project End Date:	03/30/2024
Total Funding:	$1,793,423

Previous DOE BETO funding advanced technology from lab to pilot for production of high-octane gasoline and aromatics. Overall liquid yields were increased from 36% to 82%, catalyst was moved from lab powder to low-cost commercial extrudates, and the process was scaled up 300 times. Current project goals are to (1) scale up from pilot to demonstration with Technip Energies to obtain engineering data for commercialization; (2) shift carbon number range from 4–12 to 75% as 7–17 (jet fuel); (3) reduce aromatics from approximately 50% by weight to less than 20% weight while increasing cycloalkanes to a max of 30% by weight; (4) increase energy density; and (5) minimize emissions.



COMMENTS

- Approach: The project approach aligns with the metrics defined under AOI-5 DE-FOA-0002029 in terms of gallons of product, selectivity toward jet fuel range, scalability, and hence cost. It is not clear whether product stability/compatibility, level of GHG reduction, and aromatic content (8%) as opposed to less than 20% metrics have been met or included thus far in the project. The approach is to showcase a single-step reaction for an ATJ fuel mix product using a commercially available catalyst and to qualify product against identified jet fuel blend analogues. A key innovation is a single-step reactor using a commercial catalyst from a strong, active team with substantial work on this reaction over years. Another substantial improvement is no use of H_2.

- Progress and outcomes: The verification stage has been successfully completed. The initial go/no-go was passed March 2022. Budget Period 2 work has focused on shifting the product range toward C7; lab results show up to 82.5% product in this range, although with very high aromatic content, 83.5%, of the product.
- The project involves several companies with varied capabilities that make for a comprehensive team with expertise in catalysis and scale-up. The main goal is to shift the composition of their alcohol-to-cycloalkane process to higher and more cycloalkanes with less aromatics. Their process can use any alcohol, but results for ethanol were presented.
- Challenges were presented, but they seemed to be at a high level, i.e., qualifying a suitable product. This does not address the technical challenge they are trying to overcome.
- It is interesting that they can use such a diluted form of ethanol. The discussion of the reactor's operating conditions, however, did not tie into this issue. Changing the reactor conditions is going to have a major impact on costs if the primary feedstock is at 50% concentration.
- They have passed the initial verification. They have performed experiments where they have increased the amount of cycloalkanes (and aromatics) through adjusting the operating conditions and catalysts. Without specifics besides adiabatic versus isothermal, it is difficult to understand how tunable the reactor is. All reactors are tunable with the number of potential changes that can be made to their operation.
- Without TEA and LCA, it is difficult to determine the impact and potential for this project. They have clearly shown that they can produce a better component to blend with jet fuels. It would be interesting to see the effect of other alcohols, especially methanol and butanol, on product composition.
- The progress has been good and is on track. I am concerned about interface issues between unit operations. The team seems to have obtained the results they wanted and has met goals, but they did not discuss any interface issues, which typically are what sidetracks fully integrated systems. They need to focus on one or two product streams over extended periods of time before considering commercial operation. They have kind of met the TRL 7 requirements with the Technip work, but they have not completed the system development to go to TRL 8 or TRL 9. This is a well-managed and good team with good potential to go to the next level of development and be successful.
- This project focuses on the development of a primarily ethanol-to-jet-fuel process, consolidated alcohol deoxygenation and oligomerization, which also has the potential to generate a multitude of coproducts, such as propane, butane, plastics, and other fuels beyond jet fuel. The one-step conversion approach has the potential for commercialization and for a lower-life cycle impact. The technical approach involves a team with extensive experience in scale-up, commercial catalysts, optimization of key parameters, lab development, and modeling of fuel properties and techno-economics, and they have established additional key partnerships during the span of the project. A reactor has been designed, constructed, and is currently operational; the project has reached its intended demonstration scale. The catalyst lifetime has been substantially extended, but reducing the high-aromatics content is still in progress. The project has spent only $123,401 of a total budget of $1,434,738 since starting in March 2022. As the demonstration scale is tested, the life cycle energy inputs and carbon footprint should be compared against those of conventional jet fuel production and pathways of SAF production because it is currently unknown whether this particular pathway of single-step conversion will truly be an improvement beyond the reduction in unit processes.
- The work on Hannon et al. that forms the basis of this project is seminal. It is delivering a significant increase in hydrocarbon yield and the use of the ATJ pathway. Concerns are with high levels of aromatics and cycloalkanes. Blending would be limited because of that.

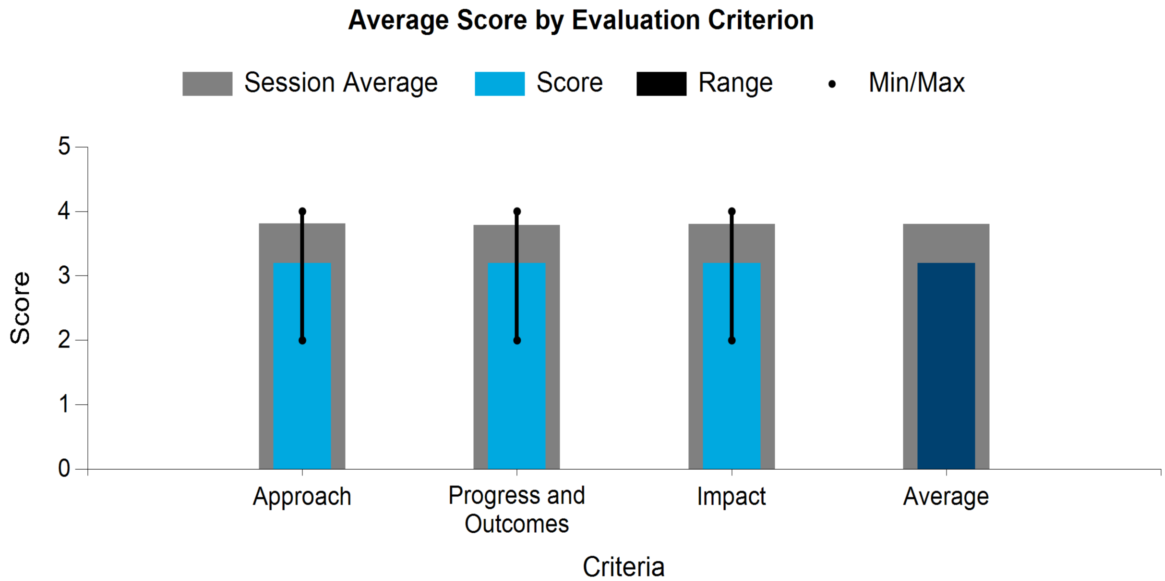
PI RESPONSE TO REVIEWER COMMENTS

- We thank you for organizing a great peer review, and we appreciate all the reviewers' observations and comments.
- Response to Comment 1: Thank you for the review and comments. The Vertimass technology converts ethanol into a variety of jet-fuel-range aromatics and cycloparaffins with smaller amounts of paraffins and isoparaffins. We intend to blend this SAF with other technologies that only produce paraffins and isoparaffins to make a more complete fuel. This is the main reason we partnered with World Energy—to complement their HEFA-derived SAF that contains no aromatics or cycloparaffins and to increase their potential volumes because we can use widely available ethanol feedstocks. We also believe that this technology will substantially advance the SOA to convert alcohols into hydrocarbons in one low-cost step.
- Response to Comment 2: Thank you for the review and comments. The combination of using different catalysts and operating conditions has allowed us to vary the product slate, and we are still determining the best combination for our SAF blendstocks. We believe this new tunable and cost-effective process has the potential to dramatically change the SAF landscape.
- Response to Comment 3: Thank you for the review and comments. Our scale-up partner, Technip Energies, is currently working on a fully integrated plant design that addresses the interfaces with an ethanol plant. Technip Energies has had commercial success with plant integration, and we will have this engineering design completed in FY 2023 Q3.
- Response to Comment 4: Thank you for the review and comments. Our scale-up partner, Technip Energies, is currently working on a fully integrated plant design that will quantify all the process inputs/outputs so that we can more accurately determine the LCA. We are also working with Life Cycle Associates and ANL to quantify the LCA.
- Response to Comment 5: Thank you for the review and comments. The Vertimass technology produces elevated levels of aromatics, but this SAF blendstock complements other SAF technologies that have zero aromatic content to make a more complete jet fuel. Thank you again, and please feel free to reach out to us with any more follow-up questions at jhannon@vertimass.com.

MULTISTREAM INTEGRATED BIOREFINERY ENABLED BY WASTE PROCESSING

Texas A&M Agrilife Research

WBS:	3.5.1.501
Presenter(s):	Susie Dai
Project Start Date:	06/01/2018
Planned Project End Date:	11/30/2023
Total Funding:	$2,795,267



COMMENTS

- Approach: The project approach aligns with the metrics defined under Topic Area 2, DE-FOA-0001689.
    - Technical lignin utilization for carbon fibers; lignin-to-asphalt binder modifier.
    - Project management: The outcomes suggest that the program is well managed via monthly teleconferences between the partner organizations and the DOE program manager.
    - The two process streams downselection is based on the TEA and performance.
- Progress and outcomes:
    - The team has made significant progress on identifying and meeting the required properties for two major applications compared to the benchmark. It is not clear if the benchmark numbers reflect the minimum carbon fiber specifications. T300, a basic carbon fiber by Toray, has a tensile strength of 3,530 Mpa, MOE 230 GPa, strain 1.5% with density and filament diameter requirements; however, for automobile applications, lower specifications are acceptable. No measurements on strain rates have been presented; this is a minimum requirement.

  - The results are not sufficient to evaluate progress on asphalt binders.
  - The addition of back-end fermentation helps remove small lignin molecules, which is required to improve carbon fiber properties to meet 1.4-GPa tensile strength.
- Impact:
  - The project team has clearly demonstrated scientific advancement and the utilization of waste streams for very-high-valued product streams. Even if small volumes are used, it will have a major impact on the biofuels industry. Thirty-one publications and three patents on this topic have also added a lot of value for the scientific and industry community. It is a bit unclear how the benchmark values were selected; a few references on this could be helpful. The team is well organized, has access to past data on lignin characterization, and has shown enthusiasm and vigor in achieving goals that align well with BETO's goals. The program lacks clarity on commercially acceptable specifications; more industry engagement is recommended.
- This project focuses on producing asphalt binders and carbon fibers from lignin. A significant analysis of the products was presented, as well as economic feasibility, along with some sensitivity analysis.
- The asphalt that can be generated has seen major improvements and has met the team's benchmarks.
- The carbon fibers have seen improvements in properties, though they have not reached their modulus or tensile strength goals.
- A TEA has been completed that found the team can achieve $1.88 for a selling price and $2.56/GGE.
- It is greatly appreciated that a sensitivity analysis was completed, but it seems that the minimum ethanol selling price is extremely sensitive to the price of the carbon fiber. A small decrease from the $20/kg assumed for carbon fiber greatly reduces or eliminates the economic feasibility.
- It may benefit the team to have more input consultants who have lignin, asphalt, and/or carbon fiber manufacturing experience.
- This project is useful to examine the potential coproduct streams from a biorefinery. It is a good exercise and poses some potential. It is more of an academic exercise than one based on reality because it takes much more than just good numbers to see any of the processes implemented in an operating biorefinery. The team listened to previous reviews and limited the coproducts, which was good and showed the potential for them to work. In the asphalt area, they might have wanted to compare what competition exists, such as lignosulfonates from pulp mills. As previously noted, they should continue to work with potential end users but recognize that they are still far from implementing these in real situations.
- This project is investigating pathways for a multistream integrated biorefinery that yields an array of products from biomass-derived lignin—including carbon fiber, asphalt binder, bioplastics, and lipids—for fuel upgrading. It incorporates LCA and TEA to evaluate possible pathways and improve process design. The diagram provided on the summary of estimated carbon dioxide emissions is difficult to interpret, although the other process diagrams are helpful for following the various options studied. The project has met its milestones for Budget Period 2, and currently it has less than 1 year remaining. The project has produced 31 publications. The presentation focused on the potential significance of the work once scaled up more than the work undertaken thus far. Consequently, it is unclear at what scales the experiments were conducted and how this can truly scale up for commercialization. Similarly, the models appear to be developed for small flows through a biorefinery. An investigation into the extent to

which the results at the laboratory scale may be representative of outcomes at the commercial scale is recommended.

- The project is quite wide in scope and would benefit from narrowing the focus areas. Resourcing appears very limited, and the project should be more specific and directed.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the reviewers' enthusiastic support of the project, including "significant progress," "well managed," "significant analysis of the products," "listened to previous reviews," "good exercise and poses some potential." With all these supportive comments, this response primarily focuses on the concerns of the project.

- For Reviewer 1, the comments are in four categories. (1) The choice of the specs and relevance to industry: "It is not clear if the benchmark numbers reflect the minimum carbon fiber specifications. T300, a basic carbon fiber by Toray, has a tensile strength of 3530 Mpa, MOE 230 GPa, strain 1.5% with density and filament diameter requirements; however, for automobile applications, lower specifications are acceptable." "It is a bit unclear how the benchmark values were selected; a few references on this can be helpful." And "The program lacks clarity on commercially acceptable specifications." We appreciate the reviewer's comment. First, we substantially considered the industrial relevance during the proposal development and project implementation. With carbon fiber as an example, the project focuses on automobile industry applications because they are the most relevant to energy efficiency and carbon emissions reduction in the transportation sectors. That said, T300 from Toray is a lower grade for the aviation industry application. Instead, we benchmarked our carbon fiber performance against DOE's automobile industry carbon fiber specifications (tensile strength of 1.72 GPa and a modulus of 172 GPa). The project aims to reach tensile strength at 2 GPa (higher than 1.72 GPa) and modulus at 100 GPa (lower than 172 GPa) [1]. Our target considered the carbon-fiber-reinforced polymer development. For the asphalt binder modifier, we also considered commercial applications. In particular, we focused on improving high-temperature performance without compromising low-temperature performance [2]. The resultant asphalt binder will improve 1 to 2 PG, which accounts for a $100 to $200 increase in market value; therefore, the lignin could be sold at $1,000 to $2,000 for the value added to the asphalt binder in a 10% mixture. The focus on high-temperature performance aims to address the climate change-related infrastructure challenges. The benchmark value was justified by previous publications from the group [2]–[4]; therefore, all benchmarks and milestones are justified, and the milestones are directly relevant to commercial potential and industrial applications. (2) "No measurements on strain rates have been presented." The strain rates were calculated in all samples. Here are some examples from Table 1: "Table 1. Strain rate for the before and after fermentation lignin (AESA: after fermentation; AESM: before fermentation and modified; AESAM: after fermentation and modified) Strain rate (1/s) Dev AES 0.000421366 5.72E-05 AESA 0.000338317 1.97E-05 AESM 0.000340513 1.32E-05 AESAM 0.000342423 3.24E-05 3." (3) "The results are not sufficient to evaluate progress on asphalt binders." The asphalt binder techniques have met the milestones from the last peer review; therefore, we are not repeating the data from the last peer review. (4) "More industry engagement is recommended." We agree with the reviewer's comment and are taking action to engage more end users, even though the lignocellulosic biorefinery had some setbacks. In fact, we have engaged different commercial partners, including those involved in SAF efforts.

- For Reviewer 2, the major concern is, "It may benefit the team to have more input consultants who have lignin, asphalt, and/or carbon fiber manufacturing experience." We agree with the comments. In fact, the team has most of the expertise on lignin and asphalt binder. We also consulted with experts on carbon fiber manufacturing and developed two additional strategies to improve carbon fiber properties.

- For Reviewer 3, the primary comment is as follows: “In the asphalt area, they might have wanted to compare what competition exists, such as lignosulfonates from pulp mills. As previously noted, they should continue to work with potential end users but recognize that they are still far from implementing these in real situations.” We actually carried out the comparison of Kraft lignin in previous studies [2]. In fact, previous studies from the team have shown that lignosulfonates will not serve the purpose because it decreases the low-temperature performance while improving the high-temperature ones. The lignin from the paper and pulping industries needs special treatment before using it as a quality asphalt binder modifier. On the contrary, the biorefinery lignin from this project, with the proper pretreatment technologies developed in this project, addressed the challenge to derive lignin with improved high-temperature performance without compromising low-temperature performance. As mentioned, we are engaging commercial partners.
- For Reviewer 4, the primary comment is, “Consequently, it is unclear at what scales the experiments were conducted and how this can truly scale up for commercialization. Similarly, the models appear to be developed for small flows through a biorefinery. An investigation into the extent to which the results at the laboratory scale may be representative of outcomes at the commercial scale is recommended.” The reviewer also has difficulties interpreting the carbon emissions data. In our quarterly reports, we thoroughly discussed carbon emissions and LCA. In fact, we will publish the data soon. We totally agree with the reviewer on the scale. We are working with NREL to scale the technology to half-dry TPD. (References: [1] doi.org/10.1002/app.39273, [2] doi.org/10.1021/acssuschemeng.6b03064, [3] doi.org/10.1039/C6GC03555H, [4] doi.org/10.1039/C7TA01187C.)

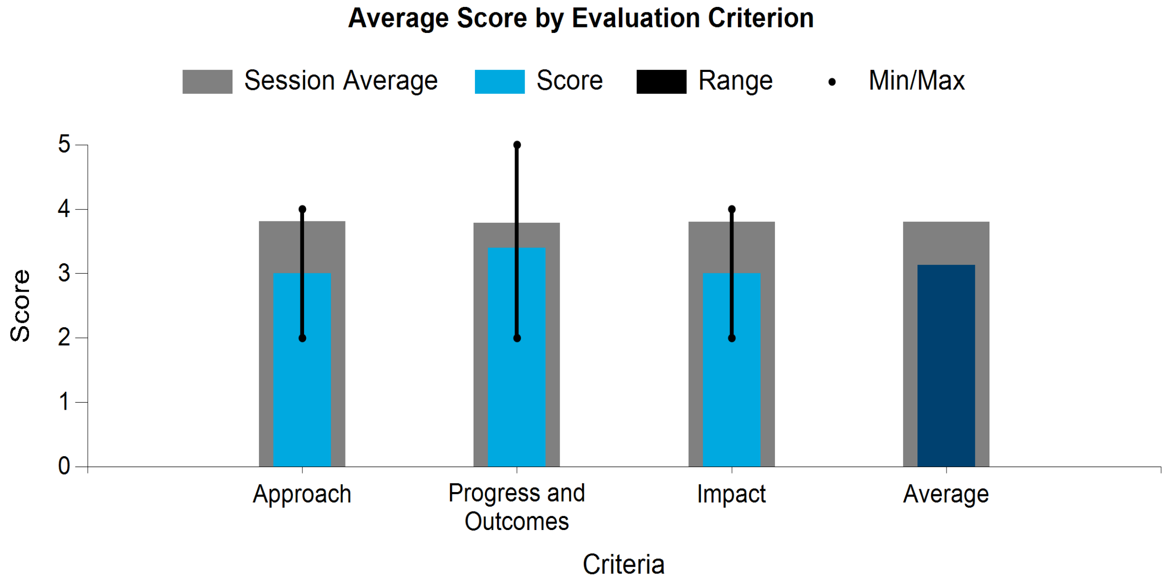
NEAR-CRITICAL FLUIDS TREATMENT FOR LIQUEFACTION AND EXTRACTION OF BIOFUELS

University of Maryland

WBS:	3.5.1.601
Presenter(s):	Ashwani Gupta; Cassie Moore
Project Start Date:	10/01/2021
Planned Project End Date:	04/30/2026
Total Funding:	$3,876,702

PROJECT DESCRIPTION

We propose to develop the liquefaction of biomass and biowaste feedstocks in the presence of near-critical fluids, such as supercritical CO_2 (sCO_2), and subcritical water to form oil products and subsequently extract hydrotreating-suitable biocrude to produce liquid biofuels and valuable chemicals. The proposed process will build on the emerging HTL process for biocrude products by using the synergistic solvent properties of sCO_2 and subcritical water to improve the quality of biocrude and provide robust operation and fuel extraction. The low viscosity and high density of these near-critical fluids will improve the process operation while the tunability in the solvent properties with temperature and pressure will provide efficient product extraction to remove the water, metal, and O content of biocrude. This improved biocrude composition will provide improved aging stability, carbon content, heating value, and compatibility to industrially established hydrotreating processes to obtain transportation fuels. In addition, near-critical fluids mitigate the energy-intensive moisture control requirements in feedstocks and thus also allow for the conversion of diverse moisture grades of biomass into liquid fuels. This improvement in biocrude quality, yield, efficient dewatering, and product extraction will provide reduced GHG emissions to beyond 70% reduction compared to petroleum-based alternatives. The integration of dewatering, liquefaction, and sCO_2-extraction can be achieved for efficient operation and potentially reduced capital costs. For this research, process components—mainly feedstock dewatering, near-critical liquefaction, and sCO_2-biocrude extraction—will be developed for continuous mode and investigated to build predictive models of their operation. These reactor studies will be carried out at an FOA-relevant scale to gain design knowledge of the operational requirements and process output. Different real feedstock samples will be examined, each from different classes, including lignocellulosic, algal, and wet biomass, and sorted municipal solid wastes. The influence of operational parameters (such as temperature, pressure, solvent/feedstock ratio, feedstock loading, residence time, and solvent requirement) on process output (such as energy input, GHG impact, water and CO_2 recyclability, product quality, and yield) and byproducts will be obtained using these process tests. Biocrude and sCO_2-extracted crude components' quality will be judged in terms of parameters such as O/C, H/C, composition, viscosity, aging stability, water content, density, and heating value. The goal will be to obtain biocrude with capabilities to be incorporated into hydrotreating plants of petroleum crude that yield transportation fuels. This will be demonstrated based on ASTM standard characterization of the extracted biocrude and its similarity with petroleum crude. Predictive process models will be developed based on these investigations, which will be further incorporated into the LCA and TEA of incorporating these components into an integrated process from feedstock-to-product deployment. These analyses will be used to determine the economic, GHG, and fuel cost impact of the process, along with the optimal conditions needed for maximizing these benefits.



COMMENTS

- The project approach aligns with the metrics defined under the FY 2021 pre-pilot: $2.75/GGE and 70% reduction.
  - Technical: sCO_2 dewatering, liquefaction under sCO_2 and sCO_2 recovery.
  - Project management: Dr. Gupta's and Dr. Sandborn's groups are working on experimental and modeling, respectively.
  - DEI: There is active participation from Historically Black Colleges and Universities McNair Scholars, interns, graduate researcher, and training.
- Progress and outcomes:
  - Batch reactions are conducted, with char and biocrude fractions quantified for verification purposes.
  - The sCO_2 process claims low metal content, water, and oxygenates in biocrude. The team compares it with biocrude feed. It would be nice to see if this can be compared with other types of biocrude, as shown in additional slides.
  - The team claims higher stability of bio-oils with respect to viscosity, acidity, and oxygen number.
  - It is unclear if the process can be scaled to meet the pressure feed requirements for the sCO_2 process at this stage. TEA/LCA work has not been started, and it is recommended to start preliminary work to estimate/understand the impact of key unit operations using sCO_2 as a fluid.
- Impact: If successful (the project started in October 2021 and has completed two budget periods; the project has passed the initial verification and completed 1 year of work post verification), it will enable the utilization of sCO_2 as a fluid/reactant medium to dewater and liquefy biomass to biocrude with low impurities and a reduction in the complexity of separations. It is, however, not clear how biomass will be fed at such high pressures and temperatures in a continuous reactor. This is a pre-pilot program with

expectations to produce enough product for characterization. The current facilities are limited to small batch reactors.

- This project looks to convert biomass to biocrude using sCO_2 for dewatering, liquefaction, and extraction. The scaled-up plant will also include LCA and TEA. The project is being led by two faculty members with many students and postdocs. They have recruited undergraduate students from the University of Texas at El Paso, a Hispanic-serving institution.

- The small-scale system that has been built though this program is quite new. The verification is complete. Students have been recruited to work on this project.

- The presentation outlined technological advantages to using sCO_2, but the main drawback has always been economics. The proposal does not yet have data on the economic feasibility, though given that it is widely known that the cost is prohibitive, some calculations could have been included. Estimates of the amount of sCO_2 needed per mass of biocrude would also be helpful to get some rough estimate. The team would also benefit from having someone with supercritical experience at the industrial scale, though that person may be difficult to find.

- The proposal does have a good DEI plan, especially with outreach and training. Recruiting from a Hispanic-serving institution is also a good step, as are the research talks at the Hispanic-serving institution.

- This project must prove concepts at a batch-scale level. The success will be in the value of the graphite product, and comparing two types of pyrolysis oils is germane and appropriate. The impacts will be less on the biofuels market because it will be on the U.S. economy. The team appropriately points out that the supply chain needs to be more internal to the United States versus foreign countries, and that is easily obtainable via the biomass resources that exist in the United States. It is a project that looks at biomass use in a different way but that could have a good impact. Good diversity efforts.

- The project team is developing a near-critical integrated liquefaction and extraction pathway to convert biomass and wastes to deployable biofuels. They have graduate and undergraduate students assigned to key tasks, including design, process modeling, lab experiments, and analysis of costs and life cycle GHG emissions. DEI efforts include implicit bias training, participant climate surveys, and recruitment and mentoring of students from historically marginalized groups in engineering. The project leadership team has previously supported summer research students in publishing their research. Following the "pipeline" outcomes from the project would be an interesting addition to these initiatives—for example, tracking the percentage of summer-term research students who pursue other research opportunities or return to this project or who apply to and enter a graduate program and comparing that against expected rates. The presentation mixed cost-specific parameters into its discussion of a stochastic LCA model under development, and key parameters related to the life cycle GHG emissions were missing from the list. It is unclear whether the project is fully tracking the flows of carbon throughout the pathway and end products (for example, the amount of carbon that might be sequestered in the generated chars). The project team may benefit from the services of an LCA practitioner or researcher to ensure that their accounting of life cycle GHG emissions (for which the team has a >70% reduction target) is thorough. The project is currently completing Task 1.0, the initial verification, and has been active since October 2021.

- The challenge is the scalability of sCO_2 processing. CapEx barriers and materials-of-construction issues with equipment remain to be addressed. The team also needs to further reduce the oxygen content of the biofuels for scalability. The project is more at TRL 2 or TRL 3.

PI RESPONSE TO REVIEWER COMMENTS

- Comments: The project approach aligns with the metrics defined under the FY 2021 pre-pilot: $2.75/GGE and 70% reduction. Technical: sCO_2 dewatering, liquefaction under sCO_2 and sCO_2 recovery. Project management: Dr. Gupta's and Dr. Sandborn's groups are working on experimental and modeling, respectively. DEI: There is active participation from Historically Black Colleges and Universities McNair Scholars, interns, graduate researcher, and training. Progress and outcomes: Batch reactions are conducted, with char and biocrude fractions quantified for verification purposes. The sCO_2 process claims low metal content, water, and oxygenates in biocrude. The team compares it with biocrude feed. It would be nice to see if this can be compared with other types of biocrude, as shown in additional slides. The team claims higher stability of bio-oils with respect to viscosity, acidity, and oxygen number. It is unclear if the process can be scaled to meet the pressure feed requirements for the sCO_2 process at this stage. TEA/LCA work has not been started, and it is recommended to start preliminary work to estimate/understand the impact of key unit operations using sCO_2 as a fluid. Impact: If successful (the project started in October 2021 and has completed two budget periods; the project has passed the initial verification and completed 1 year of work post verification), it will enable the utilization of sCO_2 as a fluid/reactant medium to dewater and liquefy biomass to biocrude with low impurities and a reduction in the complexity of separations. It is, however, not clear how biomass will be fed at such high pressures and temperatures in a continuous reactor. This is a pre-pilot program with expectations to produce enough product for characterization. The current facilities are limited to small batch reactors.

- Response: We thank the reviewer for the valuable comments. The project has just finished Budget Period 1 with passing the initial verification. The sCO_2 extraction of biocrude significantly improves the viscosity, acid number, and oxygen along with reducing the metal and water content compared to the biocrude feed. Currently, this is the extent of the literature available, and it is limited to only one type of biocrude. We will perform these studies and will provide comparisons as the project progresses. The scalability of high-pressure feeding is a technical risk associated with the process, and we intend to address this with efforts to resolve the loading and unloading times in the batch process so that it can be operated in a continuous fashion. We have started some preliminary TEA/LCA work already; we are currently looking into the impact of CO_2 and biomass feedstock availability. The NILE process will be a batch process but with capabilities to be operated in a continuous fashion. We intend to start our design into biomass loading at high pressure and temperature early in the project, with the goal to load and unload the biomass batches with low downtime and avoiding cooling or depressurization. Although the current facilities are small batch reactors, we intend to identify the operational conditions at this scale, along with potential solutions to scalability challenges, and then move to larger-scale reactor studies to minimize costs and project risk.

- Comments: This project looks to convert biomass to biocrude using sCO_2 for dewatering, liquefaction, and extraction. The scaled-up plant will also include LCA and TEA. The project is being led by two faculty members with many students and postdocs. They have recruited undergraduate students from the University of Texas at El Paso, a Hispanic-serving institution. The small-scale system that has been built though this program is quite new. The verification is complete. Students have been recruited to work on this project. The presentation outlined technological advantages to using sCO_2, but the main drawback has always been economics. The proposal does not yet have data on the economic feasibility, though given that it is widely known that the cost is prohibitive, some calculations could have been included. Estimates of the amount of sCO_2 needed per mass of biocrude would also be helpful to get some rough estimate. The team would also benefit from having someone with supercritical experience at the industrial scale, though that person may be difficult to find. The proposal does have a good DEI plan, especially with outreach and training. Recruiting from a Hispanic-serving institution is also a good step, as are the research talks at the Hispanic-serving institution.

- Response: We thank the reviewer for the valuable feedback. For the economics, we have started working on developing the TEA of the process in terms of CO_2 and biomass availability, biomass collection, biomass piles and transportation logistics, plant location, byproducts, and oil demand (and selling price contract), as some parameters. The proposed process will need at least a one-to-one ratio of sCO_2 with respect to the feed, but that is during the process, and it will not be consumed and will just act as a solvent. In the NILE process, we intend to recycle the CO_2 after usage to avoid any CO_2 loss, and one subtask is associated with CO_2 recycling via purification and pressurizing for reuse in the process. We are currently looking for partners with industrial supercritical experience for insights into potential issues at scale.
- Comments: This project must prove concepts at a batch-scale level. The success will be in the value of the graphite product, and comparing two types of pyrolysis oils is germane and appropriate. The impacts will be less on the biofuels market because it will be on the U.S. economy. The team appropriately points out that the supply chain needs to be more internal to the United States versus foreign countries, and that is easily obtainable via the biomass resources that exist in the United States. It is a project that looks at biomass use in a different way but that could have a good impact. Good diversity efforts.
- Response: We thank the reviewer for the valuable comments. The project's initial tasks are set to prove the performance improvements at the batch scale.
- Comments: The project team is developing a near-critical integrated liquefaction and extraction pathway to convert biomass and wastes to deployable biofuels. They have graduate and undergraduate students assigned to key tasks, including design, process modeling, lab experiments, and analysis of costs and life cycle GHG emissions. DEI efforts include implicit bias training, participant climate surveys, and recruitment and mentoring of students from historically marginalized groups in engineering. The project leadership team has previously supported summer research students in publishing their research. Following the "pipeline" outcomes from the project would be an interesting addition to these initiatives—for example, tracking the percentage of summer-term research students who pursue other research opportunities or return to this project or who apply to and enter a graduate program and comparing that against expected rates. The presentation mixed cost-specific parameters into its discussion of a stochastic LCA model under development, and key parameters related to the life cycle GHG emissions were missing from the list. It is unclear whether the project is fully tracking the flows of carbon throughout the pathway and end products (for example, the amount of carbon that might be sequestered in the generated chars). The project team may benefit from the services of an LCA practitioner or researcher to ensure that their accounting of life cycle GHG emissions (for which the team has a >70% reduction target) is thorough. The project is currently completing Task 1.0, the initial verification, and has been active since October 2021.
- Response: We thank the reviewer for the valuable feedback. As per the suggestion, we will include pipeline outcomes from the project to track the students, their learnings, and their path forward in research and graduate studies. Life cycle GHG emissions that originate from the feedstock logistics process (collecting, transporting, and piling feedstock), the conversion of feedstock to biocrude, and the logistics associated with moving the resulting biocrude to refineries (and other byproducts to their final destination) will be determined by the LCA from the system dynamics model (TEA) outputs. The system dynamics model for TEA will also provide the amount of biochar as an output. The carbon sequestered in the generated biochar will be determined by the LCA from the amount (and resulting final properties) of the biochar. The LCA will be performed by an undergraduate student team that will be overseen by a graduate student and an advisor from the environmental policy department.

- Comments: The challenge is the scalability of sCO_2 processing. CapEx barriers and materials-of-construction issues with equipment remain to be addressed. The team also needs to further reduce the oxygen content of the biofuels for scalability. The project is more at TRL 2 or TRL 3.
- Response: We plan to address the scalability challenges at the laboratory scale with efforts starting early in the project. We plan to modify the reaction conditions to minimize the CapEx barriers for scalable design and construction, and, additionally, these challenges will be considered in the TEA/LCA to guide the project for scalability (the TEA will include both CapEx and OpEx). Literature on hydrotreating the CO_2 extracted biofuel was found to reduce oxygen to 1.6% as the starting point. During the project, we plan to improve the conditions to further minimize the oxygen content and improve the overall compatibility of the biofuels produced. The components of the project are TRL 3, while the overall process may be at TRL 2 or TRL 3, and that is the starting point for this program.

ADVANCED LOW-EMISSION RESIDENTIAL FLUID-BED BIOMASS COMBUSTOR

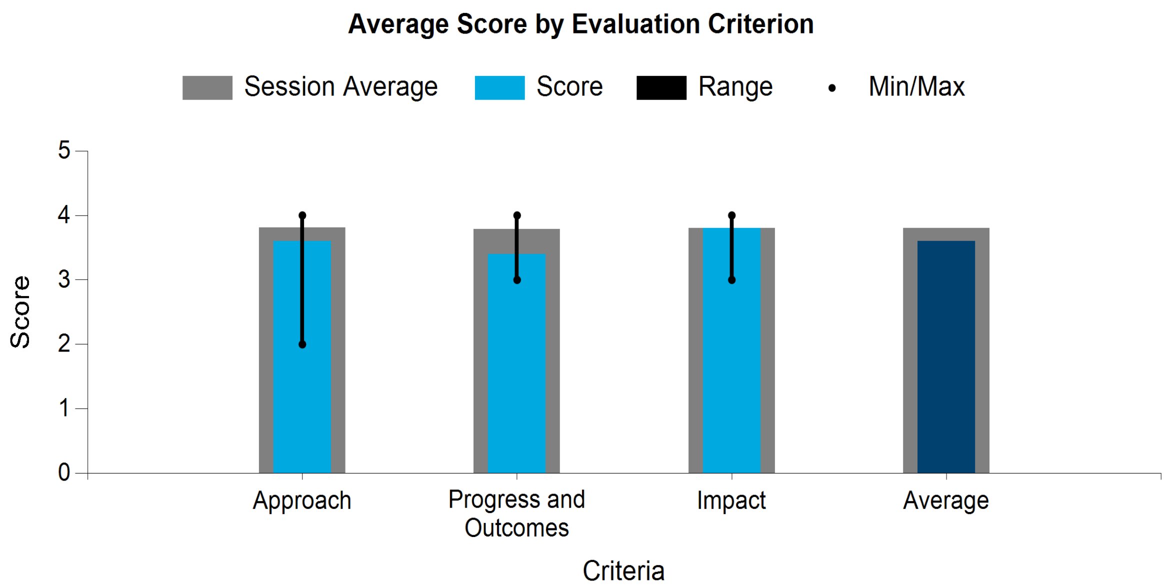
NtreTech LLC

PROJECT DESCRIPTION

WBS:	3.5.2.604
Presenter(s):	Bartev Sakadjian
Project Start Date:	10/01/2020
Planned Project End Date:	04/30/2024
Total Funding:	$3,038,823

NtreTech LLC, Babcock and Wilcox, and Ohio State University recognize the limitations of current residential wood-fired heater designs and their fixed-bed (stoker)-type operation. To achieve a step-change reduction in emissions, heater designs need to adopt more advanced combustion technologies. The novel application of fluidized-bed technology to residential wood-fired central heaters will help meet current and future regulations. Although fluidized-bed technology is currently commercially offered for large-scale utility applications, there are significant challenges to overcome to adopt the technology in residential applications. The project work will help bridge technological gaps by prototyping a transformative approach to firing wood in residential heating applications.

Fluidized-bed operation improves air/fuel mixing and increases heat transfer, which results in more complete combustion of the fuel. Due to the fluidization properties of the bed, the combustion temperature can be more uniformly controlled, which reduces the formation of NO_x. Higher combustion rates also result in lower CO and volatile organic compound (VOC) emissions. Moisture content, air velocity/staging, and bed temperature can be adjusted to control the combustion process and the emissions. The potential to use different types of bed materials, including catalytic bed additives, can further enhance combustion characteristics and decrease emissions. Due to the improved combustion process in a fluidized bed, the uncontrolled NO_X, CO, and VOC emissions are typically 10%–25% less for a given biomass fuel than for a stoker. The use of fluidized-bed technology in residential wood-fired central heaters enables a step change in emissions reductions. The use of modern sensors and low-cost microprocessors would provide the needed automation to overcome the operational complexities of a fluidized-bed wood-fired heater.



COMMENTS

- Approach: The project approach aligns with the metrics defined under (FY 2020) Topic Area 5, DE-FOA-0002203.
    - Domestic-manufactured, low-emissions, high-efficiency, residential wood heaters.
    - Quantitative goals: room wood heater—2.0 or 2.5 g/hour (cord wood alternative) particulate matter emissions limit; hydronic wood heater—0.1 lb/MMBTU particulate matter emissions limit, or 0.15 lb/MMBTU particulate matter emissions limit for forced air; amounting to a 25% emissions reduction and 5%–15% efficiency improvements.
    - Technical fluidized-bed stove/heater.
    - Project management: Babcock and Wilcox and Ohio State University as partners; NtreTech is the lead and has a process engineering specialist.
    - Issues scaling down, simplification for use, frequent load variations.
    - DEI student engagement and training, ample industry participation and guidance. Mainly skilled labor development.
- Progress and outcomes:
    - The project has completed 1 year of work.
    - The team is in the verification stage.
    - The initial stages of design, operations, and operating procedures have been conducted in the labs.
    - Downscaling from 150 MWth to 0.09 MWth was done in the past at this scale.
    - This technology is focused on chips' fluidized nature compared to other wood burners.
    - Fluidized-bed walls are heat-recuperated for hot water.
    - A steady-state fuel flow test was conducted at Ohio State University.
    - The team is reviewing cold-flow testing and modeling the pressure balance impact on a fluidized bed.
    - Process model to check for mass and energy balance and emissions/combustion efficiency load range from 25% to 100%.
- Impact: The project team has made reasonable progress on a new design for a stove. Modeling of a simplified system and the setup of equipment to verify the simplified model has been carried out. The design is bit complex for residential use and draws upon past experience on a large-scale, fluidized-bed system. Scaling down such systems is usually not easy, especially for variable-load requirements.
- The project relies on the vast experience of the company in designing larger-scale, fluidized-bed systems to design a small-scale system for residential wood heating. This heater would focus on the use of pellets or chips.
- Some fluidization work has been completed.

- The process seems too complicated for residential use, which is not monitored and transitory; however, the process shows improvement in other emissions that will likely be regulated down the road.
- This is a good assessment of key challenges. This shows a good team effort that is yielding the desired results. Using fluidized-bed technology does not seem to be a challenge because the operation is actually better at smaller scales. This team should be able to assess whether that approach is feasible from a cost and performance perspective. The desire is to produce a system that can operate unattended for extended periods of time, which will be their challenge, and they know this is an issue. It may be best suited for a central heating system than single-home use due to the potential maintenance requirements for sensors, etc. This is an area that needs to be looked at by BETO, and this team will be able to do it. Having Babcock and Wilcox as a partner is a major plus.
- This project focuses on the combustion of wood chips and wood pellets using residential-scale bubbling fluidized-bed technology. The project team has performed lab tests and design and will be fabricating a prototype and performing parametric testing. The completed progress tasks align with the project schedule. The approach includes a specific commercialization plan to be initiated in the last budget phase of the project, during which the team will be advised by an industry review committee. The project team also includes industry partners. One risk of the project is the possible complexity of a fluidized-bed heater for individual households, which may intimidate potential consumers despite automation and other simplifying features. A possible approach to mitigate this risk is to consider a different target population that is at a community scale, such as apartment buildings, college campuses and dormitories, or small-district heating networks.
- There is limited potential for the home market. The project is directed toward a more industrial user base.

PI RESPONSE TO REVIEWER COMMENTS

- The project team thanks the reviewers for providing not only the comments but also the insightful questions and discussions during the presentation. As the reviewers noted, the team brings extensive experience and background to the project and has made good progress on the development efforts. As our team progresses with our design and development efforts, we will consider the reviewers' comments in our risk analysis task as well as the design efforts and ultimately our commercialization endeavors. As noted, the complexity of the system may lead to some reluctance on the side of consumers to adopt the technology. We are mindful of the potential for the technology to impact the end user, and it is our intent to account for that and design the user interface such that it provides streamlined, simple, and easy-to-use features. Perception regarding the complex nature of fluidized-bed technology has been experienced in the past within the industrial market. The technology has since shown that it can provide ease of operation and require less operator interface than competing technologies when coupled with modern advanced controls. The project team is therefore tasked with the challenge of incorporating modern advancements in automation and controls into a residential package to help realize the advantages of the system within our target market. The operation of the unit through the various transient loads will be carried out during the Phase 3 testing and optimization tasks, which will demonstrate the system's ability to meet the desired level of operational flexibility. Transient operation is a key focus area of the project. As noted in the comments, though the development focuses on residential applications, the advances made in realizing the final design of the prototype can find applications in other markets.

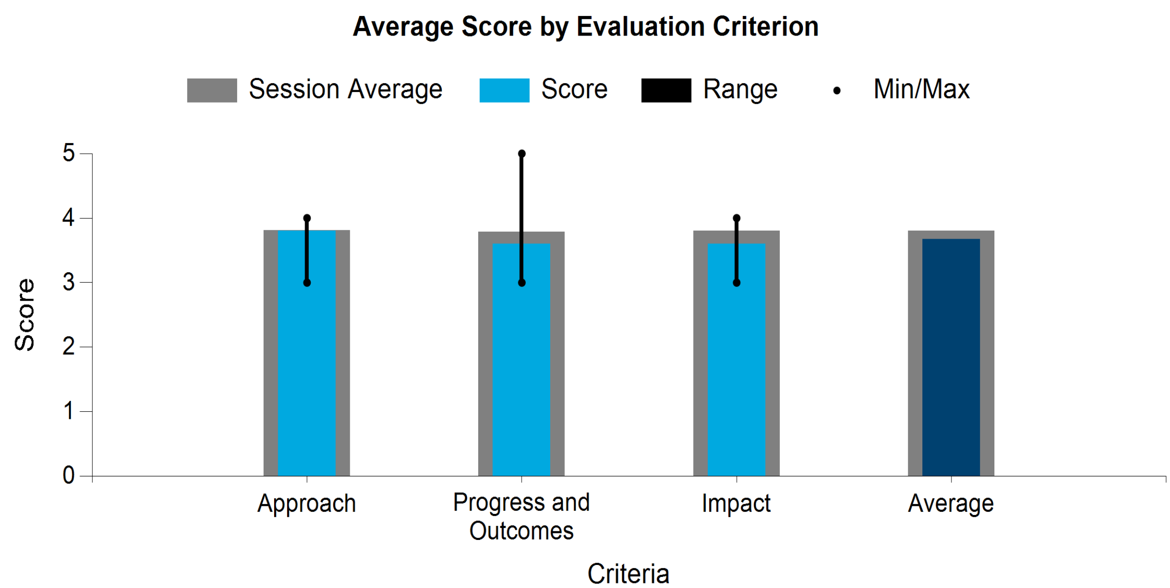
SIMULATION-DRIVEN DESIGN OPTIMIZATION AND AUTOMATION FOR CORDWOOD-FUELED ROOM HEATERS

Ohio State University

PROJECT DESCRIPTION

WBS:	3.5.2.605
Presenter(s):	Shawn Midlam-Mohler
Project Start Date:	10/01/2020
Planned Project End Date:	12/31/2025
Total Funding:	$3,143,161

The goal of this project is to position the domestic wood-fueled room heater industry to meet current and future DOE and EPA goals for efficiency and emissions by modernizing the products and product-development processes. Automation and simulation have revolutionized products and design processes in many other industry sectors, whereas these technologies have largely bypassed the domestic wood-fueled heater industry. This project will develop two wood-fired room heater prototypes to demonstrate the efficacy of these technologies to improve wood heater performance. The project team will also work to transfer this knowledge directly and broadly into the domestic woodstove industry to support their adoption of these technologies. The work unifies expertise from several organizations to form the required multidisciplinary team. The Ohio State University team brings the requisite experience in model-based design, automation for combustion/emissions control, and professional development. The University at Buffalo brings deep expertise in modeling combustion and gaseous emissions in wood combustion as well as experimental facilities for testing wood-burning appliances. ORNL provides expertise in particulate matter (PM) modeling. New Buck Corporation is a domestic stove manufacturer with more than 30 years of experience and provides prototyping capability. NAFEMS America is the primary national organization for companies conducting modeling and simulation and is well positioned to support the transfer of technology from this proposed project into the domestic woodstove industry. All partners have a track record of expertise in their respective areas.



COMMENTS

- Approach: The project approach aligns with the metrics defined under (FY 2020) Topic Area 5, DE-FOA-0002203.
    - Domestic-manufactured, low-emissions, high-efficiency, residential wood heaters.
    - Quantitative goals: room wood heater—2.0 or 2.5 g/hour (cord wood alternative) PM emissions limit; hydronic wood heater—0.1 lb/MMBTU PM emissions limit, or 0.15 lb/MMBTU PM emissions limit for forced air; amounting to a 25% emissions reduction and 5%–15% efficiency improvements.
    - Technical: Modeling and simulation-aided design of woodstoves, guided by aerospace industry practices.
    - An 8% efficiency improvement and PM emissions reduction of 65% for catalytic and 7% and 70% for non-catalytic stoves.
    - Project management: NAFEMS does education and adoption of simulation technologies and can help advance the technology.
    - NAFEM, the University of Buffalo, Ohio State University lead, ORNL, New Buck Corporation.
    - Issues: wood combustion; adoption risks for advanced models/costs of products.
- Progress and outcomes:
    - The project has completed 1 year of work.
    - The team has passed the verification stage.
    - December 2023 is the next go/no-go first prototype testing.
    - The Ohio State University CFD models and accuracy milestone has been passed.
    - Baselines stoves are meshed for CFD.
    - Two setups for testing: one at the University of Buffalo and one at Ohio State University.
    - Non-catalytic and catalytic systems are being tested for shakeout.
- The goal of this project is to work closely with the industry partner to improve their stoves based on CFD models. The project supports a number of students from two universities.
- Modeling of a particular stove has been used to see the effects mostly of modifying different aspects of secondary air. The goal is that qualitative improvements can be determined from the model and then implemented in these stoves.
- On one hand, the study is limited to one brand of stoves; however, modeling can reduce the number of costly experiments needed to optimize the wood heater. If successful, this could be a path for other heater manufacturers to improve their systems.
- I appreciated their risk analysis approach to addressing the work plan. This has the potential for implementation because it seeks to modify existing designs, not create new ones. It would have been helpful if some type of figure of merit or benchmark were provided to understand how the results were

positive, as stated in Slide 12. I am not sure the project will be able to reach TRL 7 but, surely, they can achieve TRL 6. The team should probably assess the cost of risk reduction in terms of contingency planning—scope, dollars, or time. Their estimates of efficiency may only be a modest reflection of what they can achieve. Good agreement with CFD.

- This project will develop models and automation technology to support simulations of woodstoves to be used in optimizing the design of domestic woodstoves toward low PM emissions and higher efficiencies. This has the potential for industry-wide adoption and technology improvements. The project's technical targets are to demonstrate a catalytic stove and a non-catalytic stove meeting efficiency improvement and PM emissions reduction goals by the end of the project. In this first contracted year of the project, 19% of the budget has been expended, and the work performed has primarily been simulation studies, but experimental facilities have also been established during that time, and the project team has involved multiple graduate and undergraduate students and two postdoctoral researchers at two universities. The graduate students and postdoctoral researchers are building expertise in CFD, design, and automation that will enable comprehensive modeling of the full physics of wood combustion during the project. The milestones thus far have been met as scheduled. The project team has incorporated technology transfer to the woodstove industry and mitigation of added costs into their approach and their risk management plan, increasing the chances of success in commercialization in the future.
- The efficiency improvement goals are too modest. No emissions reduction results were reported.

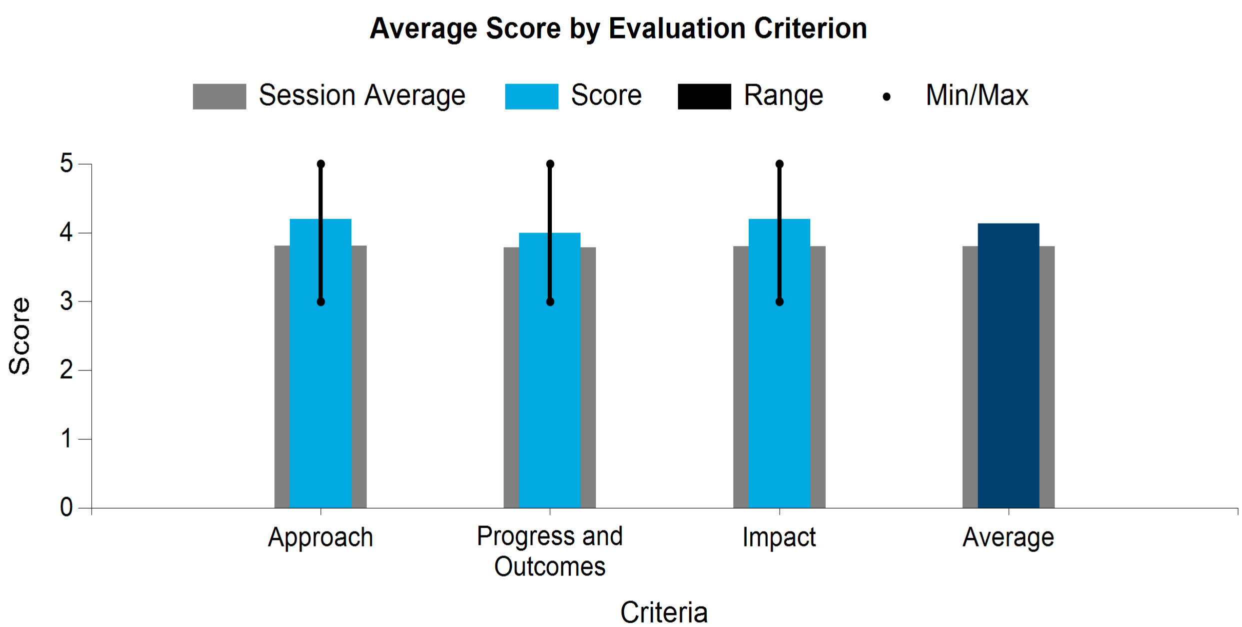
SCALING UP BIOCRUDE-DERIVED ANODE MATERIAL (BDAM)

North Carolina State University

PROJECT DESCRIPTION

WBS:	3.7.3.005
Presenter(s):	Sunkyu Park
Project Start Date:	10/01/2020
Planned Project End Date:	12/31/2025
Total Funding:	$5,492,007

The primary objective of this project is to scale up the key process ("delayed coker") for converting biocrude pyrolysis oil into high-quality graphite that is economically and environmentally preferred as anode materials in lithium-ion batteries. Lab-scale work at North Carolina State University and NREL has shown that a fraction of biocrude oils from the fast pyrolysis of woody biomass can be converted into graphite, which perform as well as commercial lithium-ion battery anode materials. The remaining biocrude is preferred for biofuels production. This project will reduce commercialization risks by scaling the initial critical carbonization process, delayed coker, which is common in most petroleum refineries. Experimental data collected in this project will be used to design, build, and operate a pilot-scale delayed coker. The reactor will be demonstrated for 500 hours with fast pyrolysis biocrude. The performance of graphite and hard carbon in lithium-ion batteries will be coupled with TEA and LCA to identify and improve the specific process steps that have the greatest impact on costs and sustainability, respectively. Once proven at scale, the new carbon materials have the potential to reduce the cost of biofuels and enhance the supply of high-quality carbon products.



COMMENTS

- Approach: The team is focusing on the production of graphite for battery electrodes with the utilization of known delayed coking processes as a key step for upgrading fast pyrolysis oils. The team comprises various university-led groups, industry, and national labs.

- Progress and outcomes: The project recently passed the initial verification and has completed only one-quarter of the work for Budget Period 1. The team has made significant progress on producing lab quantities of graphitic carbon, property comparison with commercial samples, and coupon performance tests. One proposed method is to use a catalyst for accelerated coking; this optimization was conducted. Impurity tracking and the impact of process parameters are well documented. The approach toward scale-up and work distribution is well planned.

- Impact: The team proposes a low-severity method to produce a high-demand critical material for lithium-ion batteries. Given the quality of varying types of biocrudes and intended volumes that may result if pyrolysis or HTL technologies are successful, the project is well positioned to convert biocrudes to graphite, a high-value product, by diverting some feedstock, hence improving the overall economics of the process. Overall, the team has shown great progress and is well aligned with the goals of enabling low-cost biofuels by creating additional revenue streams for bioproduct sales.
- The project aims to use pyrolysis oil to produce graphite. The team consists of multiple universities, NREL, and companies. The presenter also mentioned including a consultant who has previously worked in the graphite industry. The project will scale up a process developed by the PI.
- They have passed the initial verification and made the biocrude they will need. They are beginning to make graphite and have had batches tested. They have not yet achieved the necessary purity. They have identified issues with foaming that they need to address as they continue the project.
- There is going to be a major need for graphite to produce batteries moving forward. At the moment, there is little capacity to do so in the United States. It is not clear if that is on purpose or not. It seems that ramping up production could happen in the United States, but it has not yet happened. There are issues with reaching the necessary purity that they still need to solve. The idea that their impurities are different than those in other sources of graphite should be taken seriously because those impurities, even in parts-per-million quantities, may have a major effect on the product.
- The projected product has real value and is a high-impact material. They met the initial verification milestone. They have a new project member with experience in making graphite. The team seems adequate, and they are on track to meet their December 2023 go/no-go decision point. Their scope is good, and they should be able to provide DOE with information suitable for showing the value of the process.
- This project investigates scale-up pathways for biocrude pyrolysis oil to be converted into high-quality graphite, which is a substantial component of lithium-ion batteries. This pathway has the potential to bypass natural graphite mining and avoid its environmental impacts. The project team includes an LCA expert to accurately quantify the life cycle environmental impacts of the studied pathways as well as a TEA counterpart. They have a management plan to integrate analyses across institutions (which include academia, industry, and a national lab), and they have brought everyone together in person to coordinate within the first few months. The project started 6 to 9 months ago, and the team has multiple tasks already in progress and has completed the initial verification and production of more than 20 kg of biocrude oil by the company on the project team. Experiments on the production of biographite and analyses of its properties are underway. The project team's approach is appropriate to provide actionable data on the production of biographite and to minimize its life cycle costs and GHG emissions. This project has the potential to guide a nascent industry in the production of graphite from biomass feedstocks and to identify viable pathways for commercialization.
- The project is novel and works to address a novel need: graphite; however, the desired purity levels are still not achieved, even with acid washing. An alternate approach might need to be considered. No data on graphite quality, yield, density, etc., were provided. It would be helpful to compare it to coke-based graphite.

PI RESPONSE TO REVIEWER COMMENTS

- The project team thanks the review panel for their encouraging and thoughtful comments as well as their recognition of the novelty, work progress, management, and potential impact. Based on the reviewers' comments, we will further investigate the method to improve the graphite purity. This will include a multiple-stage acid reflux/water washing, thermal treatment (above 1,500°C), or a combination of acid washing and thermal treatment. In addition to the total inorganic impurities, we will carefully monitor individual inorganic elements because some are more sensitive than others in terms of battery performance.

SWIRL STOVE: SWIRLING COMBUSTION FOR EFFICIENT WOOD BURNING

MF Fire Inc.

PROJECT DESCRIPTION

WBS:	5.5.1.101
Presenter(s):	Paul LaPorte
Project Start Date:	10/01/2019
Planned Project End Date:	06/30/2023
Total Funding:	$1,249,747

MF Fire Inc. proposes to create and validate a novel, commercially viable technology for use in woodstove design for mixing combustion air with gasification products to achieve a more complete burn, thereby reducing emissions and increasing efficiency. This novel innovation involves the swirling of inlet air, as described in MF Fire's patent application, US 2018 / 0051886 A1. The project would leverage MF Fire's existing EPA Step 2 certified woodstove, Nova, as a baseline design with corresponding baseline data for emissions, efficiency, and CO.

A critical method to yield an optimal wood burn with low emissions and high efficiency is to homogenously mix air and gasified wood fuel in a specific ratio throughout a burn chamber. Our technology is based on proven combustion science associated with a swirl phenomenon whereby high-speed spinning air movement in a singular direction forms a vortex that centrally concentrates combustion in a burn chamber, away from walls or other impediments, leading to a near burn of available fuel, including PM. This approach has been successfully demonstrated in other fuel types (gas, diesel, oil, etc.) but never with cordwood. This innovation will lead to a substantially cleaner method for burning cordwood in a woodstove and enable industry-wide design adoption on future woodstove products.

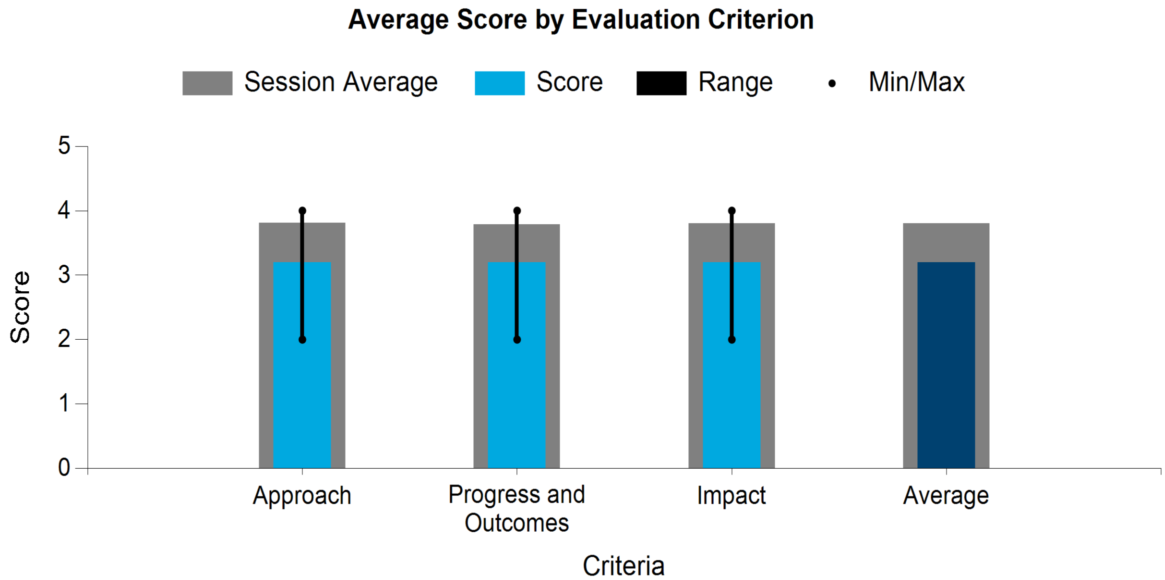
The proposed technology targets reducing particulate emissions production to less than 0.5 g/h, a 75% reduction over MF Fire's current firebox design (1.9 g/h). Initial testing of a prototype design yields significant improvements in carbon monoxide (92% reduction) and PM (PM 2.5) (75% reduction) in an open burn environment compared to testing with secondary combustion pollutant mitigation alone. These performance enhancements are comparable to the results obtained by the inclusion of a catalyst—but without the significant additional cost of the catalyst (saving consumers $300–$500). Alternatively, a catalyst can be used in combination with swirl technology for additional emissions reduction.

Historically, burn chamber geometries and airflow designs do not afford an opportunity for homogenous mixing due to dead spots, inefficient gas transport, and localized eddies, resulting in incomplete combustion and pockets of residual PM. This leads to unnecessarily high PM emissions and suboptimal efficiency. Key challenges for implementing the proposed technology involve sustaining airflow with a sufficient swirl number and an appropriate air-to-fuel ratio despite nonhomogeneous fuel characteristics.

The proposed technology will overcome imperfect, nonhomogeneous air-fuel mixtures by introducing a novel airflow system, as shown in images associated with the pending patent US 2018 / 0051886 A1. This airflow system thoroughly mixes air with fuel while concentrating combustion in a central vortex, created by the laminar, circular air movement. To optimize air-to-fuel ratio, passive (bimetallic strip) or active (air fan, electronic regulators, etc.) air control strategies will be tested and implemented.

This project has the potential to eliminate combustion inefficiencies introduced by suboptimal air movement and incomplete air-fuel mixing. The estimated impact to emissions is to reduce baseline emissions between 50%–75%, depending on the original stove burn chamber geometry and other pollution mitigation measures. It is possible, with the inclusion of a catalyst and the introduction of swirl combustion, that 0 particulate emissions could be achieved.

Efficiency gains will also be realized. A more complete burn cycle yields higher combustion efficiency because more heat potential is realized from the fuel. A lower pressure drop allows for greater heat recovery in natural draft woodstoves, improving thermal efficiency and delivered heat. In preliminary testing, net efficiency gains of 15% were achieved.



COMMENTS

- The project approach aligns with the metrics defined under (FY 2019) Topic Area 3, DE-FOA-0002029.
  - Quantitative goals: Minimum 25% reduction and 5%–15% efficiency improvement for residential wood heaters relative to the current baseline residential wood heater design. The team managed the wood heater challenge.
  - Technical: 75% reduction and overall 85% efficiency; swirling combustion.
  - The team tried conducting swirling combustion with cordwood with measuring the emissions rate to be less than the baseline 4.5 g/hour.
  - No clear DEI goals or work.
- Progress and outcomes:
  - The project claims but has not met milestones.
  - Swirl patterns were modeled in CFD to improve heat transfer.
  - Secondary air introduction approaches were used to increase swirl in the flow path.
  - Chosen swirl vane, secondary air. R1 model.
  - R2 model designs for aesthetics, removal of dead space.
  - Emissions testing is incomplete.

  - Impact: The project team has prototyped a new type of stove combustor but has not met the emissions reduction and efficiency requirements. The approach is quite new and adopted from the gas flow industry, wherein flow characteristics can be controlled in a more defined manner. The project is close to the end, and it seems to have fewer chances to showcase or meet all objectives; however, if the team can continue on its own or if there is continued funding, the project may help define the requirements for a new design. The proposed design also does not meet the criterion to support the FOA goal to make the low-cost wood burners required to serve economically weak sections of society.

- The proposed wood heater uses a swirling combustion approach to decrease emissions and increase efficiency by improving mixing of the fuel and air. The project uses CFD modeling to inform the design of the heaters and experiments to carry out.

- CFD modeling has been used to help inform the system design. Though a limited number of experiments can be carried out due to the expense, the CFD modeling did help in the design. A furnace has been built with a viewing chamber to see the flame. It seems that there is still interfacing of the metallic and glass components of the heater. Unfortunately, emissions and efficiency numbers were not presented.

- The presenter mentioned that the visual appeal is currently the main selling point. The selling price will be well out of range for those who rely on wood heat for economic reasons, which is unfortunate though needed for market introduction. As a comment, the ability to retrofit this into fireplaces may be another way to increase adoption.

- The presenter made an excellent comment about the heater burning too hot, which may lead to fewer emissions at the cost of going through cordwood too quickly.

- The project has made modest progress from the last review period. It seems to be a bit slow in achieving the goals. There is concern over the ability to address risks. I am concerned about materials-of-construction issues that may arise with implementing the swirl technology. I believe the swirl technology can be successful in achieving reduced emissions. The cost may eliminate their market opportunity.

- This project is developing a partially clear chimney for a high-end woodstove that allows users to see a fire tornado while using the stove, which would have both aesthetic value and the potential to reduce PM emissions. The project team has met the milestones and completed the tasks up to completing the prototype development, including CFD modeling and testing the first prototype. The fire tornado or swirling combustion has not yet been sustained for long periods of time, and the geometry of the prototype has changed from the first to the second version for the design to appeal to the target market of higher-income consumers, which led to design and implementation challenges with the curved glass fitting the metal chimney. There is potential for commercialization, but the target market may be small, especially because this is best suited for vacation homes in remote and/or cold climate locations; however, the project team is in an industry that has reached the same target market with previous products. The efficiency of the prototype has not yet been determined and compared to existing stoves.

- The stove is focused on a very premium market and does not reduce PM emissions compared to other models on the market. There is limited adoption potential, and the increase in efficiency is not demonstrated.

AUTOMATED WOOD STOVE UFEC23

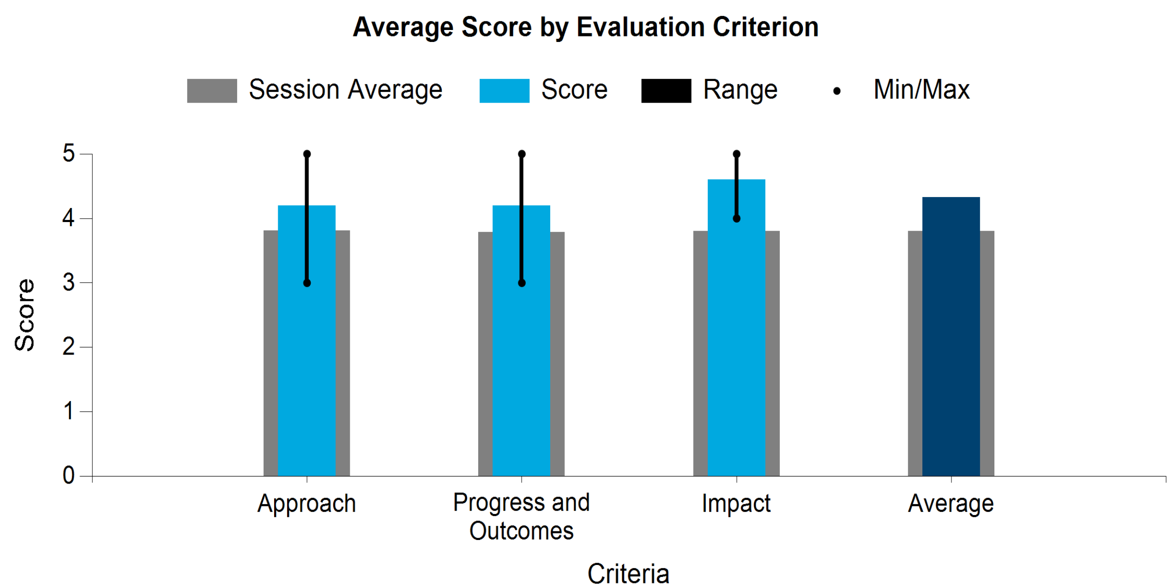
ISB Marketing

PROJECT DESCRIPTION

WBS:	5.5.1.102
Presenter(s):	Guillaume Thibodeau-Fortin; Louis-Pierre Cote
Project Start Date:	10/01/2019
Planned Project End Date:	04/30/2024
Total Funding:	$1,274,714

Our goal is to make a stove that will compensate for any "bad action" from the consumer due to their misunderstanding of the combustion process or lack of knowledge about combustion parameters in general. The critical success factors are:

- Design an automated stove that has a maximum particulate emissions rate of 1.2 g/h and an overall efficiency greater than 75% (higher heating value).
- Design an artificial intelligence algorithm that will limit emissions to no more than 2.0 g/h, regardless of the loading method used by a reasonable consumer.
- Design a stove that is easy to operate, reliable, safe, cost-effective to manufacture, and aesthetically pleasing.



COMMENTS

- The project approach aligns with the metrics defined under (FY 2019) Topic Area 3, DE-FOA-0002029.
    - Quantitative goals: Minimum 25% reduction, which aligns with BETO's FOA requirement of 50% based on a revised EPA target midway through the program
    - Technical: Flame view area, radiative heating. Smoke emissions in real time. Baseline verification and Empire Comfort System (ECS) testing

  - Project management: ISB Marketing is the PI; Stove Builder International (SBI) and ECS seem to be a small, cohesive team, heavily involved in the project
  - Issues: Emissions reduction, commercial acceptance, and costs
  - DEI: Environmental, social, and governance policies are well implemented at the level of the company scale.
- Progress and outcomes:
  - Customer survey to understand requirements—high-efficiency thermostat integrated with remote control, and good flow in areas where heater is not installed.
  - ECS baseline testing.
  - Air intakes and electronics sensor controls; air intakes primary—primary above glass and secondary air to burn gases.
  - CFD model for steady and transient station to measure and verify flue temperature, CO_2 percentage, wood gas flow rate. Key performance indicators—increase in residence time for gas flow/PM?
  - Combustion: 80% higher heating value on low fire with non-catalytic combustion.
  - Smoke sensor optical sensor, backscattered light using ambient light.
  - Demonstrated 58% emissions reduction and 12% efficiency increase.
  - Beta prototype for EPA and safety certification.
  - Negotiating with EPA for new types of tests.
- Impact: The project team has clearly demonstrated scientific advancement and a beta prototype with the required emissions reduction and efficiency improvements. Improvements include the redesign of the airflow intake, a new test method using a smoke sensor, and improving residence time for hot air and PM in the equipment. Some of the items produced using research can be stand-alone achievements, such as the smoke sensor. The company has an open and fast approach—it is listening to customers, working with regulatory bodies, contracting with the right people, and has a commercialization path.
- The goal of this project is to automate wood heaters. The project seeks a furnace that can essentially emulate a fireplace that can monitor efficiency and smoke events in real time as well as incorporate machine learning to predict and prevent smoke events. The presentation included DEI efforts, though they were not required in the FOA.
- The company has produced CFD models of the combustion process in a simulated furnace. They have met their goals for emissions and efficiency. They have also developed a smoke sensor that can be used to monitor emissions. They are at the point where they have a prototype that they would like to start commercializing. The machine learning portion was not a success and was dropped from the project.
- The fact that they are about ready to sell a real unit is great. It would be interesting to know if these units could be retrofit into an existing fireplace.
- The project obtained sufficient results from new designs to produce improved results for this technology. The team made a good analysis of challenges and then went forward to address them. The final effort

will be telling as to the value of these advancements to the SOA. This is a good team that is involved throughout the process.

- The project team is in the beta prototype step of developing an automated wood stove using machine learning to prevent smoke events and increase efficiency. The approach aims to compensate for improper woodstove user behavior. The prototype tests have demonstrated emissions reductions and efficiency increases. The project team is on track to have 25 automated stoves installed in homes in the coming winter. To meet the needs of the target population, the team is analyzing how to reduce the stove's cost while the beta prototype is being developed. There is an opportunity for sharing their air emissions testing data, combustion CFD simulation graphics, and comparisons of automated controls to standard user control on a website shared on flyers by local stores in communities that might be the most affected by the PM emissions of household stoves, thus reaching more of the target population and increasing commercialization success. The team's approach, progress, and outcomes appear promising.
- The project is more focused on the expensive end of the consumer base; however, eventually automation and technology improvements would be beneficial to the industry. I recommend ongoing support for the industry as a whole to develop lower-cost technology solutions.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you all for your comments. To provide a short update, we are continuing to improve the combustion algorithm using the signal of the smoke sensor. A complete prototype was built and is much closer to the end-user product. We had great news from the EPA: We will be able to install our product in 25 homes in the United States and Canada and have them burn for a full season before doing the emissions certification testing. This will allow us to update the combustion software following real-life experience. The conditions still need to be written and accepted by all involved parties. This news delays the discussion on the test method to use. We will wait to see how the industry adapts to the cordwood testing restrictions. SBI will attempt a certification testing using a new method on another wood heater; their experience will guide our choice for the test method. Currently, we are doing multiple different looks to present to our distributors in a few weeks. After, we will build a program to find 25 participants. The goal of the project is to test multiple technologies in the field to find what is reliable enough to go for mass production. Our wish is to be able to provide myriad wood-burning products that will introduce new technologies to the market while being affordable (small to large stoves and small to large inbuilt fireplaces).

FIRE MAPS – SECURE PERFORMANCE MONITORING AND USER ALERTS SYSTEM (FOR WOOD-BURNING STOVES)

MF Fire Inc.

PROJECT DESCRIPTION

WBS:	5.5.1.103
Presenter(s):	Paul LaPorte
Project Start Date:	10/01/2019
Planned Project End Date:	03/31/2023
Total Funding:	$1,245,144

All woodstoves are dramatically more polluting in real-world use than in a test lab. This is due in part to users who do not have sufficient knowledge or data to guide them in proper woodstove operation. MF Fire proposes to create a unique, commercially viable technology for woodstoves, called Fire MAPS (Monitoring, Alerts, and Performance System), for delivering secure, real-time performance monitoring and user guidance to improve user control and stove burn management in any existing woodstove, thereby reducing emissions and increasing efficiency. This technology establishes a first-ever comprehensive burn database that securely captures detailed burn information that enables regulators and clean air advocates to understand real-world stove use and make informed policy decisions. The use of inadequate burning conditions in woodstoves can cause an emissions increase as high as sixfold over controlled, ideal burns.

This technology would comprise (1) sensors, (2) a controller, (3) a user application or display unit, and (4) a burn database. Sensors include multiple thermocouples, a door, and bypass monitoring. The controller is an Internet of Things device, including a central processing unit and wireless connectivity. The user alert system delivers information via an application to a user device. The database powers the guidance and alerts the engine. The Fire MAPS system could be used in both new and existing woodstoves, enabling large-scale adoption for vast emissions reductions and efficiency gains. This innovation leverages unique insights gained from users of MF Fire's Catalyst (EPA Step 2 certified) woodstove, which is equipped with data-collecting sensors and a basic user alert system triggered by sensor data.

Sensor data provide critical information triggering real-time user guidance on what action to take to achieve the best results regarding low emissions and high efficiency during real-world use. Monitoring and guidance would cover a broad set of conditions and events, such as:

- Combustion phases: cold start, steady state, overfire, long/slow burns, and burnout.
- State transitions: ignition, warm reload, catalyst engagement, overfire, and door open.

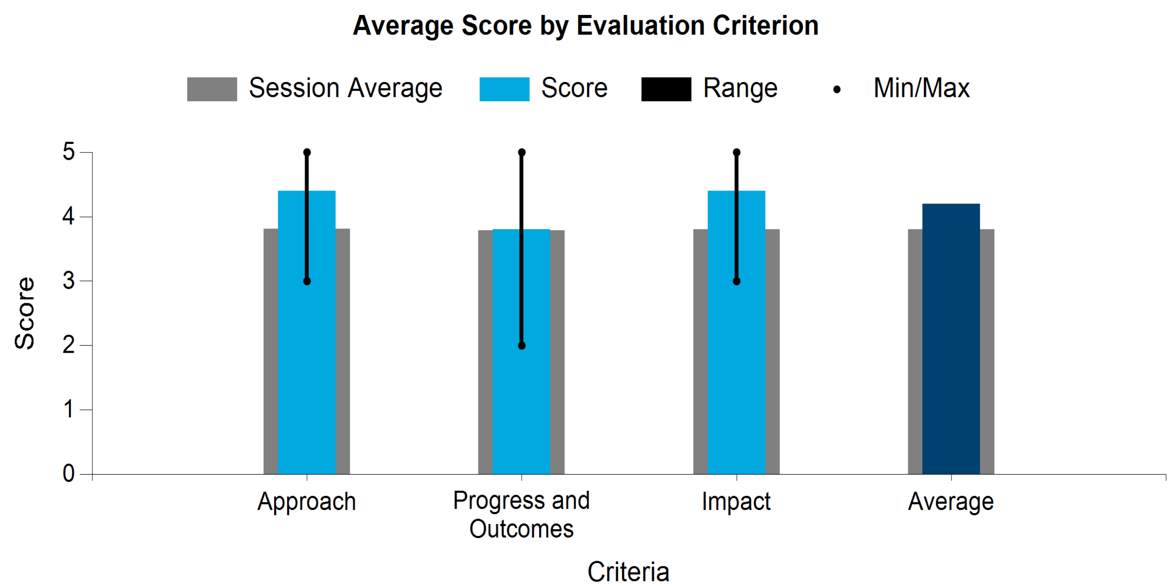
Guidance would be proactively sent to a user's device, including cell phone, tablet, or other display. This project would leverage Nova (EPA Step 2 certified) for baseline data.

Burn information would be securely and anonymously stored in a burn database to provide a comprehensive view of burn habits and real-world use, from which machine learning would help continuously improve guidance and alerts, resulting in further emissions and efficiency gains. This unique database, referred to as the Fire MAPS Database, could be used by various agencies to aid in air quality management decisions and to provide supporting evidence that various DOE and EPA programs have a positive impact.

User-specific contributions to woodstove emissions have been reported as high as a 600% increase over certified stove baseline emissions. This technology could address and suggest improvements to all these deficiencies. MF Fire estimates that the proposed technology will significantly improve user behavior and eliminate greater than 60% of user-contributed emissions, or approximately 300% of a stove's certified emissions level.

The proposed technology overcomes users' knowledge limitations and woodstove operation errors by automatically monitoring the stove's key performance indicators and providing real-time guidance that allows users to implement best practices and learn proper operation.

This project has the potential to eliminate excess emissions and improve low efficiency due to poor stove management, insufficient knowhow, and burn information. The estimated impact is a 60% real-world emissions reduction measured from in-home burning. Fire MAPS could be installed on up to 500 stoves for a pilot as part of the project to populate the burn database and expanded through commercial sales after the project to encompass thousands more.



COMMENTS

- Approach: The project approach aligns with the metrics defined under (FY 021) Topic Area 4, DE-FOA-0002936.
  - Quantitative goals: room wood heater—2.0 or 2.5 g/hour (cord wood alternative) PM emissions limit; hydronic wood heater—0.1 lb/MMBTU PM emissions limit, or 0.15 lb/MMBTU PM emissions limit for forced air; amounting to a 25% emissions reduction and 5%–15% efficiency improvements.
  - Technical software/hardware platform to reduce user-contributed emissions for nonoptimal use. It has been noticed that user-contributed emissions can be as high as 600%.
  - Hypothesis: Monitor performance in real time; helps eliminate 50%–80% of user-contributed emissions if used correctly based on guidance.
  - Mimics user conditions in the lab to create data matrix and measure impacts.
  - Uses this data to create software/hardware solution.

- Guidance system to act on basis.
- Project management was not discussed much.
- Issues: These were well discussed, and there is a need for a software/hardware system; see above.

- Progress and outcomes:
  - Fifty home trials have been completed.
  - The project has been able to collect more data than planned—30 days versus 2 years.
  - Long-term use in many cases is not 30 days, but it is the best data available.
  - The goals achieved over the large data set are not known; however, point-of-reference results show reduced emissions and increased efficiency.
  - The system includes a door sensor, thermocouple, and a stack thermocouple coupled with the controller, cloud, and application.
  - Baseline user profiles were created to compare with post-controller installed profiles. Anecdotal evidence shows a 38% reduction in emissions for a small set of data.
- Impact:
  - The project team has created a hardware system coupled with cloud and real-time guidance for customers to take action to reduce emissions and increase efficiency. The tool is model agnostic and can be used for all types of furnaces. It addresses a major concern that user-contributed emissions are much higher than the furnace rating. This allows for user training and helps reduce emissions. It can have a major impact. See above for the data analyzed thus far—38% reductions have been demonstrated, which is very significant given that wood burners have 600% emissions due to improper use. This scheme allowed for 38% reductions, which is equivalent to 600*0.4 = 240%, more than twice the base emissions rating.
- The goal of this project is to develop software that informs heater users on how to better manage their wood heater system based on their behavior collected over some time period. The software system is potentially educational as a short-term device or more performance related as a longer-term device. The device can be self-installed for personal use.
- The software/hardware platform has been developed. Their database collects information on individual users, so in that sense it can educate users about their own heater system.
- The communication relies on electricity and wired home access, which could be a problem for some disadvantaged populations or those who have the furnace in a secluded seasonal home. Communication that relies solely on cell phone access would be an improvement. The ability for the user to input their own data, such as log size, and to include atmospheric information, such as temperature/humidity, is good to have. If it does not have it, something that shows how much more efficient the heater system is using their software would be meaningful to users. A more robust system that uses more sensors may be desirable to some end users as well.
- Technologically, this project has produced a product that can help operators of wood-burning stoves achieve better operation, leading to reduced emissions and improved efficiency. Their initial results are encouraging and could lead to wider incorporation into operating units. They do need a larger sample

size because the limited testing size may not be sufficient. The education risk is high, as evidenced by other attempts to introduce technology to the public that falter after extended use. The team needs to ask themselves how much contingency is needed in their plans to achieve the predictability of having a reliable and useable product. The cost to the user is not too exorbitant, allowing for broader market adoption.

- This project addresses a critical concern in the use of woodstoves: suboptimal user behavior. The project team made a test matrix of user behaviors and then tested it in a lab and measured the impacts of those behaviors on emissions from woodstoves. This informed the creation of a free technology-agnostic application with notifications linked to a $299–$399 sensor installed by users, which is a similar setup to smart thermostats (though those are automated, and automation is not permitted in retrofitting existing woodstoves), and thus has high potential for commercialization and woodstove user adoption. The emissions from woodstoves resulting from user actions are timing-dependent and require real-time feedback to inform a user on what to do to decrease emissions, so the use of an application to direct user behavior is an impactful approach. The project team conducted more than 50 in-home trials with woodstove owners and monitored them over time to collect data on how the application (Fire MAPS) affected user behavior and unnecessary emissions. Eighty percent of test users were still using the device after the 30-day trial period, and some continued to use it two seasons later. The project team is discussing collaborations with local air quality boards who are interested in this new approach to decreasing PM emissions and has also developed a customer support and research tool with an interface that displays emissions data over time. This project has high potential for significant impact to PM emissions from woodstoves and high commercialization potential.

- Improvements in automation are not necessarily resulting in any higher PM reduction or energy efficiency. The data presented are anecdotal (five users only).

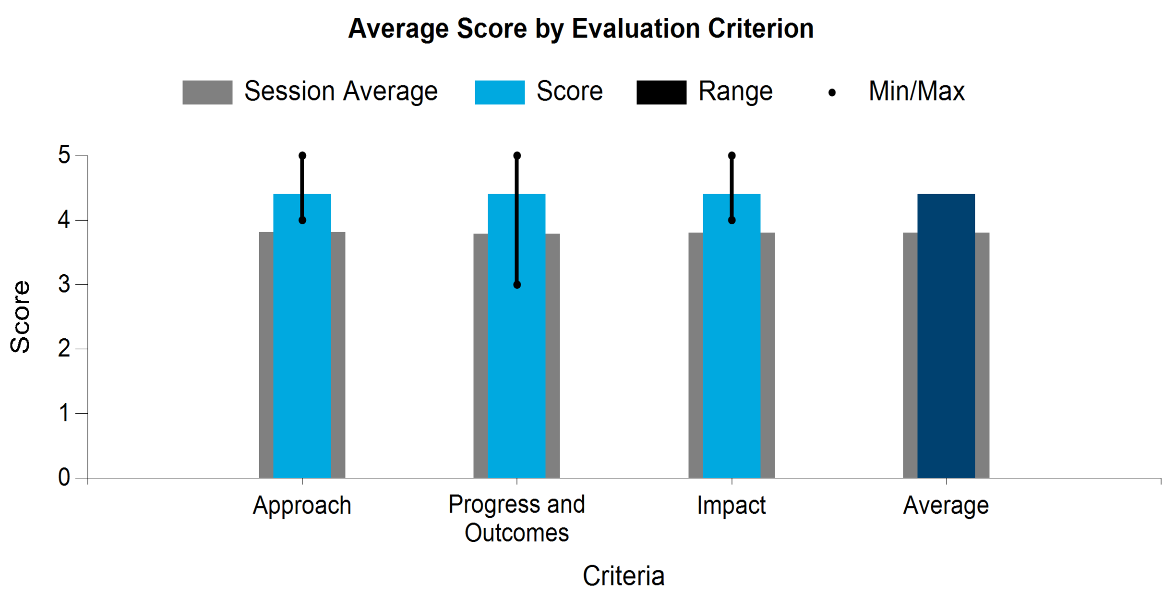
ADVANCING WOOD HEATER EVALUATION METHODOLOGY FOR ACCELERATING INNOVATION—LBNL, BNL

Brookhaven National Laboratory

PROJECT DESCRIPTION

WBS:	5.5.1.105
Presenter(s):	Rebecca Trojanowski
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total Funding:	$1,995,692

Brookhaven National Laboratory and Lawrence Berkeley National Laboratory aim to accelerate wood heater innovation and commercialization by developing rapid, cost-effective performance test methodologies for biomass-fired heaters. These simplified methods aim to reduce R&D cycle times, allowing manufacturers to efficiently evaluate performance metrics before costly certification. This project aligns with BETO's mission to support the development of low-emission, high-efficiency wood heaters, enabling broader access to clean and affordable heating solutions. Challenges lie in accurately measuring emissions, and considering concentrations, types, and burn phases, all while managing the associated costs. Our literature review explored current certification and measurement methods with recommendations for simplified methods, informing our technical approach. Specifically, our approach developed instrumentation suites suitable for both laboratory and field use. Cost considerations were paramount, but accuracy and range were also prioritized to effectively measure a spectrum of emissions, from cold start emissions to steady-state emissions. Furthermore, three virtual workshops were hosted as part of the 5th Wood Heater Design Challenge to discuss advances in wood heater design and technology, instrumentation advancements, and adoption of new technologies.



COMMENTS

- The project approach aligns with the metrics defined under (FY 2019) Topic Area 3, DE-FOA-0002029.
- Quantitative goals: Minimum 25% reduction. This aligns with the 50%–80% (in the FOA) because a standard was revised, reducing emissions to half, midway through the program, so, overall, 25% is equivalent to 50% emissions reductions relative to their current baseline residential wood heater design.

And 5%–15% efficiency improvement for residential wood heaters relative to their current baseline residential wood heater design. The team managed the wood heater challenge.

- Technical scope: Low-cost measurement method simplifying the method to test—ASTM E2779; utilize inputs from industry on standards and test method requirements.
- Project management: The Alliance for Green Heat is a collaborator, the rest of the team is from LBNL.
- Issues: Wood heating is a relatively higher emissions sector compared to comparable high-temperature industries in other sectors. It is used because of a lack of income and/or no connection with gas or the electric grid.
- Progress and outcomes:
  - The team has made significant progress on identifying and meeting the test methods. Challenges include emissions—carbon rich, flue gas flow, measured gas phase CO_2/CO; stack loss measurements for efficiency. ASTM E2779 was used to verify the stoves at different labs using the same fuel feedstock.
  - Flow measurement through dilution tunnel for flue gas; VOC, PM, and gas phase measured, also velocity.
  - Community engagement: three workshops—100 participants; industry feedback; innovations in the European Union were well incorporated.
  - Three winning teams were identified.
- Impact: The project team has clearly demonstrated scientific advancement and simplification to guide the industry on the measurement of emissions and help them standardize with some limitations. The goal of this project seems to provide a platform for testing and unification and serves as a resource for the industry to go back and look at their innovations and help them get tested. The EPA considers all the work that goes to the national labs. The winning teams get an opportunity to come test at the labs.
- This project has multiple national lab partners acting as a resource for wood heater manufacturers by developing protocols, analysis, and measurement tools that can be used to verify performance measures. They act as an interface to take inputs from manufacturers and to support them.
- The labs have set up validation facilities, developed simpler protocols, developed a user interface for analysis, and held workshops to engage and connect stakeholders.
- It is important for manufacturers to obtain this help and guidance to reduce the R&D barrier. A major issue with wood heating is the tendency for lower-income communities to rely on wood heating, and thus expensive solutions will not always be the best even though the profit margins may be higher. The role that the lab participants are playing is critical and a good fit. An industry consortium is not likely due to the fact that many companies are smaller and not able to participate in a consortium-type exercise.
- National labs provide an independent analysis for addressing the problems of emissions. They have provided an early assessment of possible improvements but also, even more importantly, the development of analytical methods that can be used. The issue will be how viable are these measurement methods going to be, and that is what they are evaluating. This effort is needed to begin to address the issues of achieving efficient wood-burning stoves. The effort is designed to be used as a monitoring tool, not a certification. There is good attendance at workshops. The involvement of the stakeholders and communities is commendable.

- The Wood Heater Design Challenge has a demonstrated impact as a previous winner has secured their own project funding and further developed their technology. The project team has also completed reviews of test methods and recommended and developed simplified woodstove emissions measurement methods. The wood heater industry has been vocal about challenges involved with certification test methods, so these outcomes from the project are aligned with industry needs. The project team has convened community engagement workshops and competitions beyond the Wood Heater Design Challenge, which catalyze exploratory R&D in this field. The project has less than 1 year remaining, and it has been achieving its milestones as scheduled. Its unique programs have brought greater attention to the needs of the wood heater industry and have supported the commercialization of promising technologies.
- The work is merited and is needed in the industry to standardize wood heater designs and provide ratings to the consumers. This is a very effective project and addresses several sustainable justice goals. It is highly recommended.

DEVELOPMENT OF FORCED-AIR COMBUSTION SYSTEMS WITH AUTOMATED CONTROLS TO REDUCE EMISSIONS FROM CORDWOOD ROOM HEATERS IN EVERYDAY USE

Oregon State University

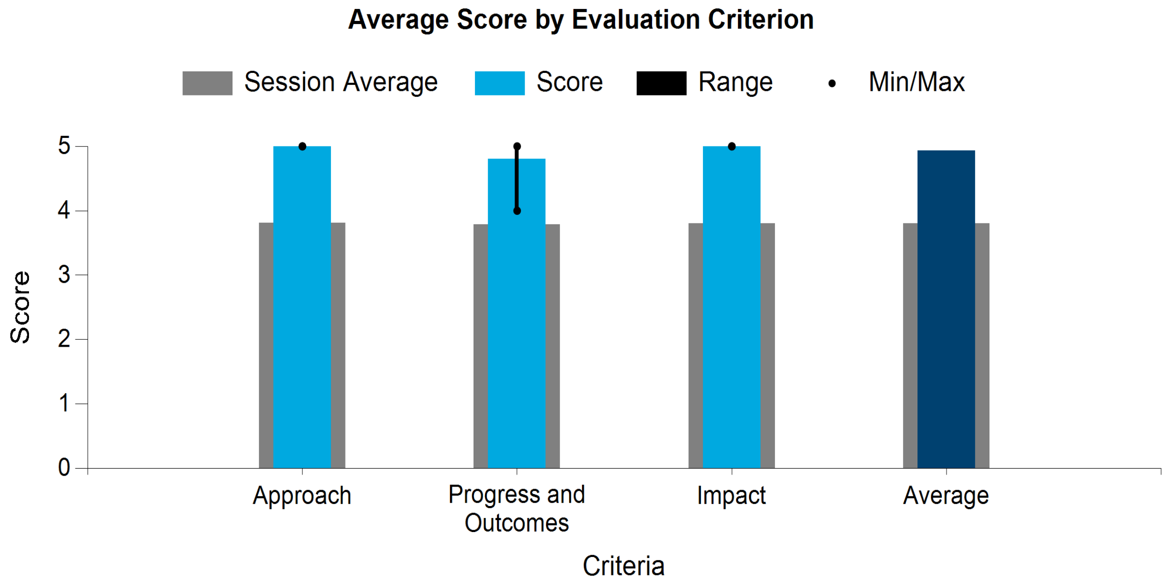
PROJECT DESCRIPTION

WBS:	5.5.1.106
Presenter(s):	Nordica MacCarty
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$3,127,067

This project aims to undertake the development needed to reduce PM emissions throughout the real-world burn cycle of cordwood room heaters by incorporating turbulent jets of forced air into the firebox. To achieve this, we will develop two retrofits that bring common legacy wood-heating stoves up to 2020 EPA emissions and efficiency requirements under the real-world operating conditions identified by extensive user research. The major tasks to achieve these outcomes include fundamental combustion experiments with small- and full-scale prototypes to inform lightweight models that will be used to develop prototypes that will be operationalized with closed-loop sensors and control algorithms. Plans are also in place for market transformation with regulatory oversight and with knowledge sharing among partner manufacturers and the industry at large.

The impacts of this work include the development of a technology and design rules that reduce PM 2.5 during both ideal and nonideal (e.g., wet wood, overfeed) operating conditions. Addressing issues with the latter is particularly important because these conditions contribute the most to PM 2.5 emissions yet have often been neglected during R&D. In addition, initially focusing on retrofit technology is key to enabling rapid and affordable implementation in underserved and tribal communities that suffer disproportionate health effects from wood smoke exposure.

Our team includes faculty and students from mechanical engineering and anthropology at two OSU campuses, Aprovecho Research Center, Blaze King Industries; three tribal communities in the Pacific Northwest; as well as industry, regulatory, and tribal advisory groups.



COMMENTS

- Approach: The project approach aligns with the metrics defined under (FY 2021) Topic Area 4, DE-FOA-0002936.
    - Quantitative goals: room wood heater—2.0 or 2.5 g/hour (cord wood alternative) PM emissions limit; hydronic wood heater—0.1 lb/MMBTU PM emissions limit, or 0.15 lb/MMBTU PM emissions limit for forced air; amounting to a 25% emissions reduction and 5%–15% efficiency improvements
    - Technical forced-air combustion; detailed combustion diagnostics chemical reactor network modeling to 2020 EPA guidelines
    - Project management guidance from industry; regulatory and tribal advisory; OSU, Aprovecho Research Center, Combustion Consulting Services, Blaze King Industries, Nez Perce Tribe; communication map seems complex but is per budget period in terms of type of communication needed
    - Design retrofit for the two most common types of used stoves
    - New project, in the seventh month, has not yet reached any go/no-go
    - The DEI project has active team members from underserved communities. The PI has a legacy of working with nonprofit organizations.
- Progress and outcomes:
    - The team is developing a combustion model using sophisticated laboratory equipment. They are ahead of schedule in the setup of the system that is required to make these measurements. The team is creating a chemical reactor network model. They are performing a baseline, prototyping, and user tests. They are focusing on market transformation and open-source design. Note that these tasks are for a period of 46 months; the project is in the seventh month.

  - Verification test baseline: 9.36 g/hour; forced-air system: 1.63 g/hour, 82.5% reduction meets criterion; baseline versus tested: 79% versus 81%.
  - The team has made great progress; it includes an advisory board from industry, regulatory, and tribal advisor.

- Impact: The project team has made significant progress in 7 months. In terms of the emissions reductions and efficiency improvement over the chosen baseline of the most commonly used stoves using forced convection, the project is promising. Overall, the team has maintained high momentum on all Tasks 1–5, and although this is not required, this will help a lot with the project's success and in forecasting challenges. The proposal is open source, directly targets low-income populations and their choice of stoves; they are performing community testing at an early stage. The team has made good use of sophisticated lab equipment to correlate data versus field-testing. This is an excellent team, and they have made great progress.

- The team consists of university, industry, tribal, and regulatory stakeholders who seek to bring legacy stoves into compliance through retrofitting using forced-air jets. The results will remain open access in that design rules will be published. The approach consists of a well-thought-out DEI plan.

- The team has started all tasks and has started measuring furnace efficiencies. The plan is to go with manual control first, then implement automatic process control.

- This project truly addresses the social justice issues associated with wood heating. Improvements in wood heating, if appropriately focused on, as this project does, can improve the health and welfare of communities that rely on wood heating.

- The team did a good job of identifying risks and an approach to mitigation. The potential to retrofit is real. There is some concern over the materials of construction for the forced-air system. They need extended testing to see if the whole approach holds up. They may want to look at retrofitting options for other stove configurations. They have an excellent risk analysis. They have made systematic progress. They have a particularly aggressive approach to involve underserved communities and hence to reach potential stakeholders and users.

- This project aims to develop design rules and a retrofit kit for existing woodstoves, with automated controls and forced-air fans, that fit the needs of underserved populations relying on cordwood heaters. The lead project team at OSU has a variety of partners on the project, involving tribes, research centers, and industry. There is a structure to their integration and collaboration, and it appears that there has been communication and progress on all fronts within these first 7 months of the project. The project team is well designed to perform impactful and reliable research; it includes an anthropologist who is conducting the user needs assessment survey, and the lead has a 25-year record in cookstoves for underserved populations. In these first 7 months, the team has passed their first go/no-go decision point, conducted more than 50 interviews with various stakeholders, obtained lab and field equipment after consultation with advisors, and began collecting data through field and user tests—while spending only $17,021 of the budget. The project has a thoughtfully developed DEI plan as well as a dissemination plan that shows high potential for implementation success of the woodstove retrofits. The cost of the retrofits are also considered; although the parts are currently roughly $400 per stove, the project team aims to develop a training program for tribal members to be installers in their communities. Overall, the project has stellar potential for impact, has made excellent progress with useful outcomes, and has a genuinely well-developed and effective approach.

- The team shows strong work with a good DEI plan and community engagement. Even by the seventh month, they have achieved the majority of the project's goals. The reviewer has no concerns regarding higher heating value. I am wondering what happens when the power/forced air is not available. Preheating of incoming secondary air should be explored. The reduction in carbon emissions does not include the energy for the fan. It is important to highlight the social justice impact and participation of the PI. The project PI clearly demonstrated an excellent passion and ownership of the goals. I strongly recommend additional support and funding on the same. Clearly, this is one of the exceptional presentations at the 2023 Project Peer Review.

PI RESPONSE TO REVIEWER COMMENTS

- Our team sincerely thanks the reviewers for the detailed feedback, kind words, and encouragement about our approach. We appreciate the notes to consider the impact of power outages, secondary air preheating, forced-air construction/durability, and carbon accounting of electricity usage, and we will look into each of these during the project. We look forward to continued progress in these areas and sharing results as they are available.

CLEAN COMBUSTION TECHNOLOGY WITH EFFICIENT AND AUTONOMOUS WOOD HEATER OPERATION OVER THE FULL CYCLE

The University of Alabama

PROJECT DESCRIPTION

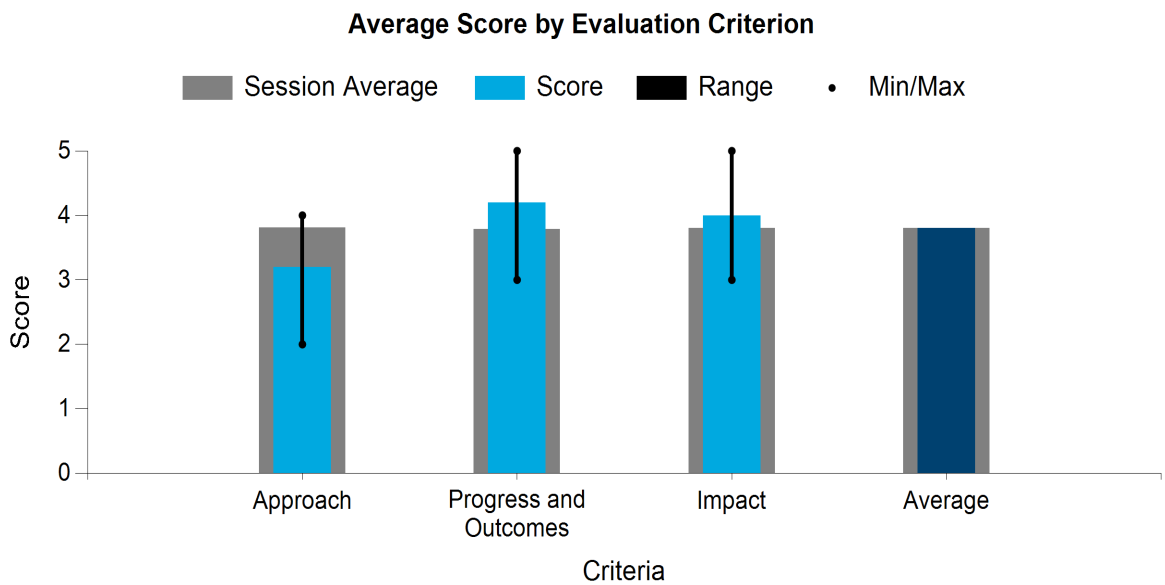
WBS:	5.5.1.107
Presenter(s):	Ajay Agrawal
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$2,080,683

The objective of this project is to develop a modern non-catalytic wood heater for residential applications using wood chips, cordwood, and wood pellets. Experimental and computational techniques will be used to advance the wood heater technology in four areas: (1) novel and innovative designs of combustion chamber geometry, airflow distribution, mixing of combustion air with gasification products, etc., to reduce emissions; (2) thermoelectric generators (TEGs) to produce electricity and manage battery power distribution to operate the wood heater independent of the grid; (3) effective heat extraction methods to increase the average efficiency; and (4) automation to optimize the operation for all phases of the wood-burning cycle, including startup, steady state, overfeeding, overnight burn, and burnout. All electrical and mechanical systems will be integrated to produce the wood heater prototype for testing. The project will use a baseline wood heater that meets the 2020 EPA regulations and is sold by our industry collaborator.

Clean combustion will be achieved by segmenting the combustor into distinct primary and secondary zones, and combustion air will be supplied by forced convection as opposed to natural convection in current systems. The combustor design will demonstrate a reduction in PM emissions by 25%–50% compared to the 2020 EPA emissions limits. Stand-alone power will be generated by solid-state TEGs integrated into the wood heater to ensure that a surplus of energy will be available to replenish the energy stored in a battery during the burn cycle. The electrical and thermal subsystems will be developed independently, and then the combined system will be integrated with the wood heater. Heat removal by radiation and natural convection will be supplemented on demand by convection heat transfer using strategically located variable-speed fan(s). The final system will demonstrate an increase in efficiency of 5%–15% compared to the baseline design. The wood heater will be automated through the evaluation of robust sensors, controller hardware/software development, and a smart control algorithm to convert sensor outputs into control signals to vary the speeds of combustion and convection airflow fans in real time. A prototype will be built and undergo extensive dilution tunnel (following EPA Method 5G) testing to optimize and quantify performance over the complete wood-burning cycle. The total cost of the wood heater installation is expected to remain within 10% of the total cost of the baseline system. The final prototype will be integrated with smart apps and will be ready for field-testing.

The wood heater developed in this project will operate at high efficiency and produce low emissions during all stages of the wood-burning cycle. The heat release rate in the wood heater will adjust to the heating load demand of the residence to always attain high efficiency. It will be a direct vent system, the first of a kind in the industry; replacing the flue pipe with a vent pipe will increase efficiency and save costs both for installation and maintenance. Results of the study will be widely disseminated to help the wood heater industry and the technical community at large.

Major participants of the project are the University of Alabama, Unforgettable Fire LLC (a small U.S. business with existing wood heater products in the market), and Virginia Tech.



COMMENTS

- Approach: The project approach aligns with the metrics defined under (FY 2021) Topic Area 4, DE-FOA-0002936.
  - Quantitative goals: room wood heater—2.0 or 2.5 g/hour (cord wood alternative) PM emissions limit; hydronic wood heater—0.1 lb/MMBTU PM emissions limit, or 0.15 lb/MMBTU PM emissions limit for forced air; amounting to a 25% emissions reduction and 5%–15% efficiency improvements Technical: Two-stage combustion gasification followed by combustion.
  - Fan-assisted heat extraction.
  - TEG to produce and manage power.
  - Automation for phase burning.
  - Project management: Virgina Tech CFD analysis.
  - DEI not mentioned.
  - Issues: Natural conversion control; catalytic high performance cost.
- Progress and outcomes:
  - The project is in the early stages and has just completed verification.
  - The team is using a component-level testing approach.
  - The baseline heater chosen is high efficiency, 1.3 g/hour and 79% efficient. This is a high-level baseline to improve beyond the market requirements.
  - The team installed a new katydid heater.
  - The team installed a soot measurement system.

  - Modeling prep work was conducted by partner Virginia Tech at the early stages.
  - The team created a 2D model, 3D concept, and fabricated a prototype.
  - The TEG design and prototype work was shared and tested to verify the vendor specification.
- Impact:
  - The project team has made significant progress in the very early phases of the project.
  - This is an expensive design but an exceptional project at a university that definitely advances the SOA and allows industry to pick and choose features that are commercially relevant. The team has high baseline and high performance goals, which is great, but they may be implemented in a smaller market. Nevertheless, the university project is on the right line. Something that might help the project and was highlighted by other reviewers as well is a focus on ash management and its impact on downstream TEG. Consider or estimate the use of wood as a fuel required for partial oxidation to overcome endotherm for gasification and its impact on overall efficiency. The DEI lacks details and is mostly built on Alabama University's existing practices. It is bit overlooked at the early stages of the project, and it can be improved.
- The project includes two universities and one company collaborating on a two-stage combustion process. The proposed heater includes forced air, two-zone combustion, TEG, and automation. The DEI plan is not very well detailed beyond working with university offices.
- Verification has been completed, and a prototype for their idea has been built. Work has been done on TEG and CFD modeling.
- The proposed furnace contains many key elements that will be valuable to better understand individually as well as in a complete system. The design is unique and complex on a technical level, relying on forced air, but it seems reasonably simple for a potential user.
- This is a good approach to looking at the combustion dynamics to craft a wood-fired system that is not normally employed in wood-burning operations. The team has made progress toward a prototype that will need validation, but they have a good plan for getting there. Some aspects of the downdraft combustion effort could improve overall efficiencies, such as heat transfer to the environment, and also augment heating the combustion chambers. The team has a good grasp of combustion issues and should be able to provide answers on the feasibility of this approach if they can get it all done. There is concern about the level of work to be done and the ability to complete it. There is little light on DEI efforts, i.e., they have offloaded that to others and perhaps need to take a larger role in that.
- The project, which started in December 2022, has completed initial verification, built a prototype of a dilution channel, and built a prototype wood heater to test individual improvements toward the goal of developing a two-stage combustion, automated wood heater with fan-assisted heat extraction and TEGs. The thermoelectric module has been designed, and preliminary laboratory tests have been conducted. Although the project is only within its first few months, it has been developing at an expeditious pace. The wood heater improvements are expected to reduce emissions and improve thermal efficiency relative to the baseline design of the industry partner. Ultimately, the results could be extended to new designs of other wood heaters, thus producing a useful impact throughout this industry. One weakness in the project's approach is their DEI plan. It appears to rely on existing efforts at the lead institution and nearby minority-serving institutions, which may cause an unjust burden to those who are working to improve DEI outcomes and who are expected to support the project without budget items allocated to their efforts. Beyond the intended engagement and recruitment of students from historically marginalized

communities in science and engineering, there is a missed opportunity to test unique ways to engage stakeholders who use wood heaters to meet their needs in the design of the autonomous wood heater or to identify ways to reduce costs in the final design so that the wood heater has commercial success if its target population is rural, low-income households.

- The DEI plan is quite weak and needs to be further developed. The integration of different unit operations is lacking, and the overall prototype design still needs to be optimized.