SYSTEMS DEVELOPMENT AND INTEGRATION PROGRAM

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

The Systems Development and Integration (SDI) Technology Area is one of 12 technology areas that were reviewed during the 2021 Bioenergy Technologies Office (BETO) Project Peer Review, which took place virtually March 8–12, March 15–16, and March 22–26, 2021. A total of 48 presentations were reviewed in the SDI session by five external experts from industry. For information about the structure, strategy, and implementation of the technology area and its relation to BETO's overall mission, please refer to the corresponding program and technology area overview presentation slide decks (https://www.energy.gov/eere/bioenergy/2021-project-peer-review-systems-development-integration).

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $157.3 million, which represents approximately 22.5% of the BETO portfolio reviewed during the 2021 Project 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 project management, 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 Liz Moore as the SDI Technology Area review lead, with contractor support from Remy Biron (BGS, LLC). In this capacity, Liz Moore was responsible for all aspects of review planning and implementation.

SDI REVIEW PANEL

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SDI REVIEW PANEL SUMMARY REPORT

Prepared by the SDI Review Panel

INTRODUCTION

The SDI team—previously Advanced Development and Optimization—is a platform for BETO to support the development of novel bioenergy technologies through verified testing and demonstration to drive the commercialization of these technologies and ultimately to support BETO's overall goal of enabling sustainable, nationwide production of biofuels that are compatible with existing transportation infrastructure. Within the SDI platform, there are currently 49 projects covering myriad technologies, readiness levels, and end users. Feedstocks range from biomass to bio-oils, and products range from drop-in fuels to improved monitoring and evaluation devices and processes. A common thread among all of them, though, is that BETO is looking to leverage prior research to accelerate commercial success across the entire platform.

Projects reviewed this year are funded under annual operating plan (AOP) and funding opportunity announcement (FOA) support from Fiscal Year (FY) 2016 onward, including Project Definition for Pilot- and Demonstration-Scale Manufacturing of Biofuels, Bioproducts, and Biopower (FY 2016); Integrated Biorefinery (IBR) Optimization (FY 2017); Process Development for Advanced Biofuels and Biopower (FY 2018); and the FY 2019 Advanced Manufacturing Office Multi-Topic FOA. Projects funded under the FY 2020 Scale Up of Bench Applications (SCUBA) were still undergoing validation and were not included in this year's review.

The SDI platform also covers the national laboratory process development units (PDUs), connecting industry stakeholders with abilities, knowledge, and resources to enable accelerated development and scaling through the "valley of death." These facilities include the Advanced Biofuels and Bioproducts Process Development Unit (ABPDU) at Lawrence Berkeley National Laboratory (LBNL), the biomass feedstock process demonstration unit at Idaho National Laboratory (INL), the integrated biorefinery facility at the National Renewable Energy Laboratory (NREL), hydrothermal liquefaction (HTL) at the Pacific Northwest National Laboratory (PNNL), and the thermochemical PDU at NREL. In addition to physical resources available for use, these laboratories produce analytical methods, process modeling tools, and other project analysis and evaluation processes for application across the entire portfolio of projects.

Traditionally, SDI, in its demonstration and market transformation and advanced development and optimization incarnations, linked other BETO platforms and consortia in one place that was right on the edge of commercial viability, pushing the lessons learned from these other platforms and consortia on the projects within its purview to help reduce risk and to accelerate commercialization. In its latest incarnation, SDI is doing this and supporting the development of models, simulations, test methods, and evaluation and development tools that clearly show the potential to make a positive impact on future project commercialization activities.

STRATEGY

Historically, the focus of this technology area was to support large projects to help achieve large-scale biofuels production. Today, although the goals have not appreciably changed, the scales and technology readiness levels (TRLs) have been reduced. Pre-pilot-, pilot-, and demonstration-scale projects are all considered within the program, which now encompasses projects with TRLs ranging from 4 to 8. At the lower end of the TRL spectrum are early research-and-development (R&D) projects from universities and research facilities as well as the national laboratory PDUs. The PDUs are clearly evolving as industry shifts directions, and during this review, they showed several major upgrades and changes to user facilities that should have long-reaching impacts on biofuels industry projects, both those that are DOE funded and privately funded. At the higher end of the TRL are several pilot- and demonstration-scale projects that show promise for getting large-scale biomass processing and biofuels production to market. With regard to funding, the balance of FOA and AOP support appears good and does a good job supporting open competition for projects to find grant funding via

FOAs while maintaining some funds for multilaboratory consortia that can be very effective; however, it is more important than ever that all projects show how they will reduce commercialization risk by eliminating barriers and making progress toward the BETO and SDI goals.

As the program evolves and administrations change, missions, goals, and targets may vary and complicate consistency, but the reviewers agree that the technology area has a good and clearly communicated strategy. The focus on early-TRL projects allows for the development of predictive models and computational tools that inform process design for pre-pilot- and pilot-scale projects; the focus on mid-TRL projects provides opportunities to utilize PDUs in the development of pilot- and demonstration-scale projects; and the selection of several late-TRL projects helps to leverage existing infrastructure and to provide projects the opportunity and guidance to create documentation and resources needed to procure commercial funding for the large-scale implementation of technology. During the review process, however, several things stood out:

- Several projects presented appear to have a direct overlap with work going on in other technology areas, including the Feedstock-Conversion Interface Consortium (FCIC). In addition, several projects within the SDI portfolio were clearly related but did not appear to be working together in any consistent or substantive way. There needs to be more transfer of knowledge among these areas to better leverage existing work and to reduce overall project risks.

- Although SDI has, for years, requested and considered industry and stakeholder input in developing strategy, FOA topics, and laboratory calls, there is an opportunity for a larger and more substantial role for stakeholders and industry to participate and better influence both program strategy and specific projects and laboratories. Industry involvement should prioritize current and future companies looking to commercially operate facilities instead of technology developers, although both should be welcome. One example of this is the deacetylation and mechanical refining (DMR) process, which is supported by BETO but shows little to no industry support for commercial-scale application.

- It was hard to identify the individual impact each project makes toward the BETO and SDI program goals, specifically that the projects understand the impact they intend to make and have identified a clear pathway to that impact. Projects often claimed success would achieve <$3/gallon gasoline equivalent (GGE) but never identified or quantified a means to do so. Whatever projects claim toward targets, there is an opportunity for all projects to identify upfront what sorts of lessons learned can be communicated even if the project fails to achieve complete success.

Overall, the largest gap visible in the SDI Technology Area is the clear communication by projects that the assumptions that have made have been or will be validated. Assumptions—whether technical, market, financial, or business—are meant to simplify preliminary efforts by reducing the quantity of unknowns faced during development. If these assumptions are not validated, projects may show a balance on a calculated sheet, but they must acknowledge that they still retain all that risk when scaling up.

STRATEGY IMPLEMENTATION AND PROGRESS

Most projects presented during this review process are a good fit for the portfolio and are clearly being managed well by both the principal investigators (PIs) and the SDI team. The projects represent a broad spectrum of approaches toward achieving the SDI goals and milestones, especially with regard to sustainable aviation fuel (SAF) production and improving biomass feedstock handling to achieve an inexpensive and energy-efficient means to getting biomass into conversion processes. Although the development of woodstoves may appear unexpected, reduction of greenhouse gas (GHG) emissions is a BETO goal, and inclusion of these projects is appropriate for the portfolio; however, several projects did not appear to support the SDI goals and milestones directly, or appeared strong but showed questionable impact on achieving those goals. The Review Panel made the following observations about projects in the portfolio:

- Projects in which the result is a computer-based tool for industry application are products much like process equipment and should be treated as such. Development should include clear industry and stakeholder input upfront as part of the project definition, as well as use case development and applications and end user development, and each of these items needs to be revisited repeatedly during the life of the project. If it is not clear not only why these products can be used but also how and by whom, their application will be limited, as will their impact on overall program goals.
- Several projects appear as though they will ultimately have low impact on the industry or its development. These projects are focused on developing a technology without a clear understanding of what industry is looking for or truly needs. These include some of the modeling and computer simulation projects, projects developing very expensive processes that require multiple coproducts to achieve some level of financial viability, and projects that either through fear of technology leakage or other confidentiality concerns could neither describe the process nor sufficiently support claims for evaluation.
- SDI's efforts to encourage demonstration-scale projects may be inspiring for the development of specialty coproducts at the expense of large-scale biomass processing to biofuels. Particularly of note are projects that are showing pretreatment processes with low impact on carbohydrate conversion to fuel products and instead focus on optimizing lignin, lipids, or specialty cellulose and carbon fiber products. Early-TRL projects such as these should be funded if they clearly inform the retiring of barriers but should not be considered for scale-up without significant techno-economic analysis (TEA) that includes validation of major assumptions.

Given the potential gaps in other BETO programs that feed projects toward the SDI portfolio, it can be difficult for SDI to be effective in developing and driving "leading-edge" projects. Occasionally, it may be necessary to consider funding "outside" projects to fill those gaps; these projects come with less prior diligence than those previously funded by BETO and carry greater risks. Within that constraint, SDI has done a good job selecting projects that can be particularly impactful. Examples include Forest Concepts' improved biomass feedstock handling and feeding engineering project, which is already showing significant impact on several other projects within the portfolio; NREL's coprocessing of bio-oils with refinery streams, which looks to accelerate the addition of biomass-sourced intermediates into existing transportation fuels infrastructure; and the T2C-Energy TRIFTS project, which converts biogas directly to a drop-in renewable diesel and has the potential to piggyback on the rapidly expanding number of commercial waste-to-energy projects.

With regard to meeting the stated program goals and targets, the current portfolio as presented is, unfortunately, difficult to evaluate. Overall, several projects look poised to help SDI and BETO meet the stated program goals and targets, but a considerable number have not demonstrated where the project fits in the big picture and what impact they will have on SDI's goals and targets. Although it has been the practice of SDI to request TEA within projects, TEA evaluation of projects continues to be weak, and most projects appear to approach the TEA as a means to justify achieving the minimum fuel selling price (MFSP) target by starting at $3/GGE and working backward. Early-TRL projects focus on developing tools, but they do not quantify the impact those tools can have, such as how much system downtime adds to MFSP and what portion can be ameliorated via an improved feeding system. Late-TRL projects, whether due to confidentiality concerns or an underlying misunderstanding of the methodology and purpose, are often not showing results that would support financing the construction of large-scale biofuels production facilities.

Finally, it is the assessment of this Review Panel that the SDI team is passionate, capable, and doing an excellent job managing projects within the portfolio. Where there appear to be difficulties with individual projects, the team is clearly working to assist and guide those projects in support of the technology area goal to assist in the commercialization of technologies to achieve large-scale biofuels production. Overall progress toward achieving the goals is good, as evidenced by the multiple projects presented that clearly show the possibility of financial viability at a larger scale of producing biofuels and bioproducts.

RECOMMENDATIONS

Following a thorough review and discussion of the 49 projects presented in the SDI portfolio, it is the assessment of the Review Panel that SDI is doing a good job of catalyzing the development and testing of bioenergy production technologies through multiple scales via project support and risk reduction methodologies. Along with that assessment, the Review Panel offers the following recommendations for consideration by the technology area to strengthen the portfolio in the near to medium term.

Recommendation 1: All projects must submit a detailed block flow diagram (BFD) or process flow diagram with quantified major inputs and outputs to show that they both understand where their project fits into the bigger picture and where proposed improvements will have an impact.

Although confidentiality concerns may play a role in reviewers not seeing these, it is the impression of the Review Panel that many projects do not supply these and cannot clearly explain where their project fits and how they will make an impact. For other technology areas, especially those at very low TRLs, it can be understandable that a project team might have difficulties here; however, commercialization projects should be able to supply and show an understanding of these basic documents.

Recommendation 2: SDI should publish a guide to conducting TEAs, require that projects provide them during validation, and reevaluate progress during the project lifetime.

Commercialization of any technology requires a clear understanding of both technical feasibility and financial viability. As projects at lower TRLs are accepted into the SDI portfolio, experience performing these TEAs may be lacking, and, as such, they may have difficulties showing pathways toward achieving stated goals and tracking progress toward them. Sensitivity analyses around TEAs are also excellent means of highlighting areas with the best opportunity to impact commercial potential. All TEAs submitted to SDI should list assumptions made and the plan to validate these assumptions to reduce the risk of scale-up.

Recommendation 3: Project closeout should include routine publication of lessons learned that will be beneficial to future projects, such as sanitized/anonymous compilations of TEAs clearly showing major targets for improvement and/or process and pathway guidance.

Failure is an integral part of the learning process, and engineering process and product development benefits from understanding why something has failed by designing around those failures in future projects. The routine publication and widescale dissemination of lessons learned after project closeout could have a major impact on guiding even projects that are not BETO funded. Whether the lesson is technical-, market-, or finance-based, future projects can see commercial deployment catalyzed by not having to learn all these lessons on their own.

SDI PROGRAMMATIC RESPONSE

INTRODUCTION

The SDI team would like to thank the Review Panel for providing their time and expertise throughout the 2021 BETO Peer Review process and for their significant feedback in the review of projects in the SDI portfolio. We appreciate the panel's comment stating that SDI has clearly communicated and acted upon its strategy to leverage prior research to accelerate commercial success across the entire platform. By interfacing with a wide range of competitively awarded projects at TRLs 3–8 and national lab AOPs, including a variety of consortia, the SDI program works to take the lessons learned from prior scale work to ultimately reduce risk during scale-up and to move these technologies toward commercialization. The Review Panel noted that in addition to SDI's traditional work de-risking technologies, its more recent work supporting the development of tools, models, and test methods is also an important step in moving toward commercialization.

AREAS OF CONCERN

In our review of the panel's summary report, we acknowledge the gaps that exist in the implementation of the SDI strategy, and we appreciate the panel for highlighting them so we may address them moving forward.

The first area of concern highlighted the importance of a balanced portfolio and the significance of ensuring that each project within the portfolio plays a part in the "bigger picture." The panel found difficulty in evaluating the SDI portfolio with regard to determining how some projects help meet the subprogram's goals and targets. There were also areas in which it appeared that the SDI project scope was overlapping with the scope of other BETO-funded projects. The Review Panel noted a need for ongoing knowledge transfer among projects after noting that some projects with clearly related scope were not coordinating with each other in ways that would provide lasting mutual benefit. In addition, the reviewers felt that SDI's focus on leveraging lessons learned should also apply to projects that are in progress and that there should be ongoing communications among projects in the portfolio to help de-risk these technologies.

The SDI team appreciates this insight from the reviewers and plans to address the main issue here by developing a true portfolio analysis process that would help us evaluate the strengths and weaknesses of the portfolio and better understand how projects are directly supporting our strategic goals. By performing this portfolio analysis on a regular basis, we can produce results that can be utilized by future Peer Review panels, inform our own decision-making process, and contribute to our strategic planning efforts and Multi-Year Program Plan (MYPP) development. We would also like to highlight that although we do encourage inter-portfolio communications through activities such as the PDU Working Group, the FCIC, and other multi-lab projects, we do see an opportunity for communications between individual projects or non-partnered entities that could be leveraged in the future. Moving forward, we will aim to find more effective methods to help these projects share new information, disseminate lessons learned, and coordinate in ways that will help overcome barriers to commercialization.

As a second area of concern, the reviewers felt that in encouraging demonstration-scale projects, SDI may, in turn, be promoting projects that favor bioproduct development over large-scale processing of biomass into biofuels. The panel emphasized that some projects favored pretreatment processes with low impact on carbohydrate conversion to fuel products and instead were focused on optimizing lignin, lipids, or specialty cellulose and carbon fiber products. Within a similar vein, the reviewers also observed a disconnect between the focus of some projects and the current direction being taken by industry and noted that the SDI could provide a greater push to commercialization for biofuel technologies by involving industry partners that focus on commercial operation of facilities rather than on technology developers.

The SDI subprogram understands the importance of industry engagement, especially because SDI works to support technologies further along the TRL spectrum. We work to ensure that industry has the opportunity to provide input through public workshops, during the independent review of proposals for competitive solicitations and national lab AOPs, and via feedback through this Peer Review process. BETO and SDI regularly incorporate stakeholder feedback into strategic planning efforts and will continue to work to ensure that projects within the portfolio are well positioned to share knowledge and transfer technology to industry for commercialization efforts. To this effect, SDI makes a best effort to award projects across the TRL spectrum, from lower-TRL unit operations through demonstration-scale biorefineries. We believe that it is important to award projects focused on the design and operation of integrated facilities, but also to support technology development that can increase efficiencies of individual unit operations. Through stakeholder engagement and industry coordination, we work to identify existing barriers to commercialization; and through our funding solicitations, we target technologies that are primed to address these barriers. Our projects work to scale up these individual technologies and integrate them into pre-pilot-, pilot-, and demonstration-scale plants.

In the overall review of the SDI portfolio, the Review Panel provided **three** recommendations:

Recommendation 1: All projects must submit a detailed BFD or process flow diagram with quantified major inputs and outputs to show that they both understand where their project fits into the bigger picture and where proposed improvements will have an impact.

The program thanks the reviewers for this recommendation. It is a documented best practice within SDI to require a BFD as a deliverable for full application to BETO-funded solicitations, but we will take the feedback from the reviewers and continue to adapt this requirement to ensure that we are requesting the best and most pertinent data from our projects. By combining this requirement with our plan to implement a portfolio analysis process, we can help projects better understand where they fit into the technology pathway and help BETO understand where projects fit into our strategic vision. We believe that it is important that our projects not only advance the state of technology (SOT) for the unit operations relevant to the project, but also that these improved unit operations can be integrated with the biofuels/bioproducts production pathway.

Recommendation 2: SDI should publish a guide to conducting TEAs, require that projects provide them during validation, and reevaluate progress during the project lifetime.

Standardization of TEA development would be extremely beneficial for our projects. We understand the importance of standardization when drawing comparisons among TEAs for similar technologies or pathways. SDI, in collaboration with the other BETO subprograms, will publish a guide to conducting TEAs, require that projects provide them during validation, and reevaluate progress during the project lifetime. As a focus of this guide, we will work to ensure that all assumptions are clearly documented and validated and that projects no longer “work backward” from an MFSP target in order to guarantee a result.

Recommendation 3: Project closeout should include routine publication of lessons learned that will be beneficial to future projects, such as sanitized/anonymous compilations of TEAs clearly showing major targets for improvement and/or process and pathway guidance.

The SDI team agrees with this recommendation and recognizes the importance of disseminating lessons learned to the industry as a whole. Through federal reporting requirements, BETO requires publication of final technical reports through the Office of Scientific and Technical Information during project closeout. These final reports are free of proprietary information but include highly beneficial lessons learned that can be accessed by the public. To increase access to this information, SDI will publish an annual compilation of lessons learned from these projects. The compilation will include lessons learned from projects across the BETO portfolio, and it will be shared among our projects as well as disseminated to a larger audience, including academia and industry. The SDI team values information sharing and believes that dissemination of this knowledge is integral to our overall goal of de-risking technologies. We will work to ensure that stakeholders are aware of these resources, and we will encourage our projects to adapt their approach as new lessons learned are released.

CONCLUSION

Again, we thank the Review Panel for their thoughtful review of the projects within the SDI portfolio and for taking the time to engage with our project performers during the 2021 BETO Peer Review. Your insightful questions and detailed feedback have provided the SDI team the opportunity to reflect on the strengths and weaknesses of the portfolio and to reassess our approach to meeting our strategic goals. The recommendations given by the panel have been well received by the SDI team, and we will work to incorporate them into our management of existing projects in the portfolio as well as for future projects. We look forward to the 2023 BETO Peer Review, where we will highlight the growth of our portfolio during the next 2 years, and to finding new ways in which we can improve our work.

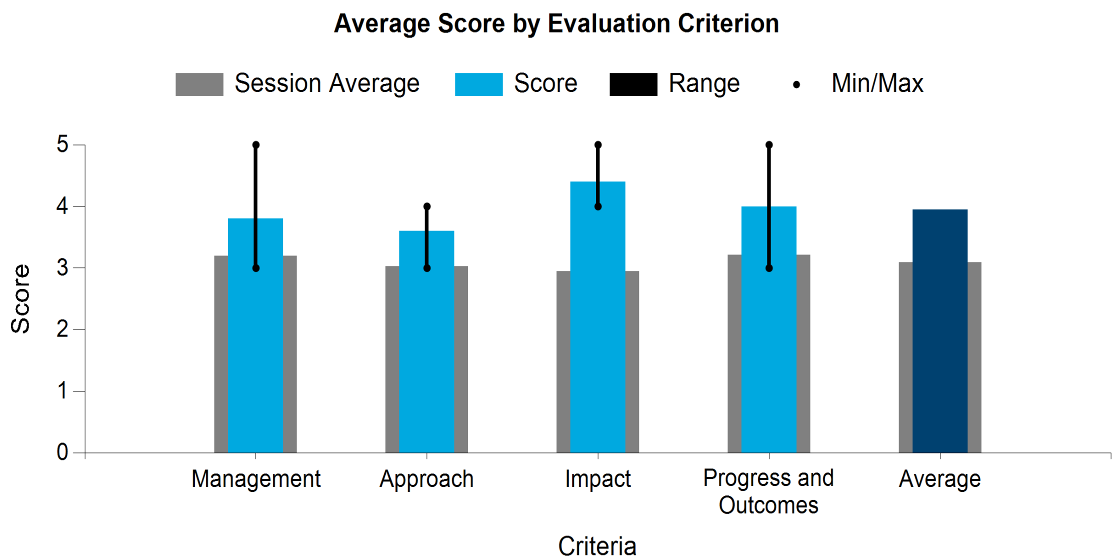
BIOMASS FEEDSTOCK NATIONAL USER FACILITY UPGRADE

Idaho National Laboratory

PROJECT DESCRIPTION

WBS:	1.2.3.10
Presenter(s):	Luke Williams
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$15,000,000

The purpose of the Biomass Feedstock National User Facility (BFNUF) upgrade is to expand upon the uniform format processing of the original user facility design. This upgrade is taking place in three installments of $5 million over 3 years and seeks to transform the BFNUF into a user facility that can transform any waste material into a conversion-ready feedstock. These feedstocks will have improved flow properties, less variability, and reduced scaling risks to achieve the greatest positive impact on the problems that exist in the current bioenergy industry. The main challenge of this upgrade will be anticipating all the potential waste streams that could be transformed into feedstocks and the variety of downstream conversion process needs. This challenge is being addressed by holding broad stakeholder workshops and individual interviews to gather feedback on potential waste streams, conversion methods, and possible contaminants. The outcome of these stakeholder interviews has been a facility design that meets user needs by being flexible enough to operate at a variety of scales while having wide-ranging analytical capabilities and the ability to scale up processes. Currently, more than 80% of the equipment purchased in the first round of funding is on-site, and capabilities in particle size control in three dimensions and fines analysis, among other processes, have been completed.



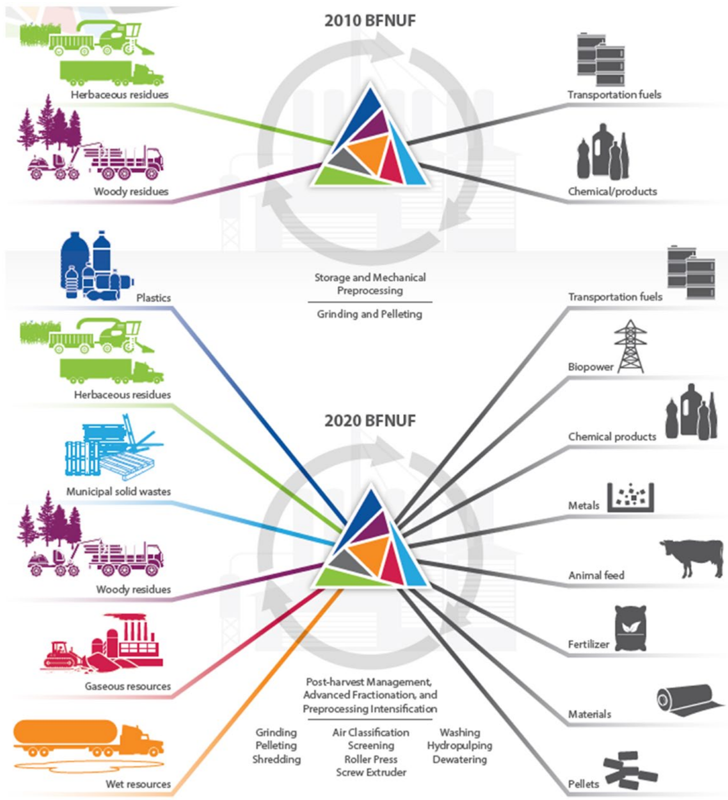


Photo courtesy of INL

COMMENTS

- This is more than an appropriate upgrade of the BFNUF. It is somewhat unclear who the external stakeholders are: How were they selected? What is the TRL? What are the different scales, such as waste industry, universities (small scale)? What is the customer target? Are all wastes to all specs? What are the cost/throughput targets? Is it too much change? Is it doable?

- It is not clear if there are any projects in industry or within BETO that drove the need to upgrade the facility. Specific examples would be of benefit to understand the approach to the upgrades. The process of determining what new equipment is purchased by the PDU was not discussed. There is a risk not mentioned in the presentation that the equipment at the PDU will not be of interest to industry. It is not clear if any new process design is required for the municipal solid waste (MSW) processing or if BFNUF is using designs already used in recycling facilities. The project has done a significant amount of work gathering user feedback and incorporating that feedback into their design. Management has correctly believed that the time and effort required to properly build this facility was worth the investment. The new facility appears to focus on fractionated feedstocks, but the presentation did not state whether the system will be set up so that the same analytical techniques can be applied to feedstocks and systems that cannot or will not afford the upfront capital. The presentation stated that there was a desire to be flexible in the setup, but it did not discuss how that would take place physically at the BFNUF. It is not clear if equipment is readily mobile or if units can be integrated like Lego blocks together. Original equipment manufacturers (OEMs) did not appear to be involved in the design. Many other projects are working toward the development of proper mechanisms of corrosion (MOC) for equipment. It is not obvious whether any of the upgrades specifically work to evaluate MOC. Hopefully, BFNUF is not entirely focused only on what facilities should do, but also on what they are likely to do, and have not rid the facility of valuable units of operation, such as the hammer mill. Specific examples provided of potential feed systems show a good range of the diverse, upfront work that this facility can do. It is not clear if and when the data management system will be integrated with FCIC Task 8.

- The workshop findings (slide 4) were hardly surprising and would not have been surprising a decade ago, but that does not make them any less true, and continued upgrading of the BFNUF to help deal with them makes tremendous sense. The team has done good work in surveying stakeholders. There is clear progress on broadening the capabilities of the BFNUF. It is appropriate for two-thirds of the way through. This is an exceptionally valuable facility, allowing many users who would otherwise be lost in the feedstock preprocessing area access to expertise and a wide range of equipment. Expanding it to meet the expanded feedstock interests of BETO is money well spent.
- This project has a clear focus, an excellent approach, and it shows a clear impact to industry upon completion. The analogy of the grist versus roller mill is apt, and it looks toward the future for application beyond typical biomass feedstocks.
- This project has the potential to be very high impact because feedstock handling and feeding is a huge issue in biomass projects, and the project team appears to be making excellent progress toward their goals. The approach may need to be revised because it is unclear that the scope is sufficiently limited. It appears that the project wants to be able to process all feedstocks for all comers, which is not possible. Further, although the project states that there are methods for narrowing the scope and ordering priorities, the process for doing this was not outlined. Finally, the management plan needs development. The project structure seems limited—a plan based solely on the size of or feedstock feeding speed does not seem appropriate. No communications plan was outlined, nor were handoffs outlined. It is difficult to see if the project is meeting its milestones.

PI RESPONSE TO REVIEWER COMMENTS

I thank the reviewers for the positive feedback on the appropriateness and need for upgrading the BFNUF. Questions related to our selection of stakeholders, the determination of needed equipment, and the facility capability requirements are addressed below. The external stakeholders are broadly covered by national lab, university, and industry partners. This inherently covers a wide range of TRLs, roughly from 1–5, and a variety of waste materials that could be transformed into feedstocks for a variety of conversion processes. Although all these partners were offered a seat at the table during the recent workshop, the bulk of the outreach was directed toward industry and evaluating their needs. Reaching out to industry and focusing on more industrially relevant conversion processes should allow the new BFNUF to expand the base of research partners to higher TRLs that operate beyond the traditional national laboratory and academic groups. This industry outreach also allows us to focus on making feedstocks for more mature conversion processes, such as gasification, as opposed to only pyrolysis. Because many feedstock needs for "thermochem" processes are similar, we are hoping that the "all wastes to all specs" ends up following similar fractionation pathways for each conversion partner. Equipment was generally determined by trying to address a partner's needs, for example, on something such as particle size characterization, and selection was refined by discussion and sample testing with OEMs. Determination of our partners' needs occurred through workshops and interviews. These interviews led us to identify specific problem contaminants that needed to be removed, such as chlorine from MSW, which helped guide the equipment selection. The analytical systems being installed in the new BFNUF will be used to characterize all wastes that enter the facility before, during, and after processing. This broad characterization scheme will allow external entities to adopt processing strategies to meet their own requirements for feedstock quality and capital expenditures (CapEx) based on learnings from the BFNUF. Regarding the facility capability requirements, many of the units scheduled to be purchased as part of this upgrade are at a scale where samples can be manually transferred between various pieces of equipment and sampled for analysis. So, in a sense, they will be able to be connected like Lego blocks. The goal is to work with OEMs to make sure that we understand equipment capabilities well enough that we can also scale up feedstock production from the kilogram scale to the ton scale for testing promising preprocessing methods. Some of the larger-scale PDU equipment from the first build (such as the pellet mill) is mobile and can be loaned to industry as needed. Note that the upgrade is not looking to evaluate specific materials of construction as much as making sure that we have the ability to investigate material wear through techniques such as microscopy. If industry wants to test a specific material of construction, we have the ability to swap out parts (such as hammers in a mill) to test various materials and report back.

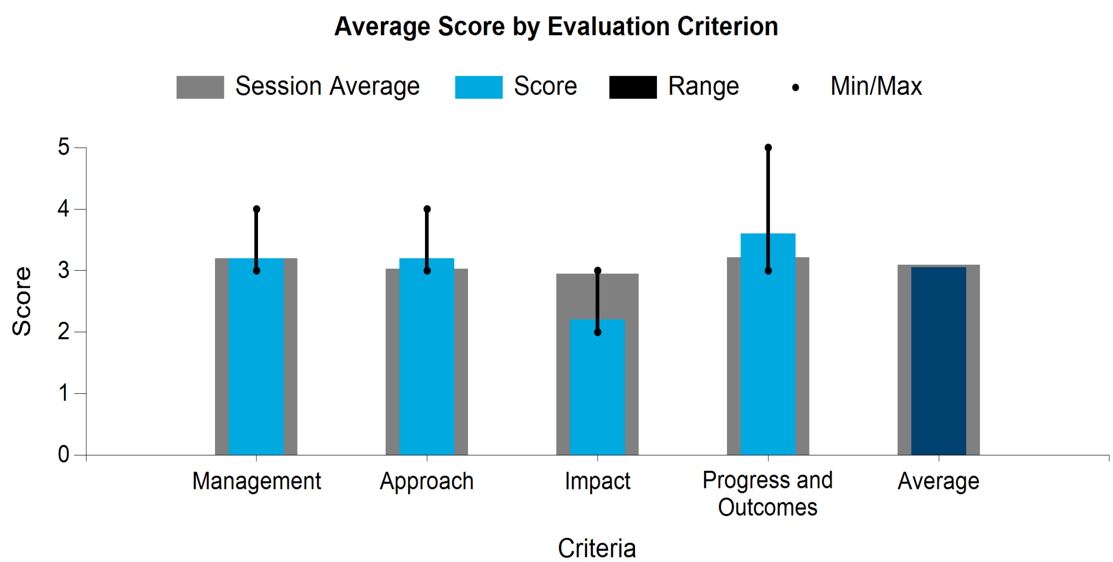
INTEGRATED COMPUTATIONAL TOOLS TO OPTIMIZE AND DE-RISK FEEDSTOCK HANDLING AND HIGH-PRESSURE REACTOR

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.1.1.001
Presenter(s):	Peter Ciesielski
Project Start Date:	10/01/2017
Planned Project End Date:	12/31/2020
Total DOE Funding:	$2,251,667

Biomass feedstocks exhibit inherent heterogeneity and vastly different materials properties from common granular feedstocks for which many solids handling unit operations were designed. These features have proven a significant impediment to the implementation of robust, continual biomass feeding systems for second-generation biorefineries. To address these challenges, we are developing integrated, experimentally validated simulations for several common feed handling and reactor feeding systems. We are building upon previous investments from DOE that developed state-of-the-art (SOA) modeling and simulation tools under the Consortium for Computational Physics and Chemistry (CCPC), the FCIC, and other BETO-funded projects. We are leveraging and extending these tools to model the solids handling processes that constitute the front end of the Red Rock Biofuels (RRB) gasification and Fischer-Tropsch conversion process. This key partnership facilitates experimental validation of the simulations and provides immediate impact whereby the resultant models are being used to optimize and de-risk commercial-scale deployment of the RRB process. Specifically, we are developing simulations for the feed hoppers, compression screw feeder, and conveyor/pyrolyzer units employed in the RRB process. The parameterization of these models for feedstock-specific scenarios have been informed by multimodal characterization of the structure, physical properties, and flow behavior of various feedstocks. This validated simulation tool kit can be generalized to aid in optimizing and de-risking other biomass conversion processes that use these common solids handling/reactor feeding units. In addition, we will provide correlations that can be used to adjust optimal operating conditions based on feedstock parameters. This project is making substantial progress toward understanding and overcoming the barriers associated with handling and feeding biomass, which will facilitate and de-risk the commercial-scale deployment of second-generation biorefineries.



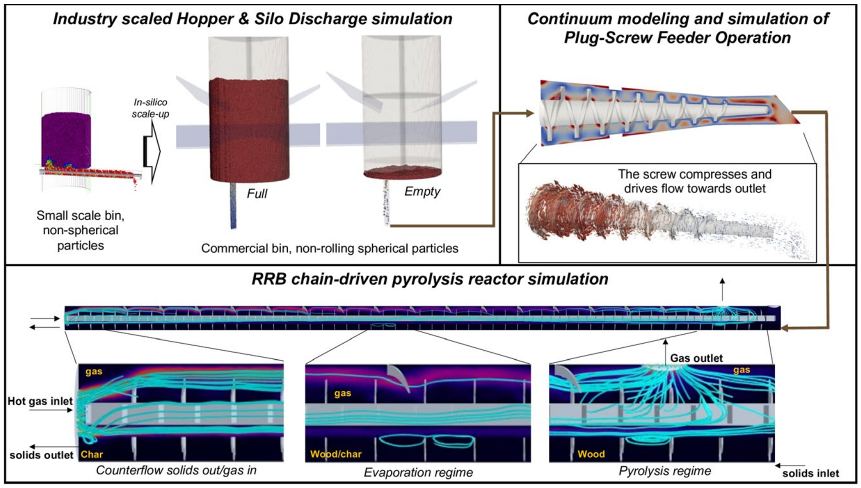


Photo courtesy of NREL

COMMENTS

- This is an ambitious project to use multiphysics modeling for biomass feeding and a high-pressure reactor. It is unclear that the level of computational complexity chosen for the modeling of these operations is justified through the actual results and the value added to the actual design of these operations. How did the team arrive at the balance between the computational complexity versus simpler but still rigorous modeling? What is the extra complexity achieving? One possible downside is the difficulty of generalizing the methodology beyond the currently targeted specific operations, units, and biomass definition. How is it checked that the selected characterization of the biomass feed is what is required to define this type of predictive model? The idea of generating simplified models from the more complex and computationally intensive ones is very reasonable, but what type and how these simplified models are defined and "fitted" was not clear. This is a fertile field, and I encourage the project participants to investigate the advantages and disadvantages to the well-defined and published existing methodologies.

- The management plan is a bit light for a four-organization group—industry, lab, academic—scattered around the country. The approach is solid, and the involvement of RRB, Jenike & Johanson, and Valmet is a plus. There is some issue of translation of the results to any other situation, but the approach should be of fairly general applicability. There has been a huge amount of work done in silo and hopper discharge, bridging, ratholing, flow regimes, etc. How unique and innovative is the approach here? In the high-temperature reactor modeling, it is difficult to see any chemistry explicitly involved. Even the finite element method (FEM) model appears not to have any terms accounting for the pyrolytic deconstruction of biomass. This is another project where the overlap with the FCIC is obvious. Is there any collaboration/communication? Where does this go from here? Will the models be widely available, or must each new project start from scratch with the approach developed here?

- The project looks well organized and executed. The table of risks and mitigation strategies was especially helpful. I would like to have seen more information on how tasks were coordinated instead of resumes of the team. One drawback of this project is its narrow impact and approach. The amount of resources taken—"pushing the envelope of…high-performance computing (HPC) resources"—seems to be too high for widespread use. How will these results be used outside of RRB? The approach was well thought out and executed. The validation of the high-temperature simulations will be very valuable. Again, however, it is unclear how this can be more widely used. The team mentioned two methods of modeling particles: spherical with high rolling resistance and glued spheres. It would have been nice to understand which model worked best under which conditions. Perhaps this can be a learning that is applied elsewhere? This is a nice project with excellent progress.

- This project is lacking in specific data to allow meaningful evaluation. Under impact, the team presented a table with no numbers on either axis, and the percentage of downtime increases the cost per gallon of fuel; however, what is the current state of the equipment? What level of improvement is needed to reach economic targets? And what progress has been made toward the level of improvement? In addition, it is unclear whether the findings will be shared with industry as a whole and whether the team is communicating with the other projects doing similar modeling work.

- What was the problem that led to this project? I did not see the problem as well defined. If lower packing density means less throughput, solving high moisture content would require less throughput and yield (slide 17). Reducing overall yield is generally an unacceptable solution in a *pro forma*, but the duration of this lower throughput was not discussed or how the system was going to identify high periods of moisture. High moisture content means more heat-up time? These insights are not very strong. But sometimes an experiment does not lead to new insights. Past attempts to solve the problem and the lessons learned from those attempts were not discussed. The presentation of the approach to this project would have benefitted by an understanding of the history of the project.

  The size range of particles in the simulation was not defined. If the model has been validated (slide 18), the presentation should have gone into the results of the validation test. From what was presented, it was not clear how the model was validated either in the setup, the execution, or the results. Only one set of data (on a screw) was presented, and it was not clear if that screw had a modified design, and if not, why the experiment was done in the first place. It is not clear whether a discrete element method (DEM) model is consistently used by Jenike & Johanson in other similar projects or why this effort was required here but not elsewhere. The method and manner of modeling chips have been done in collaboration with BETO teams doing similar work, but the approaches discussed by the groups are different. It seems this project could benefit from such a collaboration, but more information is needed to understand this relationship.

  The state of the RRB commercial project was not clear. The project appears to impact the selection of the capital equipment and design, which could be a material impact to that overall project. The relationship of torque developed on the feed screw was done empirically at room temperature. The results of this testing will be completely different at actual run temperatures, and it is not clear if the model will be developed to predict this impact. The duration of the validation tests was not made clear. It was not clear what design parameters were being tested or determined by the model. It appears it is sizing information, but without temperature effects, it is doubtful that the model will properly demonstrate actual operation. It is not a sufficient answer to explain that modeling is too expensive to include all the complexities if the complexities are what is causing the failures in the field. It is not clear what experiment or data resulted in the two approaches discussed in the presentation. It would be of benefit to understand the advantages and disadvantages of both.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their engagement and discussion during the virtual Project Peer Review meeting and for their follow-on constructive comments and questions. Responses to each set of comments are provided next. As for many projects with joint government and industry funding, some outcomes will be shared broadly, and some will remain proprietary. We anticipate that many of the methods and results for the flow modeling will be published in journal papers and released as open-source software. The pyrolysis modeling work involves details that are trade secrets. Nonetheless, some of the particle-scale pyrolysis models that were partly funded by this project have been published. We acknowledged in the presentation (slide 5) that the modeling work complements activities in the FCIC and the CCPC. The PI and the co-PI for this project have active involvement in both of those consortia and hence are leveraging knowledge gained across the projects. Unfortunately, there is currently not a forum for communicating findings between this project and the other projects funded via the IBR optimization program. Some comments and questions are mainly about the pros and cons of the physics-based computational models developed here compared to more traditional (and simpler) engineering models. This is a good point and one that we may not have fully addressed in the presentation.

Generally speaking, physics-based models can provide insights into complex phenomena, like those that occur in biomass processing, that simpler low-order and empirically based models cannot. The fully 3D simulations can be used to troubleshoot existing equipment and reactor designs in substantial detail as well as suggest new novel designs that have potentially increased performance. Although physics-based computational models may not be necessary for every unit operation in well-established process industries, lignocellulosic biorefining is a nascent industry that has experienced widespread problems with materials handling and reactor feeding, thus motivating the development of physics-based models for those unit operations. Unfortunately, the allotted 20 minutes did not allow us to report all the experimental work, including details of the validation studies. The DEM models of bulk material flow in hoppers and silos were validated against discharge from a two-story conical hopper. The computational fluid dynamics (CFD) models of flow in compression screw feeders was validated against the operation of two actual feeders: one at room temperature in a pilot-scale experiment and one in production. The kinetics part of the pyrolysis models was validated by small-scale experiments and was further supported by findings in related projects at NREL. When coupled with established physical models for flow, mass transfer, and evaporation, we have reasonably high confidence in the simulation methods.

The evaluation of moisture content was not as much about feedstock variation but to identify what moisture content the process should target. Jenike does supplement bulk material property measurements and engineering analysis with DEM simulations to help identify materials handling solutions, depending on the material and client needs. The team is aware of the large amount of existing work on the engineering and design of hoppers and silos. Milled biomass has been shown to challenge some of the assumptions commonly used in the established approaches. The DEM models used here can now provide predictions of flow phenomena that the traditional engineering analysis cannot, such as periodic slugging flow. The pyrolysis model makes use of an extensive set of kinetics equations that were left out due to space limitations. Please see the response about interactions with the FCIC and the public dissemination of the modeling methods. Although we plan to release the modeling methods via journal publications and as open-source software, the reviewer observes that the computational resources may limit their widespread use. We acknowledge that this is a valid concern. We encourage interested parties to partner with NREL or other DOE labs to further develop the modeling methods (if necessary) and perform simulations on HPC resources to meet their needs. The trade-offs between representative spherical versus glued-sphere particle approaches in the DEM models was partly explored by Lattanzi and Stickel. Further evaluation of the two approaches for predicting flow phenomena in a full-scale silo is being performed now.

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

Forest Concepts, LLC

PROJECT DESCRIPTION

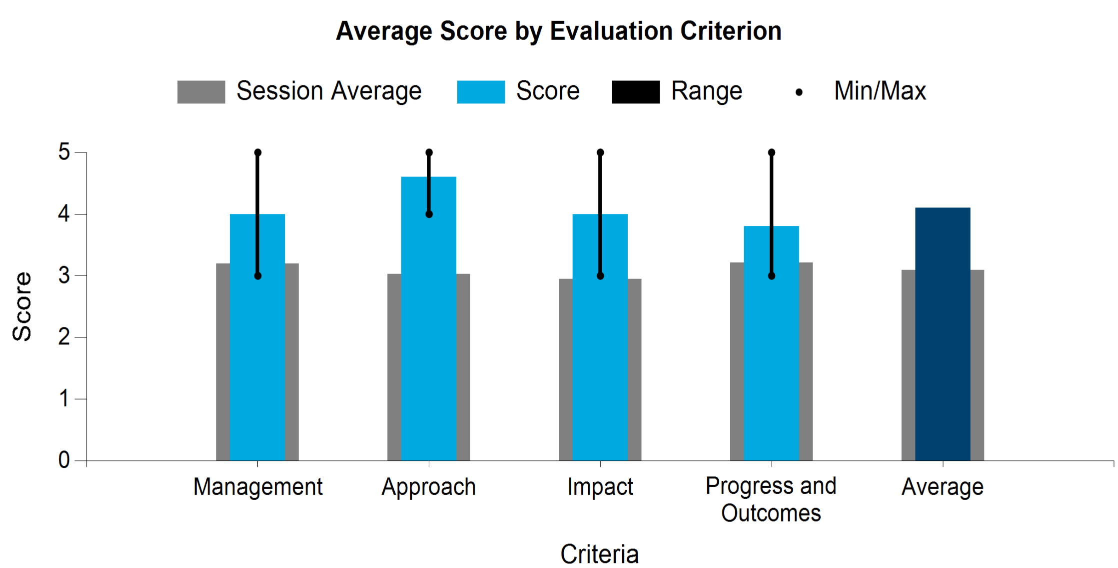
WBS:	3.1.1.002
Presenter(s):	James Dooley
Project Start Date:	06/01/2018
Planned Project End Date:	10/31/2021
Total DOE Funding:	$1,849,411

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 IBR.

The overarching goal comprises two subgoals: (1) develop and validate a comprehensive computational model to predict mechanical and rheological behavior of biomass flow to enable systematic and reliable design of a 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 [PSD], true density, bulk density, and moisture content) and external mechanical properties (including temperature and pressure).

The project team includes Forest Concepts, LLC, Pennsylvania State University, and Amaron Energy, Inc. 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. Amaron Energy provides biochar materials and industry perspective.

New equipment to be developed include a 250-mm cubical triaxial tester (CTT) to provide biomass mechanical properties data, a large gas pycnometer to quantify biomass particle density, and other lab devices to ensure simulations are populated with biomass-specific data. Biomass materials used in the project include milled wood chips and corn stover.



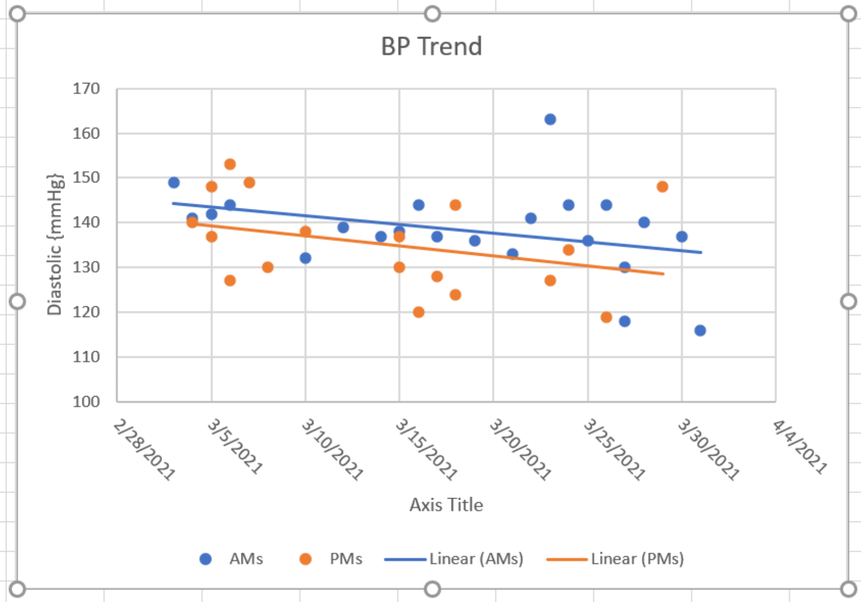


Photo courtesy of Forest Concepts, LLC

COMMENTS

- This is an excellent project that directly addresses a gap in the current technology and provides a solution to the industry as a whole. The presentation would have benefited from the addition of more economic analysis.

- This is an interesting project and a conceptual model of biomass ("cat fur"). Some of the assumptions and limitations of the approach are unclear from the presentation and slides. Some good insights are derived from the work (e.g., importance of flowability), but, in general, the experimental work and the data analysis look to be of higher quality than the modeling work.

- This is a solid management plan and outreach plan. Amaron Energy seems to appear on the title slide but not in the management plan? The new CTT and the plan for its use seem very promising. There is a trade-off with more fundamental, particle-based modeling, but it is probably much more practical for commercial design and operations. The flow models cover a range of those applied practically in multiple industries, and may extend well beyond biomass, or at least beyond to the sort we see in biofuels production.

- The diameter of the biomass selected did not reflect the full size range used in industry (up to 50 mm). It is not clear why the project limited itself to the 6-mm biomass size. Many gasification projects utilize chips up to 50 mm. Although Forest Concepts is working with the FCIC group, it is not clear if there was knowledge sharing between the FCIC and this project despite it being a goal (slide 4) of this project. It is unclear what features or attributes of biomass were not covered by existing lab protocols or test devices at the start of this project—i.e., it is not clear whether the bulk flow properties of powders apply to biomass or whether these properties have proven to be insufficient to characterize biomass flow. The project is validating their model at multiple facilities and comparing the results and methods used for the validation. This is an excellent approach. It would be good to coordinate the testing limits with others in BETO to ensure that the temperature range is relevant to all upfront equipment. There is a concern that 150°C is not high enough for screw feeders or other equipment connected to high-temperature reactors. It was very well explained why the new equipment was selected, how it is used, and what it can provide. But it was unclear whether there have been failures in industry that the team can point to for the incorrect measurement of these parameters. I appreciate that risk management was shared. The project appears to be task orientated toward resolving risks and challenges in this project. Collaboration with ASTM or other protocol-developing bodies is not part of this project. If the methods used are an improvement, then these methods can and should become part of a new testing standard.

- This project is well organized and executed. The approach is especially well thought out and is likely to be very impactful. Focusing on developing parameters for current, widely accepted, and widely used flow models is an excellent method to enable industry to attack and overcome the well-known biomass flow issues. That the team developed a testing apparatus that can measure these properties makes the project even more valuable and meritorious. This is an exceptional project and one that should be a model for other projects.

PI RESPONSE TO REVIEWER COMMENTS

- The project team thanks the Review Panel for their time and thoughtful comments. The focus of our proposal and project is to enable the use of existing bulk flow models by quantifying biomass mechanical and physical properties across a range of temperatures and pressures typical of feedstock handling systems. Unfortunately, existing powder and soil property testers are not scaled for use with comminuted biomass feedstocks with particle sizes ranging from 1–30 mm and having the high elasticity and plasticity of biomaterials; thus, we focused our efforts on the laboratory devices and protocols to characterize milled biomass mechanical properties needed for simulations and models. Known bulk flow models were used to validate the utility of the measured properties with typical feedstock materials handling equipment. Other projects funded by this same FOA are more focused on model development and the simulation of flow within conversion facilities. We developed a CTT to measure stresses and strains in three orthogonal directions to overcome a shear cell limitation of only measuring in one confined plane. The CTT was scaled to work with the full range of common biomass feedstock materials, including fuel chips. The materials chosen for this project are the preferred species and particle sizes for ongoing biochemical and thermochemical research funded by DOE BETO. Their use leverages prior data sets and provides direct comparison to modeling efforts by the Purdue IBR project. The project team fully expects to evaluate a wider range of particle shapes, sizes, and species once this proof-of-concept work is complete. The existing CTT device and model development are currently focused on moderate temperature (<150°C) and moderate pressure (<350-kPa) flow regimes typical of feedstock handling systems. They also fully cover the flow regimes of the biomass infeed and biochar outfeed of cooperator Amaron Energy's fast pyrolysis system, as well as Forest Concepts' own feedstock production equipment. The Forest Concepts prototype CTT is a first-of-a kind device, never before used with biomass feedstocks. Data gathered from more than 250 test runs are proving the efficacy of the device to produce bulk material parameters needed for flow modeling. The market transformation plan anticipates that market prototypes and commercial versions will be appropriately specified and scaled based on voice of the customer and appreciative design methods into a family of products that meet the needs of various sectors of the emerging bioeconomy.

INTEGRATED PROCESS OPTIMIZATION FOR BIOCHEMICAL CONVERSION

University of Arkansas

PROJECT DESCRIPTION

WBS:	3.1.1.003
Presenter(s):	Sandra Eksioglu
Project Start Date:	04/01/2018
Planned Project End Date:	03/31/2021
Total DOE Funding:	$1,999,999

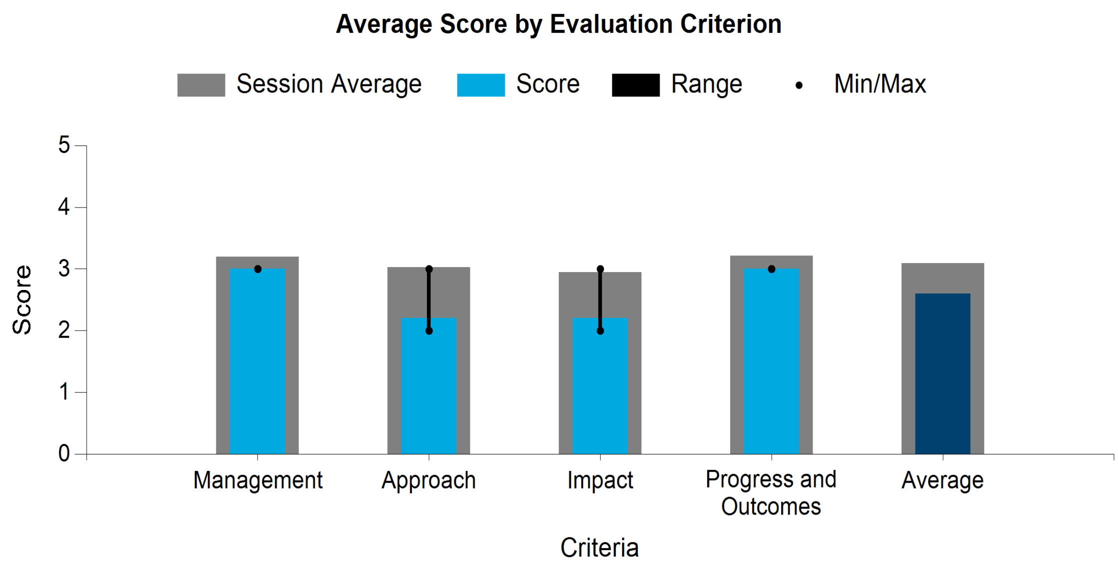
The main objective of this research project is to develop analytical tools to enable a biorefinery to identify an optimal integrated process design that ensures a reliable, cost-effective, sustainable, robust, and continuous feeding of biomass feedstocks to achieve the design throughput of the reactor.

The analytical models developed include the DEM and the mathematical optimization models. DEM models provide functional relationships between biomass characteristics (such as moisture level, density, and PSD) and biomass behavior (such as flowability, size reduction, and failure) in processing equipment. Specifically, bonded-sphere DEM models are developed and validated. DEM-based regression functions are then developed for predicting bulk density (used to quantify flowability and calculate the limits of the equipment capacity) and size reduction, which are needed by the mathematical model. The mathematical model takes a systems view of the processes to identify (1) optimal process parameters to ensure a continuous flow of biomass to the reactor; (2) optimal buffer location and size to optimize costs, equipment utilization, and throughput; and (3) blendstocks that ensure system requirements are met in the face of biomass quality variations.

Experimental and numerical analysis motivated the proposed changes to the current approach of controlling the process. The proposed process control: (1) sequences bales based on moisture level; (2) incorporates additional storage in the system; (3) drives the infeed of bales in the system based on inventory level and target rate of the reactor; and (4) uses different feedstocks to meet the process requirements with respect to ash and carbohydrate contents.

A systematic and quantitative evaluation of DEM performance against analytical, empirical, and experimental results/data at the particle, lab, and PDU scales have shown that the model can accurately predict biomass particle behavior in the proposed process and meet the criteria set in the go/no-go decision points. For the mathematical optimization models, we conducted an extensive numerical analysis using historical data from the PDU at INL. These results indicate that (1) the proposed system control leads to a 7.5% reduction in the unit cost and processing time of biomass compared to basic control; (2) short sequences of bales, created based on moisture level, lead to reductions in processing time and cost; and (3) blending biomass allows the system to meet process requirements at all times.

Analytical results from the models will be validated at a PDU at 1 dry ton/hour for 2 weeks. This technology will be tested on corn stover, switchgrass, and miscanthus. The analytical models will be integrated into an alpha version of a cloud-based decision support system (DSS), which will be available on the web and free of charge. This DSS will serve as a training tool for bioenergy stakeholders (industry practitioners, government, academia, etc.).



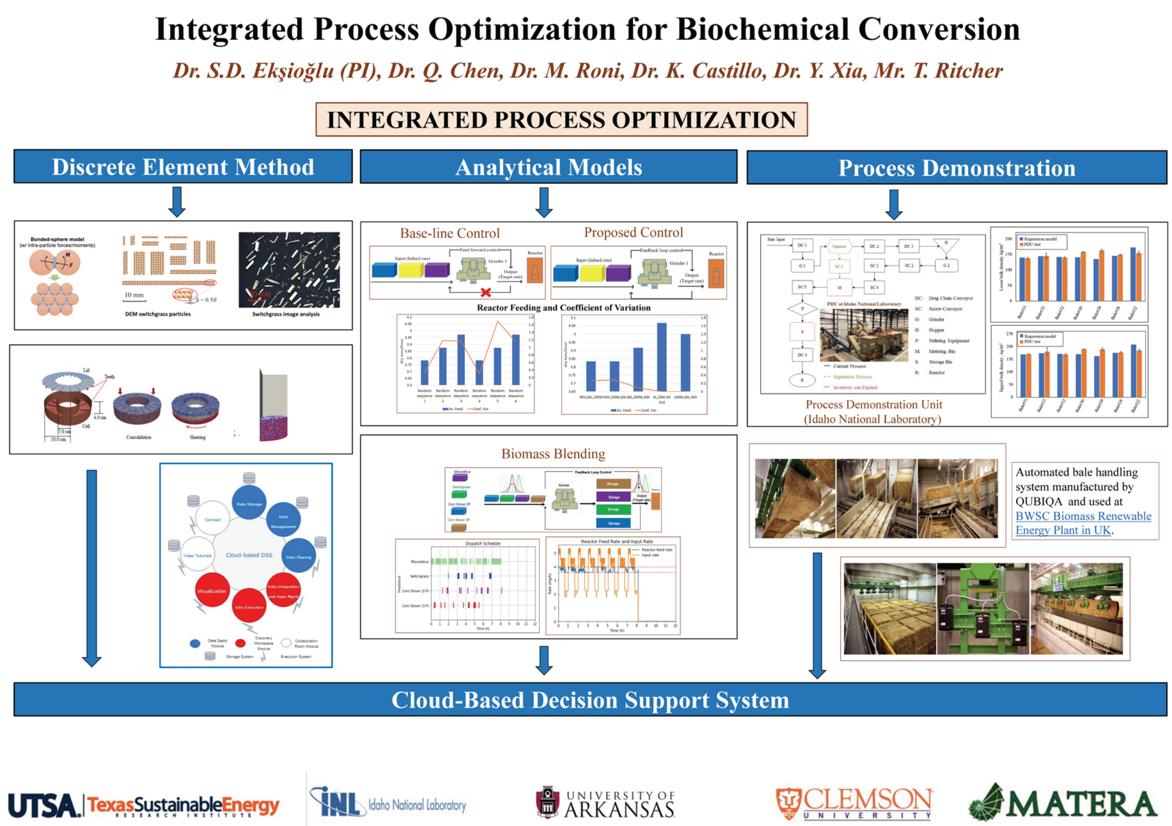


Photo courtesy of University of Arkansas

COMMENTS

- This is an interesting project looking at bale feeding and sequencing options. The stochastic modeling approach looks to be the right way to go, after the deterministic model has been fully validated. There are some questions on how different but similar bales (old versus new, wet versus dry) should be addressed and identified.

- The management plan seems a bit superficial for five organizations in four or five different states, universities, and labs. The industry bale sequencing seems very unlikely to be feasible in a typical biorefinery, and it is, in effect, transferring quality control responsibility to the receiving party ("customer"), which is exactly what we are taught is the wrong approach in quality assurance. The supplier should be responsible for quality control, even if the supplier is simply another functional group in the same organization. Given the pace at which material will arrive and be temporarily stored and processed, it seems unlikely that this sort of automated selection process can work. A 1,000-ton-per-day biorefinery will receive 25–50 semitrucks/day, 24/365, and just the geometry of stacking, testing, and moving the bales to the feeder will be hectic enough without on-the-run quality control and sorting. There simply is not an indication that this will be practical in the real world.

- The project appears to have met its initial goals with respect to the DEM model. This will be especially useful. The jump from the DEM model to the analytical model seems huge. It is unclear how they are connected. Is the information developed with DEM even used in the analytical model? A better connection should be shown. In fact, the analytical model said that lack of data was a big hurdle in the analytical modeling. Why wouldn't the DEM be used to aid the second stage of modeling, or was it? With respect to the analytical model, it is unclear if the project will have a significant impact due to issues with scaling up. Right now, the only scale-up goals with the project are to the pilot plant level, but that will not be sufficient. The need to move large amounts of baled feedstocks in a large biorefinery is a significant issue and will not be addressed. Although the researchers point out that technologies such as radio frequency identification (RFID) are used in consumer industries, such as Amazon, it is unclear whether they will really be transferrable and/or sufficient. The potential logistical issues need considerable thought and attention. It is not even clear how the "blending" will occur. The management plan was not very well developed and could be expanded. No project risks were identified, and there is little, if any, collaboration with industry representatives. It looks to be siloed within the research community. On the positive side, I like that they are using different types of baled feedstocks, and it appears that they have shown that water content is the most important factor to control to ensure reasonable process performance; however, this conclusion should be more prominent, and, as noted, some discussion of logistics should be included.

- The project seems very focused with limited applicability. The bale sequencing concept, although good in theory, seems very impractical to apply at scale. As with several of the biomass properties models projects, it seems focused on macrophysical properties and considers neither chemistry nor microphysical properties, such as fibrils, that can impact flowability.

- It is unclear what validation testing has been done so far. Short-term reliability testing should not be confused with understanding the long-term reliability, which is what is put into *pro forma* modeling (or should be). Long-term reliability testing is needed as well. It is not clear if the model differentiates between intrinsic and extrinsic ash. Other FCIC studies have shown this difference to be critical in modeling reliability. There is an opportunity here to compare the bonded-sphere model against other models in the development elsewhere at BETO. It is unclear if this project is collaborating with other projects within the FCIC or BETO. Bale sequencing at a large scale appears to be an impractical methodology for a large facility. Other projects have demonstrated the necessity of multiple feedstock attributes to determine bulk flow. It is not clear what attributes are being modeled in this project and whether these are sufficient. It is unclear why the project believed there to be a lack of data for corn stover or biomass feed handling. Numerous projects have utilized the same feedstocks on DOE-funded projects. It is unclear which data they believed to be missing from the historical data set and whether the data could have been obtained by speaking with those other PIs. It is not clear what feedstocks are being studied—miscanthus, corn stover, and switchgrass are all mentioned in the presentation. It is not clear what problem or project motivated the combination of these feedstocks. It is not clear whether other factors are included in the model, such as ash content, carbohydrate content, pressure, and ambient temperature. Validation is planned for budget period three, but the overall validation plan (duration, etc.) was not available at this time. The project recognized the need for data at this stage; however, to develop models, it would be better if some validation testing were planned simultaneously with the ongoing modeling effort.

PI RESPONSE TO REVIEWER COMMENTS

- The research team thanks the reviewers for evaluating our project and the feedback provided. We have read and addressed the issues identified to the best of our abilities. This is the approach we followed in preparing this response. We have prepared three separate documents. First, we prepared this current document, which summarizes our answers to questions you asked. We try to keep our answers focused. Second, we prepared a data summary document, which summarizes the data we use. Third, we compiled two journal papers.

- Thank you for reviewing our project and for your feedback. The data we are provided with focus on moisture level of biomass feedstock, carbohydrate, and ash content. We do not have specific data about how long each bale has been stored. It is assumed that biomass is harvested and collected in the current season.

- Thank you for reviewing our project and for your feedback. Below, we summarize our response.

  Data used: The data sets we use are presented in the supplementary document attached to this report. Here, we list only the sets of data utilized in this study: historical, technical, process-related data for switchgrass. These data are collected at the PDU at INL. These data are grouped based on the moisture level (low, medium, and high) of biomass and equipment (e.g., grinder, pelleting, separation unit). The data consist of energy consumption, in-feed rate, density, etc.

  Data utilized for the TEA: These data are collected at INL's PDU and consist of purchasing cost, operation cost, energy consumption, and maximum operating capacity of equipment (grinders, conveyors, etc.). Energy consumption is grouped based on the moisture level of biomass.

  Biomass characteristics: These data are collected at DuPont and a report prepared by researchers affiliated with the SunGrant Initiative and INL. The DuPont data present carbohydrate and ash contents of corn stover two-pass and corn stover three-pass. These data are collected via sampling during the 2014 and 2015 harvesting seasons. The data from the SunGrant Initiative and INL present the distribution of ash and carbohydrate content of a number of feedstocks, including switchgrass and miscanthus.

  Visual description of equipment: We provide technical drawings, pictures, and dimensions of equipment in the PDU. This equipment is modeled in our analytical models.

  Data utilized in the DEM: We provide the data utilized in the DEM model, such as the physical and mechanical characteristics of switchgrass, the results of the compression tests, density, and PSD.

  Challenges with data collection: The following were some of the challenges we faced with data collection. We will explain the role of these data in refining the models we propose.

  - Equipment clogging: Equipment clogging is a function of many parameters (e.g., moisture level, ash content, PSD, equipment setting). Recording these data for different scenarios is challenging and requires additional efforts. For example, processing high-moisture bales for a prolonged amount of time and at a high infeed rate leads to clogging of grinders; however, the PDU operator, aware of this effect, adjusts the infeed rate of the equipment and controls the moisture level of the bales processed to reduce the chances of equipment clogging. Thus, we have only sporadic data, which is not enough to derive a model that describes these relationships. Additionally, were we to have data from a full-scale plant that operated 8 hours/day and every day of the week, we could collect data about equipment clogging to evaluate what other factors impact clogging.

- Lack of data related to miscanthus: There are no historical data at INL's PDU related to the processing of miscanthus. The models we propose are developed for and validated by using data from the PDU; thus, we have no technical and process-related data for miscanthus.

- Unit level-specific data that are needed for modeling: Let us give an example here. We wanted to model the relationship among equipment settings (e.g., infeed rate of the system, screen size, rotational speed of grinders) and PSD. To accomplish this, one should be testing the system (the PDU) using different combinations of infeed rate, screen size, etc. These data were not available at INL. DEM modeling needs mechanical characterization data to validate models; however, these data are scarce. Thus, there is a need for high-quality characterization tests, which are expensive.

Testing and validation: Our model validation process consists of two parts: (1) initially, we validate the performance of each equipment, and (2) next, we validate system-level performance. The focus of budget period one is on the development and validation of the DEM model. These are unit-level models. This validation was completed in budget period one. We presented the results in the first go/no-go review presentation. Our team met the budget period one go/no-go criteria. The focus of budget period two is on the development of the process control optimization model. This is a system-level model, which takes as inputs the unit-level equipment performances under a variety of process conditions. So far, the data utilized for the development of the process control model are validated at the individual equipment level (based on budget period one tasks); however, the system-level performance of the modeling results is not validated yet and will be part of the budget period three efforts.

The following summarizes the testing that has been conducted or is planned to be conducted soon. At the end of this document, we provide details about the tests we have conducted during budget period one and budget period two.

- Unit-level, short-term testing: We conducted 10 tests at INL's PDU during 2019 and 2020. These tests were used to collect data about (1) the bulk and tap density of biomass in bale format and after grinding and for different moisture contents, (2) the impact of screen size and moisture level on equipment clogging (SC-4 and DC-6), (3) the impact of screen size on pelleting, and (4) the impact of mill processing speed and moisture level on density.

- Long-term, system-level testing scheduled for June 2021: A total of 77 bales of corn stover, 44 bales of switchgrass, and 33 bales of miscanthus will be delivered to INL for processing. This amount of biomass will be processed within 80 hours at a rate of 1 ton/hour. The models developed will guide the processing of biomass. The data will be analyzed, and updates will be devised for processing of the next batch in July 2021.

- Long-term, system-level testing scheduled for July 2021: A total of 77 bales of corn stover, 44 bales of switchgrass, and 33 bales miscanthus will be delivered to INL for processing. This amount of biomass will be processed within 80 hours at a rate of 1 ton/hour.

Feedstock used:

- DEM model: The model is developed and tested using switchgrass. This is mainly due to the availability of data about switchgrass at INL.

- Process optimization model: The model is developed for switchgrass. We selected switchgrass because of the available data collected at INL. To develop this model, we used the technical, process, and cost-related data collected at INL.
- Biomass blending model: The model is developed using data about corn stover two-pass, corn-stover three-pass, miscanthus, and switchgrass. Above, we explain the data sources used for the biomass characteristics. In this model, we needed technical and process-related data about every feedstock; however, because we do not have such data for other feedstocks besides switchgrass, we assume the same technical and process-related data for corn stover two-pass, corn-stover three-pass, and miscanthus.

Modeling approach: In the proposed models, we consider only total ash content. The composition of ash (e.g., impact of intrinsic and extrinsic ash) is not within the scope of this research. The definition of the reliability of our model is "the probability that the system maintains a continuous feeding of the reactor to achieve 90% of the reactor's designed throughput." As such, the aim of this project is to address long-term reliability issues. Via our numerical analysis, we show how this can be achieved via careful planning of upstream equipment operations. As part of the statement of project objectives (SOPO), one of our tasks is to demonstrate a representative scenario (obtained from the modeling results) of a long-term reliability scenario. Via our numerical analysis, we show that the model can achieve a continuous feeding of the reactor. Details of this model and the results are presented in the manuscript that we are submitting with this document (Liu et al.).

Bale sequencing: Because most reviewers questioned the practicality of the bale sequencing, our answer to their questions is summarized at the end of this document to avoid repetition.

On the bonded-sphere model and collaboration: The bonded-sphere particle model used for the pilot-scale unit operation simulations in this project was adopted from the FCIC. The bonded-sphere particle model was first adapted to simulate fractured pine particles by an FCIC researcher (Dr. Xia of INL, also a co-PI of this project) and published in "Discrete element modeling of deformable pinewood chips in cyclic loading test" (*Powder Technology*) and later adopted by this project to simulate switchgrass particles and published in "Discrete element modeling of switchgrass particles under compression and rotational shear" (*Biomass & Bioenergy*). The pros and cons of the bonded-sphere particle model, as well as some other more advanced particle shape models, are discussed in the journal article published by FCIC researchers in "A review of computational models for the flow of milled biomass I: Discrete-particle models" (*ACS Sustainable Chemistry & Engineering*). The project co-PI, Dr. Chen of Clemson University, maintains routine communications with the FCIC and adapts the suitable FCIC modeling techniques for deployment in pilot-scale unit operation simulations. The developed bonded-sphere model is publicly available in the open-source code LIGGGHTS-INL, managed by INL co-PI Dr. Xia and hosted on the GitHub repository (https://github.com/idaholab/LIGGGHTS-INL), so other researchers can access and evaluate this model. The references to our published papers are also included in the repository.

Thank you for reviewing our project and for your feedback. In the following, we summarize our response.

How the DEM and analytical models are connected: The two models are connected in two ways. The data collected via simulations of the DEM model are used to develop a regression function that calculates the bulk density of biomass as a function of moisture level and PSD (quantified using size parameters D50, D90, and D10). The model is developed for predicting the bulk densities for cave-in-rock switchgrass after a grinder. The model also develops regression functions for cultivar. Another set of regression models for predicting bulk densities for switchgrass after a grinder is as follows: Biomass density is used to calculate the mass and volume of biomass in the system. This impacts the amount of biomass flowing in the system and the amount of biomass stored in the metering bin. Let *Xt* be the amount of biomass (tons) fed into the system in period *t*. Let *Vt* be the infeed rate (speed of the conveyor belt in m/min). Let *?t* be the mass of biomass per meter of conveyor belt. This value is impacted by the dimensions of the bale and by the density of the bale; thus, we calculate *?t* using the regression functions above. In the optimization model, we have: $Xt \leq\ ?t\ Vt$. This equation determines the maximum amount of biomass fed into the system in every time period. This amount is impacted by biomass density. Biomass density changes after grinder 1 and 2. Changes in density impact the volume that the product takes. The equipment has volumetric capacities. We calculate this capacity using the dimensions of the equipment and the biomass density; thus, in the analytical models, we ensure that biomass flow (*Xt*) in each equipment does not surpass this volumetric capacity as density changes.

Biomass density and flowability are affected by particle sizes, and grinder 1 and grinder 2 are the two main locations in the proposed system where particle size changes. DEM models will provide the output PSDs as a function of input particle size and grinder setting (grinding speed and screen size). These regression models will be used to estimate the volumetric capacity of the equipment (which is a function of particle size and density) in the analytical models. The following figure shows the simulation results of grinder 2. The rightmost figure shows the output PSD after grinder 2. (The figure is not included here; see the submitted document.)

The use of DEM in the second stage of modeling: Our response to Reviewer 2 lists the data we have and the data we are missing. We have also attached a document that summarizes the data we used in this study. We would like to point out that we are missing some unit-level specific data that we could have potentially used to refine our analytical model. Let us give an example: We wanted to model the relationship among equipment setting (e.g., infeed rate of the system, screen size, rotational speed of the grinders) and PSD. To accomplish this, one should be testing the system (the PDU) using different combinations of infeed rate, screen size, etc. These data were not available at INL. A natural question is: Why not use DEM models to generate these data? Unfortunately, we could not do that because to build a DEM model, verify, and validate this model, one needs data. For example, let us say that we have a few data points that tell us how the infeed rate of 1, 2, and 3 tons/hour and the processing speed of grinders 1, 2, and 3 tons/hour impacts the distribution of the biomass particle size. You can use these data to build a DEM model that simulates the relationship between infeed rate, the processing speed of the grinder, and particle size. This DEM model works well when the infeed rate and processing speed are within 1 and 3 tons/hour. The DEM model will not work for data outside this range. To summarize: We believe that the work we have conducted is online with what we had planned with respect to the DEM and analytical models. The truth is, during our research, we identified some excellent extensions of our models, which we would have liked to spend more time on. Were we to have detailed unit-level data, we believe we would have accomplished much more.

Practical challenges with moving large numbers of bales in a large biorefinery: The team researched automated materials handling systems. We found two companies that make automated materials handling systems that are currently used in biorefineries. This system allows biorefineries to handle up to 105 bales/hour. Details about the equipment manufacturers and the bioenergy manufacturers can be found at the end of this document under the section "Bale Sequencing." To summarize, the research team believes that the technology exists for (1) collecting data about biomass characteristics via RFID technology, (2) collecting data about the current status of the moisture level via sensors, and (3) sorting/feeding large numbers of bales of a particular moisture level via multiple feeding lines.

The use of RFIDs in the bioenergy industry: The team researched the use of RFIDs in the bioenergy sector. Based on this research, RFID technology is currently used by the European bioenergy sector. Work presents the design for a low-cost, miniaturized, chipless RFID tag for short-range biomass tracking and monitoring. An article published in *ArgiTech Tomorrow* talks about the use of RFIDs in the agriculture system. The article states, "Bales of hay can be tagged, capturing the date harvested, the field where it was harvested, the temperature, weight, moisture level and the nutritional information to be captured and stored. RFID has many potentials that busy farmers are seeking." Equipment can read RFID cards in incoming bales. Processbio is the company that produces this equipment. Please read our section about "Bale Sequencing" at the end of this document to see how this equipment and other equipment produced by Processbio are used at Sleaford Renewable Energy Plant in the United Kingdom.

How will the blending occur? We expect that processed biomass of a particular biomass type will be stored in dedicated bins. A mix of processed biomass will be fed into the reactor in every time period to ensure that the blend meets the biochemical conversion specifications as designed by NREL. These specifications are a total structural carbohydrate of 59.1%, 5% ash content, and a moisture content of 20%. The models we propose capture these requirements.

Management plan: The PI and co-PIs of this project meet every other week. During these meetings, we discuss the progress of the work of different tasks. Task-specific teams meet weekly to discuss the progress of work. The team communicates regularly via email. The team met in person two times, both at INL. Two postdoctoral students have spent extensive periods of time (more than 6 months each) at INL, Clemson University, and the University of Arkansas. This has helped in collecting data, developing models, and writing papers.

Project risks: The main risk we faced relates to data collection (as outlined in our response to Reviewer 3).

Collaboration with industry: The project team is working very closely with researchers and the PDU operators at INL. The research team has been in conference calls and face-to-face meetings and has exchanged numerous emails with the INL team. The project team has also identified an advisory board consisting of Dan Burciaga, Steve Hartig, and Glenn Farris. Members of the advisory board have attended conference calls with the team and the DOE program manager. The team has discussed the models developed and the practicality of these models with the advisory board. Dan Burciaga leads the ThermoChem Recovery International (TRI) commercialization and technology development. He has expanded its scope to biopower and biorefineries with a focus on integrated facilities for optimum economic performance. He has more than 30 years of experience in technology development, engineering services, operations, and construction. Steve Hartig is an advisor consultant at Hartig and Associates. He has broad experience across biofuels, specialty materials, polymers, chemicals, and in multiple industries, including the industrial, automotive, electronic, biomedical, and coatings fields. Glenn Farris is the director of product strategy for the North America branch of AGCO Corporation. He spent more than 25 years in project development as well as developing, advising, and commercializing new technology in the biomass energy field. Budget period three will focus on developing a market analysis of the technology developed. Mr. Ritcher of Matera, Inc., a co-PI, will lead this effort. Observations will be synthesized in a market reception report with recommendations on areas of concern or additional risk identified by the research efforts. This report will propose characteristics to homogenize for multiple process classes that are cost-effective and applicable to multiple technologies.

- Thank you for your input.

  Management plan: The research team includes five organizations, each leading different, unique, and well-defined tasks. The University of Arkansas is leading the development of the analytical models. Clemson University is leading the DEM model. The Clemson University co-PI has a laboratory that is equipped with characterization and mechanical testing for the materials of interest in this project. The University of Texas at San Antonio (UTSA) will be leading the development of an online DSS to disseminate the models developed. The UTSA co-PI has access to the UTSA Center for Simulation, Visualization, and Real Time Prediction, a facility that will be used to perform the simulations and visualizations of real problem instances. The cloud computing infrastructure in the UTSA Open Cloud Institute will be used to support the development of the DSS. Matera is leading the commercialization efforts. INL will be leading our model validation via the PDU and is providing historical data from the

PDU. The co-PIs are experts in the corresponding field of study. The expertise that each brings in this work is unique. Notice that the PI was a faculty member at the University of Clemson but recently moved to the University of Arkansas. Three of the co-PIs on this research team (the University of Arkansas, UTSA, and INL) have worked together for many years on a number of projects and research papers. The team meets regularly two times per month via Webex. The co-PIs have visited INL two times to discuss the progress of this project. Two postdoctoral students have spent extended periods of time at INL, Clemson University, and the University of Arkansas. In summary, each organization is leading unique efforts. The scope of our system modeling is broad, and to achieve meaningful outcomes, we need to use experts from different fields. This work cannot be accomplished only by experts of analytical modeling and without help from experts in DEM modeling. INL will enable testing and validating the models at large scale. UTSA, via its Open Cloud Institute, will provide companies with access to the tools we have developed. Matera will contribute to developing our commercialization plan.

Practicality of bale sequencing: We understand the concern posed by this reviewer. In the section titled "Bale Sequencing," we address these concerns by summarizing the current practices in two power plants in Europe. For example, the materials handling systems of Sleaford Renewable Energy Plant in the United Kingdom facilitates the processing of 105 bales/hour. Given the information we have collected, we believe that there is a possibility to make sequencing practical by (1) standardizing the bale format, (2) using RFID systems to record and read information about bales from the point of harvest to storage at a biorefinery, (3) sensing and real-time monitoring of biomass attributes, (4) using automated process control, and (5) using automated bale handling systems. In the section about bale sequencing, we summarize the existing technology that can be used to make sequencing practical. We invite this reviewer to watch the two videos listed in the references that show how these systems work in practice.

- Thank you for your comments.

  The focus of this project: The reviewer makes a good point that the data we have collected and used for testing and validation did come from INL's PDU. As a result, one can question its applicability; however, we focused on the PDU because it provided us with historical data about its operations (at the unit and system level), which we could not have obtained from other sources. Because our system model integrates unit-level with system-level operations, it is very important that there is consistency in the data we used and the models we built; however, the models we developed can easily be used by other companies to model their system-level operations. Further, the lessons we have learned by using our models can positively impact the practice. For example, we document the role of sequencing on the system's performance. In our journal paper, we summarize a number of simple rules for sequencing bales that practitioners can use to improve processes.

  Practicality of bale sequencing: We understand the concern posed by this reviewer. In the section titled "Bale Sequencing," we address these concerns by summarizing current practices in Europe. Given the information we have collected, we believe that there is a possibility to make sequencing practical by (1) standardizing the bale format, (2) using RFID systems to record and read information about bales from the point of harvest to storage at a biorefinery, (3) sensing and real-time monitoring of biomass attributes, (4) using automated process control, and (5) using automated bale handling systems. In the section about bale sequencing, we summarize the existing technology that can be used to make sequencing practical.

  Capturing the chemistry and microphysical properties of biomass: The focus of our research is to use DEM models and analytical models to improve the system's performance. Unfortunately, the chemistry of biomass cannot be directly modeled via DEM models; however, if there were to exist data quantifying how chemistry changes the flowability, this may be considered implicitly in the model, i.e., by introducing an empirical model parameter that links some chemistry property to mechanical property. But, fundamentally, DEMs are not designed to account for chemistry property. The analytical models proposed are mathematical models of the system. These models capture relationships among equipment, inventory, and the amount of biomass flowing in the system. If we were to have data that demonstrate how the chemistry of biomass impacts the performance of equipment and the flow of biomass, we could incorporate those in the model; however, such data were not available to the team. (This addresses the comments on sequencing; we submitted a document that has figures that will help the reviewers understand our comments.)

Bale sequencing: The reviewers point out the impracticality of bale sequencing at a large scale. The team appreciates the comment and understands this reviewer's concerns. The team researched existing bale handling systems, and the following paragraph summarizes what the team found. A number of companies in the bioenergy sector in Europe are using automated bale handling systems. For example, Processbio, a Danish equipment manufacturer, has manufactured conveyors and robotic cranes to handle bales. Qubiqa, another European company located in Denmark and Poland, has produced automated materials handling equipment. Figure 1 [not pictured] presents some of the materials handling equipment produced by Processbio.

- The video demonstrates how the Processbio automated handling system is being used by the Sleaford Renewable Energy Plant in the United Kingdom. The automated system facilitates the processing of 105 bales/hour in this facility. Below, we summarize the content of this video. "Biomass registration" registers the incoming bales using RFID cards. Cranes are used to unload the trucks and simultaneously move a number of bales to conveyors within the facility. Notice the sensors that are attached to the robotic cranes. These sensors are used to measure the weight and moisture level of each bale as the bales are picked up from storage to be delivered to the processing lanes. Multiple processing lines are used to feed the burners.

- Automated bale handling system at Sleaford Power Plant in the United Kingdom. Figure 1: Automated bale handling equipment by Processbio. (The figure is not included here; see the submitted document.) Automated bale handling equipment manufactured by Qubiqa. (The figure is not included here; see the submitted document.) Automated bale handling equipment manufactured by Qubiqa. (The figure is not included here; see the submitted document.) Bales are unloaded from trucks via automated cranes at BWSC Biomass Renewable Energy Plant. (The figure is not included here; see the submitted document.) Bales are moved to/from storage via automated cranes at the BWSC biomass renewable energy plant. (The figure is not included here; see the submitted document.) Bales are fed to the reactors via multiple lines.

  Figure 2: Automated bale handling equipment by Qubiqa. Video demonstrates how Qubiqa's automated materials handling system is used by the BWSC biomass renewable energy plant in Snetterton, United Kingdom. Notice the sensors in the cranes that measure weight and moisture level. We believe that such a system facilitates (1) collection of data about biomass characteristics via RFID technology, (2) collection of data about the current status of the moisture level via sensors, and (3) sorting/feeding of bales of a particular moisture level via multiple feeding lines. In summary, we believe that such a system has the capability to make use of the models we propose.

Summary of PDU tests conducted so far:

- 2019-07-17 PDU test: Seven switchgrass bales were tested on this day. There were five low-moisture bales (5%–15%), one medium (15%–25%), and one high-moisture (25%–35%) bale. Bulk density tests were done on these bales to get the loose and tapped bulk densities. Sieve analysis was done to get the PSD of the bales. A moisture content determination test was also done to get the moisture contents of the bales. All these tests were conducted on materials taken after grinder 1 and after grinder 2, and three samples were tested for each bale. The screen size for grinder 1 is 3 inches, and grinder 2 is ¼ inch. These tests were done to get the information on the biomass characteristics.

- 2019-08-08 PDU test: Five switchgrass bales were tested on this day. Four bales were low-moisture bales (5%–15%), and one bale at 25%. A moisture content determination test was done to get the moisture content of the bales both after grinder 1 and after grinder 2, and three samples were tested for each bale. The screen size for grinder 1 is 3 inches, and grinder 2 is ¼ inch. One bale processing could not be finished on this day; instead, it was processed on August 14, 2019.

- 2019-08-14 PDU test: Four switchgrass bales were tested on this day. There were three low-moisture bales (5%–15%) and one bale at 25%. A moisture content determination test was done to get the moisture contents of the bale both after grinder 1 and after grinder 2, and three samples were tested for each bale. The screen size for grinder 1 is 3 inches, and grinder 2 is 1 inch. One bale processing could not be finished on this day, so it was carried forward to August 15, 2019.

- 2019-08-15 PDU test: Three switchgrass bales were tested on this day. There were three high-moisture bales (25%–35%). A moisture content determination test was done to get the moisture contents of the bales. Tests were done both after grinder 1 and after grinder 2, and three samples were tested for each bale. The screen size for grinder 1 is 3 inches, and grinder 2 is 1 inch. All these August 2019 tests were done on bales at various moistures and screen sizes to look at failure in SC-4 and in the DC-6 transition to the hammer mill.

- 2020-03-16 PDU test: One switchgrass bale was milled. The screen size for grinder 1 is 3 inches, and grinder 2 is 7/16 inch. Then pelleting was done at 9 l/d die. This test was run to test whether the PDU is working properly.

- 2020-06-15 and 2020-06-26 PDU test: Eight low-moisture bales were processed on June 15, 2020, and one low-moisture bale was processed on June 26, 2020. All nine bales could not be processed on a single run because the metering bin was full, and the materials inside it had to be discharged. Pelleting was first attempted at INL, but it was unsuccessful. The material was too dry, and particles were larger. The material was carried to GreenGold mill, and pelleting was attempted again. While pelleting, it plugged both the INL pellet mill and the GreenGold mill. Pelleting could not be done at GreenGold either (except for a small amount of produced pellets, approximately 1 dry ton), and the materials had to be discarded. While pelleting at INL, different infeed rates (3.5 Hz and 17 Hz) were tried. The pellet mill motor was set at 60 Hz. Steam was also added at different levels. Different settings were tested, but none generated good-quality pellets.

- 2020-07-09 PDU test: Nine switchgrass bales were tested. All were medium-moisture bales. Three different mill speeds (40 Hz, 50 Hz, 60 Hz) and three different infeed rates (2 Hz, 3 Hz, 4 Hz, approximately 2 dry tons/hour, 3 dry tons/hour, 4 dry tons/hour, respectively). The screen size of grinder 1 is 3 inches, and grinder 2 is ¼ inch. Bulk density, sieve analysis, and moisture content determination tests were also done. Pelleting of the material was conducted on July 14, 2020, at GreenGold.

- 2020-07-23 PDU test: Nine switchgrass bales were tested at varying mill speeds (40 Hz, 50 Hz, 60 Hz) and feed rates (2 Hz, 3 Hz, 4 Hz). The stage 1 grinder is set at 3 inches, and the stage 2 grinder is set at ¼ inch. Bulk density, sieve analysis, and moisture content determination tests were also done. The material was pelleted at GreenGold.
- 2020-08-24 PDU test: Nine bales of switchgrass were tested of high moisture at 25% with a 3-inch screen in the Vermeer. The stage 1 grinder is set at 3 inches, and the stage 2 grinder is set at ¼ inch. The run was cancelled because the bales were too wet.
- 2020-08-31 PDU test: Nine bales of switchgrass were tested of high moisture at 25% with a 3-inch screen in the Vermeer. The stage 1 grinder is set at 3 inches, and the stage 2 grinder is set at ¼ inch. Three different mill speeds (40 Hz, 50 Hz, 60 Hz) and three different infeed rates (2 Hz, 3 Hz, 4 Hz) were used. Bulk density, sieve analysis, and moisture content determination tests were also done.

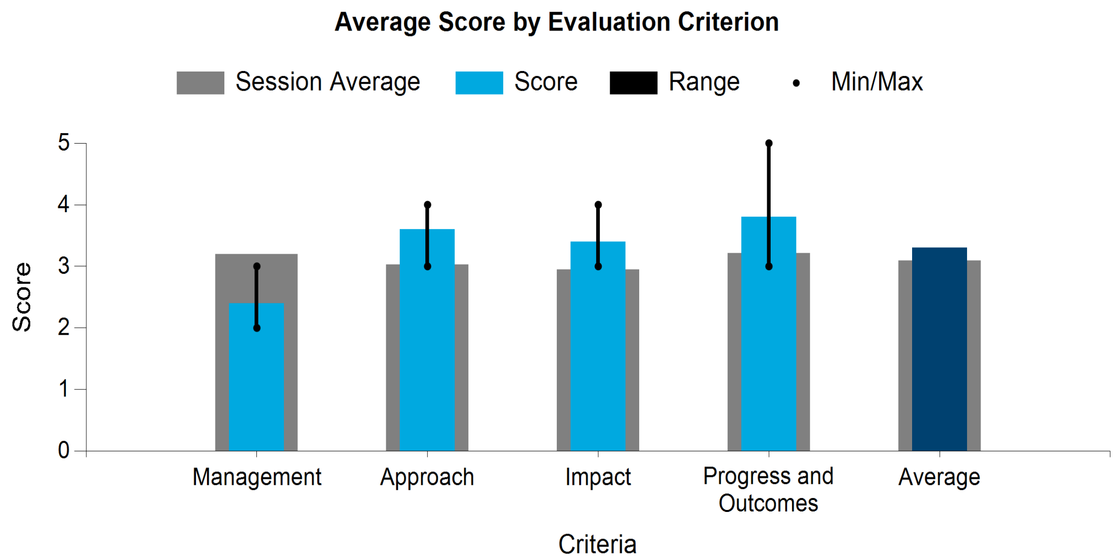
ANALYTICAL MODELING OF BIOMASS TRANSPORT AND FEEDING SYSTEMS

Purdue University

PROJECT DESCRIPTION

WBS:	3.1.1.005
Presenter(s):	Michael Ladisch
Project Start Date:	03/01/2018
Planned Project End Date:	02/28/2021
Total DOE Funding:	$2,319,822

The movement of lignocellulosic biomass solids between and within unit operations of a biorefinery remains a challenge due to the difficult materials handling characteristics of solid forms of biomass materials and aqueous slurries formed in a biorefinery. The purpose of this project is to (1) develop strong and innovative computational models that rigorously represent the flow performance of biomass materials during biomass preprocessing, (2) verify models in cooperation with INL, and (3) support technology development and engineering solutions that economically and sustainably overcome critical barriers associated with solids handling in biorefineries. The near-term impact will be validated models that predict flow behavior during feeding and that define critical operating ranges. This will provide a quantitative basis for new equipment designs for U.S. industry relevant to addressing operational reliability issues experienced by DOE-supported pioneer biorefineries. A major impediment to reliable biorefinery operation is moving solids from one unit operation to another without plugging. Anticipated outcomes are usable, scientifically based computational tools for process analysis that simplify process design, enhance operational reliability, reduce CapEx and operating expenditures (OpEx), and support BETO's mission and the MYPP goals.



COMMENTS

- This is a good blend of computational and empirical models, with good industry contact. It is unclear whether there are any communications/interactions with the FCIC. It is also unclear why there is the pivot to the liquefaction of feed; it is a good approach to solving the reactor feeding issue, but could the general concept have been tested/modeled simply by creating a biomass/water slurry?

- This is an interesting project looking to analyze biomass feeding and transport methodologies from a very broad perspective. The purpose and goals of the project's work (the "analysis") are quite unclear, although the work looks to be of high technical quality. For example, it is quite unclear whether some of the modeling for the processing units is meant for predictive purposes or for process modeling.

- The management plan as presented is not adequate for a project with six collaborators. The title slide does not mention the lead (Purdue), the project management slide does not mention Pennsylvania State, and it is really just an organizational chart and a list of scheduled meetings. The approach looks solid, and the connection of modeling with data acquisition in realistic equipment at INL is important. The INL PDU is probably the only way many projects like this could be done. There has been substantial progress on both the modeling and the experiment, which is in line with the expectations and the funding costed to date. The design of experiment on three pathways to stover liquefaction was a nice touch.

- Other than the project makeup, the presentation did not go into any management aspects, including collaboration with other parties or risks. The equipment has been modeled previously in similar ways. The presentation did not provide an adequate description of how their modeling effort differed from previous attempts and what they intended to learn from the model that had not been otherwise validated. Maleic acid production does not seem to line up with the stated project objectives. The economic advantage or the cost of maleic acid production was not made clear. Although the project discussed in the question-and-answer period how they arrived at the root cause of the maleic acid production, the overall inclusion in this project remains unclear at this time. It appears to be a tangent to the project objectives, which could result in slowing down the overall progress of the project. The scope of the modeling effort covered both pre-reaction and reactor unit operations. These have vastly different kinetics at work, which impact the required complexity of the model. The initial torque measured on the 65% moisture content sheared versus pelleted showed opposite behaviors in the first 60 seconds. It is unclear if this was matched by the model predictions.

- The complex and overarching project is making excellent progress on meeting its goals. The decision to go to a pelleted feedstock appears to be a very good one, but it should have been better explained within the presentation, and some type of analysis on the trade-offs should have been done. The impact of this project should be very good, but it is not clear if this will be the case due to the narrow process definition. It is good that these were developed with the labs and academia and not a single proprietary process. How broadly can these results be disseminated? This would have been a great addition to the presentation—some idea of the generalization of the results. The management plan presented was average, but it appears that it must be working due to their results.

PI RESPONSE TO REVIEWER COMMENTS

- We have invited representatives of the FCIC to join the stakeholder meeting, which will also include others, to share our results and to discuss what other data might be needed in addition to what we have obtained with this project and what may be available from the FCIC. Until this point, for the compression feed screw modeling effort, our FEM model requires (modified) Drucker-Prager cap parameters for corn stover, which are not in the FCIC database. The liquefaction experiments support the compression screw and upstream solids handling as an analytical method rather than a process development effort for this project. One parameter that must be addressed (or verified) is that the material that has been processed at the front end results in a material form that is readily processed into solid slurries up to 300 g/L.

- We understand the reviewer's comment, and we appreciate the suggestions. This is actually a modeling project to address specific and identified technical needs for improving biorefinery operation, whereas some other presentations in this part of the Peer Review were more oriented toward process development. The modeling and verification targets equipment and equipment specifications of systems (in this case, at the front end) that are already being tested for use in pioneer biorefineries, and it addresses programmatic objectives of this BETO program. The project overview summarizes the goals at a high level. Briefly stated, the objective of this project is representative of the TRL (TRL 3 to 4), with project aims aligning with programmatic goals. Although some explanation was given during this short presentation, we understand the need for more background, and we will endeavor to do this in future presentations. The modeling work itself has two technical objectives. First, the high-fidelity FEM and CFD simulations are meant for engineering design, e.g., design of equipment. These simulations require significant expertise to set up and take a long time to run. We are also developing a reduced-order model of the feed screw, which has fewer input parameters and runs in a matter of seconds to minutes. This model relies on insight from the high-fidelity model to develop. The reduced-order model is intended for process models and quick decision-making.

- We thank the reviewer for these comments, and we agree that management is important because the project involves multiple disciplinary elements and investigators and several different locations. The slide itself, if viewed as a stand-alone slide, needs to have more detail, but it was presented in this manner to summarize the key elements, with the discussion that had accompanied the slide explaining how this is managed, with final decisions being made by the PI (Ladisch at Purdue) after all the inputs are obtained. We have worked hard to provide frequent and efficient communications. On another note, maleic acid production is not within the scope of this project, and research on this has not been carried out as part of EE0008256, nor was it presented in the PowerPoint. (Perhaps there was another presentation during another part of the Peer Review by different investigators?) This is not part of the BETO programmatic goals for our work. Please note that the PowerPoint deck for the Peer Review followed the format that was requested by DOE. This included placing the quad chart (slide 26), milestones (Gantt) (slide 27), project risks and mitigation (slide 28), and publications and patents (slide 29) after the summary slide (slide 25). Project risks and mitigations are given on slide 28. The FEM model developed in this project is significantly different from the other models for compression feed screws. One BETO project utilizes a DEM model, which is a fundamentally different approach to materials modeling. FEM modeling is a continuum approach and is highly scalable. The DEM modeling approach is a particle-based approach and does not scale well. Indeed, the DEM model is not capable of modeling the number of particles found in the real system. Further, materials characterization is much easier for the FEM model than the DEM model. Another BETO project uses a CFD continuum simulation to model material movement through the feed screw. This project provided little detail on how the material is modeled other than saying it is treated as a non-Newtonian, viscous fluid; hence, it is difficult to understand how that model works and how the material parameters are measured. Our model uses an elastoplastic (modified) Drucker-Prager cap material model, which is a common model for particulate materials. This model can capture shear band formation and permanent material deformation, characteristics that are fundamental to particulate material dynamics. Viscous CFD models cannot capture this fundamental material behavior. In addition, we calibrate our material model parameters using standard, independent experiments rather than "back fitting" material parameters to obtain a good match to experimental results. The compression feed screw model is independent of the slurry model. The compression feed screw model is intended for modeling material feeding upstream of the chemical reactor, whereas the slurry model is intended for modeling the material downstream of the reactor. We have addressed the key goals and milestones (see high-level summary on slide 28). The project is on schedule given the delay of the budget period two go/no-go review (which occurred in August) due to the unusual circumstances in 2020.
- Purdue University is not given on the first slide and will be dominantly displayed in the future. The management slide does not mention Penn State because Penn State is not part of this contract, although there is a cooperative working relationship between Purdue, its collaborators, and Penn State researchers (and other institutions as well). On management, we agree with the reviewer. The management slide was designed for describing interactions during the oral presentation, per instructions, so it will be organized differently for stand-alone viewing.

- The selection of pellets was briefly mentioned during the presentation (loose stover does not form slurries exceeding approximately 150 g/L). The reviewer is correct that a comparison slide is needed, and it is something we will add in future presentations, although there was not time to do it during the short Peer Review presentation. The narrow definition of the process (i.e., slide 7) is consistent with the goals of the project as funded, and the programmatic goals of this particular BETO program, which is to model and predict the behavior of corn stover particles as they make their way from inlet of the refinery to the first step (i.e., pretreatment). Results have already begun to be disseminated (slides 29 and 30), and we plan to broadly distribute the results at a stakeholder meeting on May 19 as well as through publication. We agree with the reviewer on describing the dissemination—these slides were included, but they were placed after the summary, per instructions that we received for the format and structure of this presentation. Dissemination is at the heart of our efforts, and it is our overall goal to make a difference in helping pioneer refineries overcome some of the challenges that have been encountered due to materials handling.

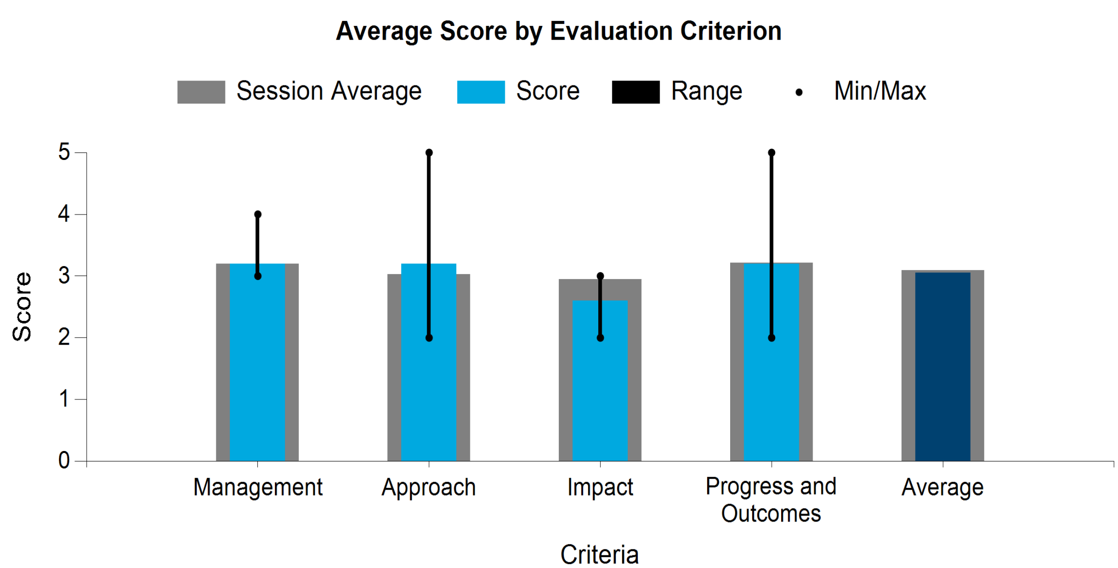
DEVELOPING HYDROTREATING MODELS USING MACHINE LEARNING

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	3.1.1.009
Presenter(s):	Mariefel Olarte
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$235,000

We will develop machine-learning algorithms that will model and predict expected hydrotreating conversions given specific bio-oil and biocrude inputs, such as feed composition, temperature, pressure, and catalyst. These algorithms are key to the eventual development of a full-application machine-learning model that enables a technology adopter to evaluate the feasibility of a single feed or a blend of feeds from among available options of biocrude sources in the market. A full-application machine-learning model can also give nonintuitive insight into considering alternatives to a disrupted supply chain or when feedstock diversification is needed. Having accurate, predictive, model-based data will reduce the need for costly experiments to test every possibility. In our work, publicly available data sets were initially used and then augmented by hydrotreating-relevant literature data. The end-of-the-project outcome is a developed machine-learning algorithm of the underlying hydrotreating chemistry that accurately predicts product properties such as simulated boiling ranges. Appropriate critical material attributes of the feedstock and oil products will be incorporated if available and applicable. Thus far, we were successful in probing the impact of the added literature data set to the original molecular transformer algorithm, specifically for hydrotreating application. This work will benefit partner projects for additional insight into their provided data, possibly leading to targeted experiments to achieve their project goals. This work will also benefit entities with interest in hydrotreating and will enable them to predict simulated boiling point ranges.



Project: Developing Hydrotreating Models using Machine Learning
WBS: 3.1.1.009

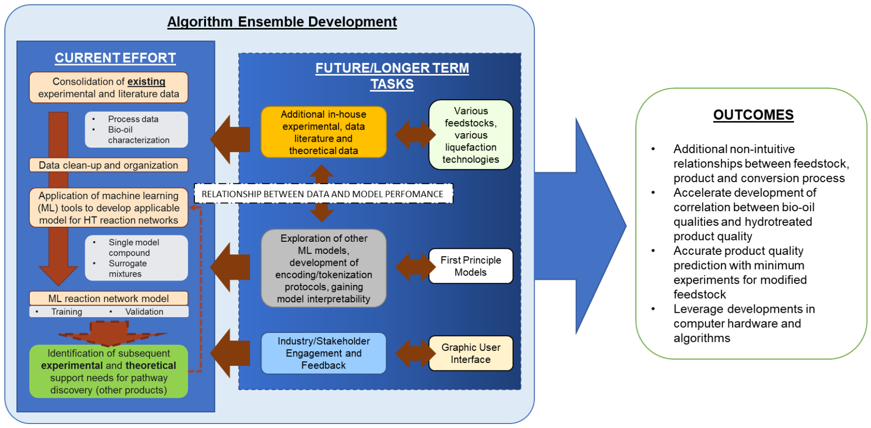


Photo courtesy of PNNL

COMMENTS

- This is a new development at PNNL to develop hydrotreating models using machine learning. Why is the approach using exclusively machine learning and not combining it with first-principle models that exist at the lab? How are the data to be used and validated? Are there enough data (validated, repeatable, at known conditions) to do this? How do you know the data quality? There are some serious questions about the final results presented that show a comparison of the accuracy percentage for results using very differently sized test samples, and these should not be compared so simplistically. The approach is unclear and doubtful in terms of the value for the design and operations.

- The management and progress are reasonable given the stated objectives. The issue here is that machine learning, which is essentially a misnomer for advanced statistical modeling, is being misapplied to a process that is much more amenable to physics- and chemistry-based modeling. Parameters in physically meaningful models for kinetics, fluid flow, heat transfer, and mass transfer can and have been regressed from experimental data, providing models that are both "explainable" and extendable to conditions and catalysts outside of the data training set. There seems to be little likelihood that the models produced will be of much use, certainly not of much general use.

- The project is an innovative approach to reduce risk in developing hydrotreating processes. The management plan was weak in that the overall plan was not outlined, and there does not seem to be interaction with industry or steering committees to ensure that the project is on the right track. The plan does outline risks and mitigation strategies, which is important. The approach looks well thought out and feasible, and preliminary results are encouraging; however, it is concerning that the addition of only a few reactions changed the accuracy of the model so much. In addition, the impact may not be significant because the goal of 70% accuracy seems low, and there appears to be no industry buy-in; however, the project is in its early stages, and it can be improved by reaching out to industry partners and consortia to ensure that they are on the right track and that the models developed would be useful. Evaluation of the 70% accuracy by outside groups is also suggested.

- This is an interesting project that needs more direct industry involvement, at least on an advisory board level. The end product goal is an accuracy of at least 70%, but how useful is a model with only 30% accuracy? With projects of this sort, it should be clear what is useful, not only what is achievable. Should the project not be able to achieve "useful" by project completion, a clear path should at least be required in the final report.

- This is a very good modeling approach that should be mirrored by other projects. The significance or insignificance of adding only a few reactions to such a large number and obtaining such different results needs to be better explained. To someone not doing machine learning daily, this is a very confusing result. The project explained this finding confidently and assuredly, but it is not obvious that this is a typical result. The data set appeared limited to lower carbon number compounds. It is not clear when or how this can be expanded or if there is a significant training set available for high carbon numbers. Because these appear so often in biorefineries, the overall impact of this to a fuel-producing facility may be limited as a result. It is excellent news that chemical companies in industry have also seen the value of this project and are pursuing it. The project would like to expand on this work in another project by incorporating kinetic data to increase its accuracy. The availability of this kinetic data will be more limited but could have a major impact on the accuracy of the project. There are a lot of modeling projects being worked on. This project is a new approach, which could result in either the reduction of the need for many models in the future or, less likely, the elimination of them entirely. It is an exciting new approach and a new concept in development by the national labs. It will require more than this project to be successful, however, because the target accuracy for this project is still relatively low. It would be of benefit to understand whether the interested industry parties want to utilize what is in development for *this* project or for a future version that is planned.

PI RESPONSE TO REVIEWER COMMENTS

- The insightful comments provided by the reviewers are greatly appreciated. We appreciate the panel's assessment that machine learning provides an innovative tool that can help reduce the risk in developing hydrotreating processes, which is a necessary step in thermochemical conversion processes that requires the production of hydrocarbons from oxygenated feedstocks. We have a big picture vision/long-term goal in using machine learning for hydrotreating—that is, we would like machine learning tools to be used by industry and researchers to model and predict expected hydrotreating conversions given specific bio-oil and biocrude inputs. This long-term goal would have incorporated the development of ensembles of models trained on data spanning various biomass feedstock sources, liquefaction technologies, and their subsequent hydrotreating, coprocessing, and distillation. This long-term effort will also incorporate the development of an application programming interface and graphical user interface that would enable both inputs for prediction and inputs for additional training data by the user to allow for appropriate customization. Currently, our 3-year project goal is to develop a model for hydrotreating that incorporates available literature and theoretical and experimental data that will enable a prediction of the product boiling point range, a property related to the extent/conversion yield of hydrotreating. To get there, we wish to show the utility using available data. The project is in its initial stage and would benefit from having dependable resources, especially at the crucial early developmental period and considering that planned activities were already lean.

  We agree with the reviewer's suggestion of engaging an external board to provide input. Early on, we engaged with a commercial entity interested in developing the algorithm with us, but, due to lack of funds, we lost this opportunity to collaborate. We will incorporate plans to gain feedback from an external board of stakeholders in our future planning. It will also enable us to get feedback on the current 70% or better accuracy threshold.

  The performance improvement observed after the incorporation of a curated, albeit smaller, set of reactions in the training set is an indication that the predictive model can be fine-tuned for hydrotreating or any target chemistry by using targeted additions of small amounts of relevant reaction data. One way to look at this is that the model learned how to interpret what reaction centers are based on given reactant and product pairs in the general United States Patent and Trademark Office training set (more than 800,000 entries) while gaining specialization on hydrotreating reactions by adding the hydrotreating-specific data sets (374 entries). We can see the advantages of building targeted models with smaller data sets after training on a larger general training set, especially because conducting experiments can be expensive. We aim to understand the impact of the reaction of family-specific data sets on a general algorithm's predictive capability. It is like an engineering student majoring in a particular field of study after going through basic engineering courses. We realize that this may reduce the model's general applicability; however, that is not an impediment in our target goal as long as we make sure that we are not overfitting (e.g., using the same test set as the training set). Overfitting artificially increases the model's accuracy but limits its ability to generate accurate predictions of similar, though not the same, inputs. Still, we are currently working on improving the data curation and the model interpretability to ensure that we are not overfitting within the hydrotreating target chemistry application. Last, working on machine-learning models does not preclude us from working with existing first-principle models. We believe that machine-learning models can provide insights that are not traditionally generated by models that are currently used. In the long term, we aim to couple both approaches to develop chemistry-informed machine-learning models capable of providing reliable predictions outside the training data regime; however, the first step toward this ambitious goal requires understanding the factors that influence the predictive capability of the machine-learning models that we are currently deploying.

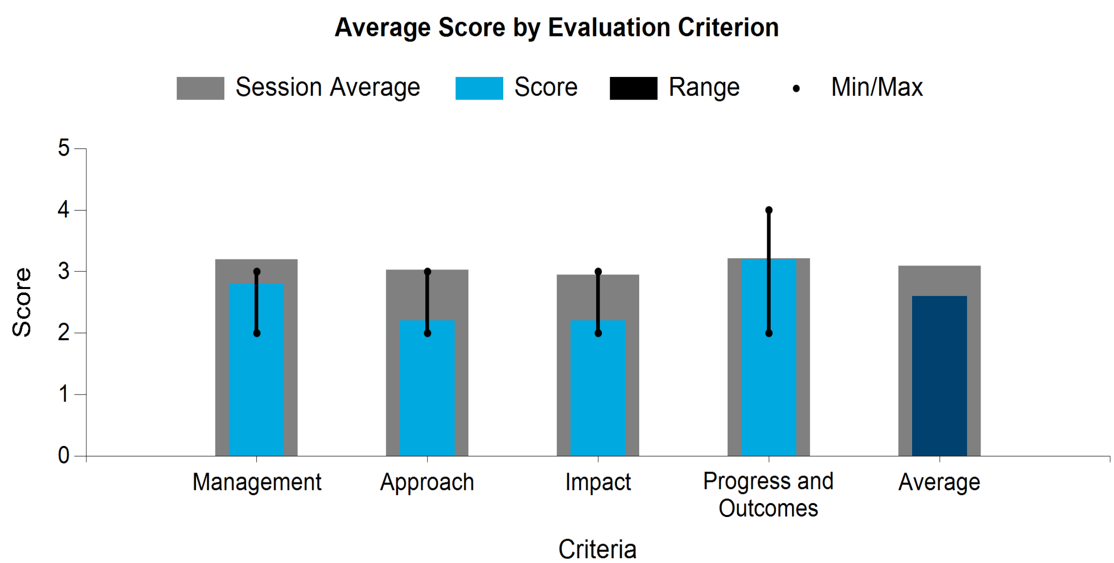
VIRTUAL ENGINEERING OF LOW-TEMPERATURE CONVERSION

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.1.1.010
Presenter(s):	Jonathan Stickel
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$590,000

The development of virtual engineering capabilities, which systematically connect computational models of unit operations and predict outcomes for an entire conversion process, leverages BETO's investments in high-fidelity computational models, Aspen Plus-based TEA capabilities, and NREL's state-of-the-art IBR research facility physical process demonstration pilot plant. This project is working toward a basic working suite of software that can be used to simulate and optimize low-temperature conversion of biomass, from feedstock handling to fuel upgrading, where virtual engineering will be demonstrated using high-fidelity mechanistic models for a subset of unit operations (enzymatic hydrolysis and bioreaction), with placeholder, lower-fidelity models used for the others. The general software framework, including a notebook-style graphical user interface and TEA integration, have been developed and demonstrated. Efficient surrogate models are being developed for the computationally expensive unit operation models. The virtual engineering software, once developed to a usable state, will be released as open source to facilitate further enhancements from a wide range of users and software developers.



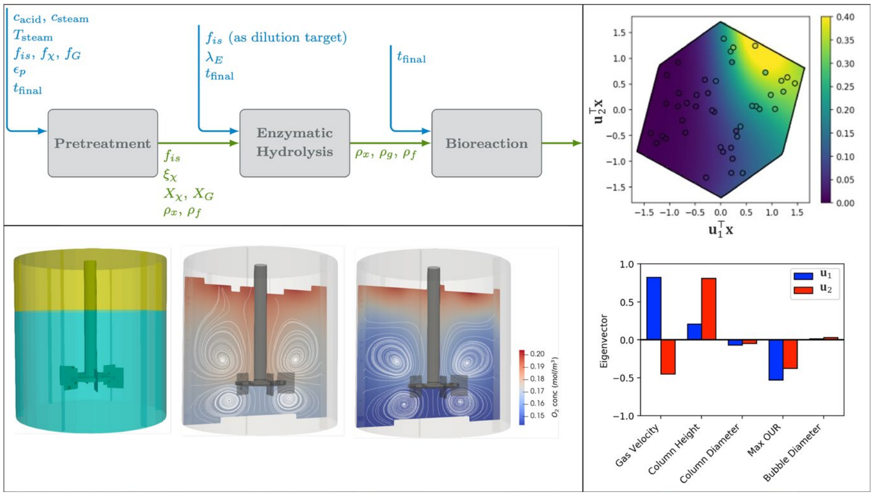


Photo courtesy of NREL

COMMENTS

- This is a complex modeling project with an unclear purpose and value generation. It appears to be more of an exercise in computing than generating value for the development of process technology. Further, the team does not seem to be very aware of other, more advanced and suitable developments (such as the I environment from Fossil Energy). Some of the stated TEA assumptions looked to be quite inadequate.

- It is not clear that this project is needed. The development of the unit operation models that require HPC for convergence limits the usefulness of this for the biomass community at large. It seems that a better approach may be to use these high-powered models to develop simpler versions that can be incorporated into existing Aspen models and/or used on other formats. This project is using a significant amount of resources (computing, model development, etc.), and it does not appear that the payback and usefulness are worth it. To this reviewer, it looks like this was a project designed to do “as many cool things as possible” without considering the future usefulness.

- The problem here is that this has long been available in commercial process simulators. And although many of them are comparatively weak in several aspects of bioprocessing, it is simpler to embed custom code in them than to start from scratch. The dimension reduction is old hat. I worked on it in the mid-1980s, and even then, I was too late to beat Aspen and SimSci to market with it. If this is done at all, it needs to be done in cooperation with simulator vendors because they are the ones that are going to supply software to end users. Trying to go directly to end users is not a viable strategy. The work itself is fine, and open-source models (the rigorous ones), hopefully, will be adapted by software vendors, but the dimension reduction and other simplification work is likely to be abandoned in favor of their own proprietary approaches.

- The software engineer was not part of the team to start with. It is not clear if the software engineer has any familiarity with this type of process. Familiarity to a process is important in the development of a user interface/user experience. The project needs to spend more time on the development of the user experience upfront so that they can obtain and develop the right features for the software on the back end. The need of this project is very unclear. Models of things such as aerobic bioreactions exist even outside of an HPC environment or specifically Aspen. The project did not make clear why these existing models are ineffective. Surrogate models appear to have been made based on HPC-based modes for extended use outside of the need for an HPC, but a comparison to existing, non-HPC models was not clear. Although the project is using a risk management tool, none of the risks presented had anything to do with validating this complex software model and the inherent risks therein. It appears that limited input was given in developing the graphical user interface. Features, requirements, wire frames, etc., do not appear to have been laid out for this project. Tuning a model to near 10% is expected to be the difficult part of the project, and the project reflects that challenge (approximately 6 months to 30% and another 18 months to 10%). The project appears to understand the difficulty, but the steps between these two milestones is unclear. The project appears to be doing similar work to the team within the FCIC, but it is not partnering with them or sharing information at this point. If this project is trying to be an open-source tool, it would make sense that these two platforms collaborate. The project plan and metrics for measuring progress are lacking. The project is working on an immensely complex task, but there is not any real definition of what systems are being studied, or feedstocks, pretreatment systems, or other process variables. I am confused about integration of Aspen and the virtual engineering TEA work. The validation study needs to be explained—what tests will be done to "validate" it? One organism with one feedstock? What acid levels? How many permutations are there? It would have been valuable to better demonstrate how this modeling effort differs from others in the industry and within BETO.

- Although this project seems to have some immediate significance, it is unclear how these models will be rolled out. Is the intent to move from HPC to improved Aspen blocks? The focus appears very narrow—e.g., the effort with the mechanistic model looks to be sufficient for the pilot plant, but there is not enough analysis to show that it will be relevant at a larger scale. More clarity of the application to industry need would have helped the presentation.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their engagement and discussion during the virtual Peer Review meeting and for their follow-on constructive comments and questions. This virtual engineering project is a new and complex undertaking in the biomass conversion space, and it was challenging to fully communicate all the parts of the project and anticipated impact in the allotted 20 minutes. It also worth noting that, although the full scope of virtual engineering (as a general concept) is extensive, *the current effort is a seed project*, with the primary goal of providing a *proof of concept*. Fully featured software, with features and an interface that have undergone usability testing with domain experts, will be developed in future work. Applicability to industry will be clearer at that point, but two potential use cases are envisioned: (1) The virtual engineering software will have predefined sets of interchangeable conversion unit operations and selectable unit sizes, using low-order or surrogate models, from which various scenarios can be simulated. With this use case, virtual engineering software can also provide a powerful visual medium for disseminating scientific and engineering information and educating industry, researchers, and the general public about SOA bioconversion processes. (2) Industry can work with NREL staff to implement new models, either computationally intensive or low-order, for other unit operation designs, and these models can then be plugged into the virtual engineering software to simulate them as part of an entire conversion process.

  Regarding our software implementation versus using Aspen Plus: Aspen Tech makes great software for the dedicated purpose of simulating process systems, typically steady state, in the petrochemical and other well-established industries; however, it is not designed to be a flexible platform for simulating novel unit operation models written in different programming languages or for interfacing with HPC resources. Rather than using Aspen Plus, it was more straightforward for us to implement our own virtual engineering software using the Python programming language. We are also implementing surrogate models in our virtual engineering software rather than integrating them into Aspen, thus keeping the same virtual engineering software interface for multiple use cases. TEA happens by first running a process simulation in the virtual engineering software (with SOA mechanistic models) and then providing that information to NREL's existing Aspen Plus workflow. Finally, our virtual engineering software will be released as open source and hence will not require a costly license to use (excepting integration with Aspen Plus-based TEA). The virtual engineering project aims toward a flexible platform that can employ a mix of both low- and high-fidelity models. Our framework will leverage DOE's HPC resources for high-fidelity predictive simulations that many engineering software products are unable to use effectively.

Regarding other systems engineering software, such as the Institute for the Design of Advanced Energy Systems (IDAES) and Wind Plant Integrated Systems Design and Engineering Model (WISDEM®): We are aware of other systems-modeling software such as these. Members of our team maintain regular communications with the developers of both tools. These are sets of modeling software with purposes specific to their applications (including predicting power generation, structural analysis, and system optimization). This virtual engineering project was partly inspired by these software packages, but it has its own characteristics unique to biomass conversion applications. As the project progresses, especially when developing optimization capabilities, we will look more closely at IDAES and WISDEM to see what concepts and software libraries might be borrowed from them.

Regarding the scale of the process simulation: I am sorry the presentation was not clear about what system scales the virtual engineering software can simulate. It can simulate any process scale, from laboratory to industry scale. In fact, the high-fidelity bioreactor model targeted for surrogate modeling is for a full-scale bubble-column reactor (500 m^3), but we have also performed simulations with a lab-scale bioreactor (500 mL).

Regarding the purpose of the HPC models: We are currently implementing CFD models, requiring HPC resources, for enzymatic hydrolysis and bioreaction. Yes, low-order models exist that do not require the HPC, and the virtual engineering software is set up to use them by user choice or to automatically fall back to them when no HPC hardware is detected. These low-order models are "zero-dimensional" and presume the reactors are well mixed, a condition that can require an impractical amount of energy to achieve. The CFD models can predict the relationship between mixing speed and/or aeration rate (and hence energy costs) with reactor performance (productivity/yield).

Regarding the validation against experiments: The individual unit operation models have been validated separately in previous work; hence, only a limited set of conditions is used to validate the virtual engineering software. Here, experimental validation of sequential unit operations is used to ensure that the virtual engineering software takes in inputs and provides outputs that correspond to parameters commonly used by experimentalists. Further, quantitative agreement is evaluated to verify that the virtual engineering software is connecting the unit operations correctly and as another check on the suitability of the models to represent actual low-temperature conversion processes.

Regarding partnering with the FCIC: The FCIC is focused on feedstock handling and preprocessing, whereas the virtual engineering software currently covers conversion operations. Models for preprocessing steps can be easily integrated within our Python framework and will be part of our future efforts.

Regarding the project management and measuring progress: We have quarterly milestones and a mid-project go/no-go. All milestones have been met to date.

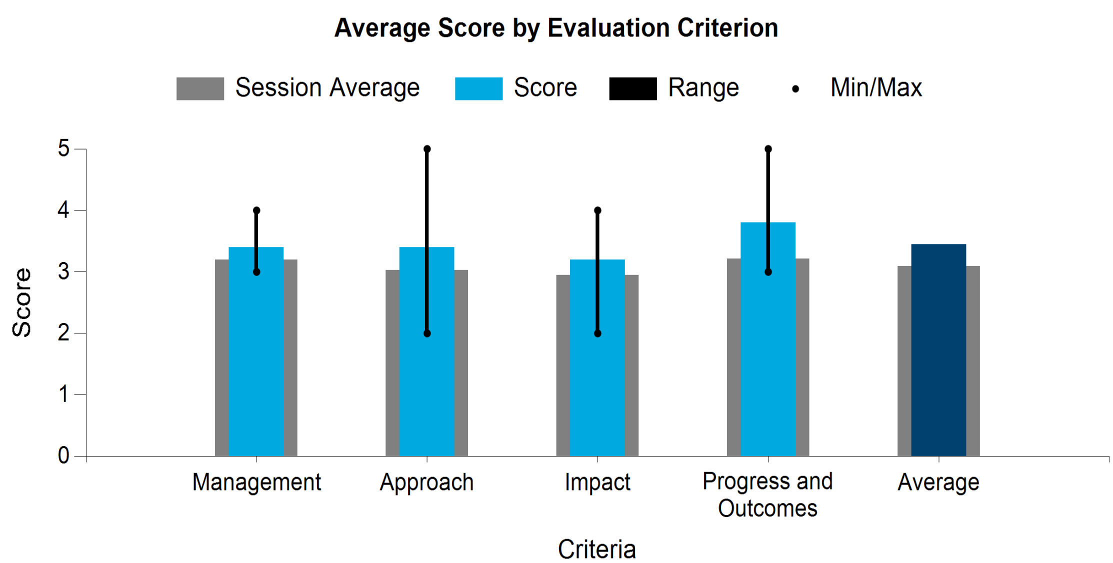
PROCESS MONITORING AND PREDICTIONS OF BIOREFINERY PERFORMANCE

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.1.1.011
Presenter(s):	Anne Starace
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$1,300,000

Online process monitoring coupled with rapid predictive tools will be essential to refineries of the future to provide real-time feedback and process control on new, renewable feeds and their accompanying processes and products. This project will provide refinery operators with tools to predict product component concentrations in minutes from online, slipstream mass spectra, allowing for the rapid detection of off-specification product. We will arrive at a template for predictive tool generation through the development of a specific tool as a starting point—coprocessing of pyrolysis oils and vacuum gas oil over fluid catalytic cracking (FCC) catalysts.



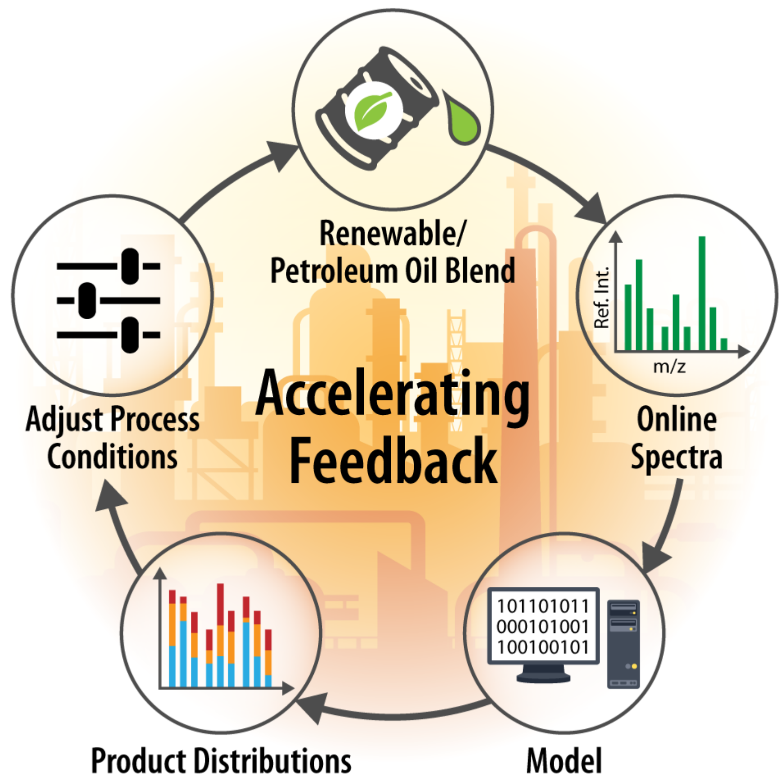


Photo courtesy of NREL

COMMENTS

- It is not clear what kinds of pyrolysis oil were used (age, feedstock, ash content, etc.) or how those feedstocks were chosen. The scale of validation is important because this tool may be used in a refinery to reduce the risk of plant shutdown by alerting operators to a potential problem requiring diversion of the pyrolysis oil product sooner. NREL cannot rely on short-term validation testing for this program. Work appears to have been done to show little impact at a low-level blend, but how the validation was conducted is unclear. It is not clear how the catalyst activity tied into the model or how this model is to be used to predict FCC catalyst performance over time as well. The risk of off-specification is much greater than $100,000 per event. If refiners cannot trust a consistent feedstock with predictable performance, they will simply not use pyrolysis oil. It is not worth the cost to a refinery to halt operations to integrate this technology. The economic advantage of the use of pyrolysis oil versus the increased risk of upset should be clarified. The only way to quantify the risk is to perform long-term reliability tests. It is unclear if this project builds on lessons learned from other past American Recovery and Reinvestment Act projects. There should be a significant amount of data available to help build the database and artificial intelligence. The focus of this project on refinery operations instead of on a generic biofuel facility is important. Refineries are a great target to incorporate biofuel technology.

- The project seems overly complicated. It is unclear why the chosen approach is selected over existing and proven control and optimization techniques. There is very little understanding of the targeted industry or the standard and more modern techniques in use (e.g., refinery optimization). The addition of complex analytical online techniques needs to be checked against reliability and value generation.

- The project has a well-thought-out and technically sound approach to this issue and is making great progress. The ability to have online real-time analyses of various biorefinery streams for process control will be invaluable. Based on the success of this project, it is hoped that this can be extended to other processes and process streams. It is great that the project has enlisted the help of Phillips 66 and the bio-oil coprocessing review board. It is concerning that the management team listed industrial relevancy as a risk. It is unclear if this means interest, or that this is not yet commercialized, or what; however, working to engage these outside parties is excellent and should be extended to others, if possible.

- This is a good project that appears to have made excellent progress. In addition to online process monitoring, the pathway toward predictive process control should prove very useful to industry. Additional focus on adaptation to changing process conditions (e.g., catalyst poisoning) could make this a very powerful tool.

- This is generically similar to approaches that have been used for many years in refineries. The specific mass spectrometer tool may be an advance over previous practice, but spectra and "fingerprinting" are long-established online tools. The work demonstrated that the approach could be useful, but this was predictable from numerous examples of prior work. It appears to be no more than the application of a (possibly) new analytical instrument in a familiar way to a familiar process with an expected result.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their comments and feedback. We appreciate the reviewers highlighting our strengths of building on time-tested approaches used in industry and applying them to a new tool for the optimization of existing refineries for the conversion of renewable starting materials. The tool developed in this project will also quickly alert operators to problems that might require the diversion of renewable feeds, reducing the risk of shutdown. The data used to build the model will also build understanding of coprocessing renewable feeds in existing refineries, further de-risking this exciting near-term pathway to renewable fuels and chemicals. Moving forward with this work, we will expand our industry engagement and develop comprehensive risk identification with mitigation strategies for the implementation of this approach in industry, leveraging existing monitoring tools in refineries, where applicable, and expanding them to new feeds that have properties outside of those of petroleum feeds. Additionally, we will work in conjunction with other projects, such as the bio-oil coprocessing project, to perform longer-term durability tests. Lastly, once we have successfully built this predictive tool, we will work to develop tools to inform adaptive responses to suboptimal product or potential impeding process upsets to correct them rapidly and efficiently.

  We would like to briefly address some specific reviewer comments here. This project works closely with the bio-oil coprocessing project and planned pilot-scale runs, coordinating to use the same pine-derived bio-oils and vacuum gas oils. The model's prediction of product compositions is validated against gas chromatographic analyses of the condensed product. The feed-to-catalyst ratio as well as the number of regeneration cycles of the catalyst are carefully tracked parameters so that the model can be developed to identify catalyst deactivation. Although there are significant amounts of previous data, they are insufficient on their own to provide a basis for a machine-learning model. When the use of the data for a machine-learning model was not considered when the data were collected, which overwhelmingly has been the case, each data point must be paired with relevant metadata to ensure that each data point has the same, complete set of metadata to accompany it—a laborious process that usually eliminates many data points. We hope this provides the reviewers more clarity on these specific points.

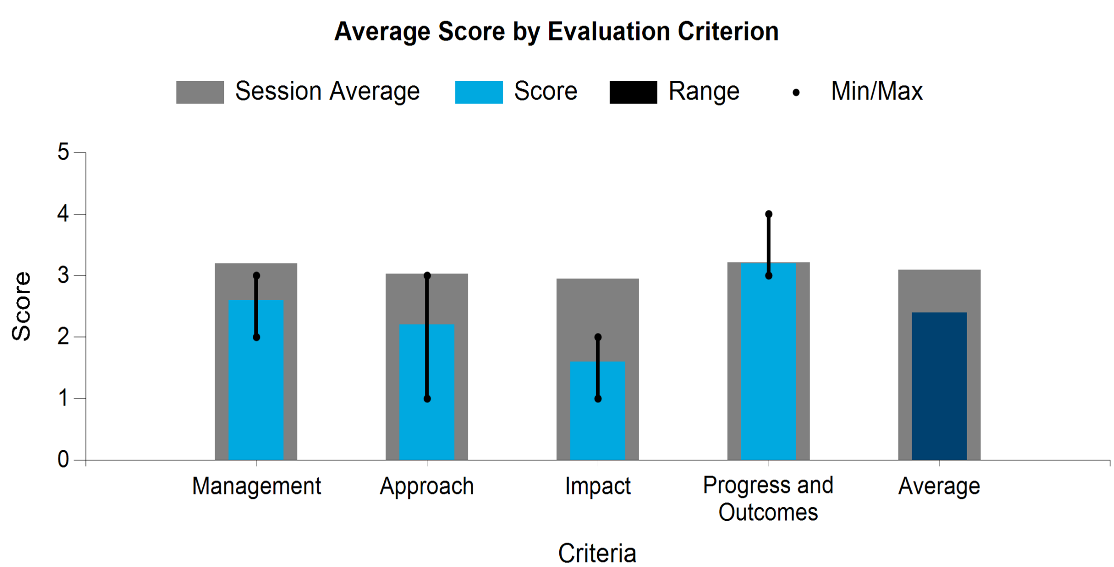
MODELING FLOW BEHAVIOR IN A DISC REFINER FOR DEACETYLATION AND MECHANICAL REFINING PROCESS

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.1.1.012
Presenter(s):	Xiaowen Chen
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$400,000

Disc refining is a critical step in the DMR pretreatment process, which is effective in breaking down the biomass structures to increase enzyme accessibility and sugar yield in biofuel production; however, it is an energy-intensive process, which limits its commercialization in the biorefinery industry. A technological gap exists in adopting the disc refining technology in biorefineries from the pulping industry due to different objectives. This project aims to advance the scientific understanding of the disc refining process for biofuel production. By developing and validating a physics-based model, this project will provide a tool to assist refiner plate design and process parameter optimization in achieving lower energy consumption in the disc refining process. Accurate modeling of the refiner relies on resolving the geometric feature details of the refiner plate. Disc refiner simulations are extremely computationally demanding due to the high complexity of the disc refiner geometry. We took advantage of the axisymmetric characteristics of the refiner plate in reducing the computational complexity while maintaining high fidelity. Our model demonstrated high accuracy, within 5%, in predicting energy consumption compared with experimental results at different operating conditions. We discovered that the energy consumption and energy efficiency increase with the increase in the rotation speed and the decrease in the refiner plate gap.



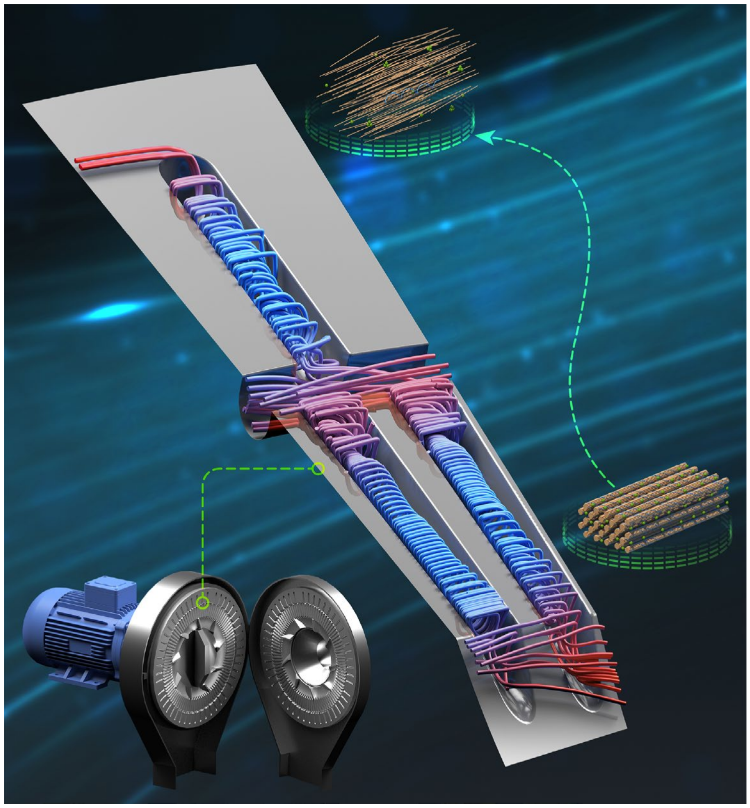


Photo courtesy of NREL

COMMENTS

- As discussed in other forums, the use of only the DMR front-end process is limiting to the overall development of the biorefinery industry. This effort may only be valuable if other technology companies adopt the DMR pretreatment, which is yet to be seen. The project did not make it clear whether the energy consumption of the disc refiner is the cause of others not adopting the DMR process. Integration of this project with the FCIC was not noted. It is unclear how this model can be validated if the specific shear energy cannot be measured empirically. I would have liked to have seen more information on how this model was planned to be validated and the risks going forward. If the specific shear energy cannot be measured, it would be good if the kinks can be correlated to another measurable value that is already being measured by the OEMs. New designs are not discussed in the presentation. It is unclear how this project is making an impact so far. Although 3D scanning is a good technology, the repeated pattern on the disc refiner would seem to lend itself to simply measuring and creating in AutoCAD if Andritz did not already possess the model. This project is one of the few working in direct partnership with an OEM to advance the development of a specific piece of technology for the industry. The economic impact of reduced disc-refining electrical consumption to a large project is unclear.

- At some point, we must ask why we keep spending on the DMR process when it is unlikely ever to be commercially viable. This is tweaking a single-unit operation and sophisticated modeling that is hard to justify by any real-world promise of the technology. The management plan is superficial but okay. The progress against stated goals has been acceptable. The major issue is that the project targets an approximate 5% cost reduction in a process that has never run commercially and most likely never will. The focus is a single, somewhat idiosyncratic piece of equipment that is part of an equally idiosyncratic conversion process.

- This looks to be the development of a commercial unit from Andritz by NREL using public money. The complexity and advancement are unclear. The methodologies seems relatively straightforward. It is unclear why this work is being funded by BETO.

- The project is making good progress toward its goals; however, the overall impact of reaching their goals on the overall cost of fuel and the reduction in GHG emissions is unclear. The presentation mentioned that it would reduce energy and thus costs and that disc refiners require a significant amount of energy, but they failed to provide an estimate of their expected reduction and/or the impact of this reduction. This is unfortunate. The project also noted that they may have an impact on the amount of enzyme required and thus on the overall fuel price, but this was not quantified or estimated either. Working with Andritz is really good because they are a leader in this area; however, the project should ensure that the results are transferable to other processes and that it is not limited to the specific disc refiner. It is likely that the project will provide good transferable results and measurable, albeit likely low-level impacts, but the project team failed to provide any backup for these issues. The approach may have been overkill for this specific project. It seems like it could have been modeled using simpler methods. Couldn't a basic computer-aided design drawing of that Andritz model been sufficient? By scanning the specific disk refiner, are we narrowing the modeling to not only that model but to that specific piece of equipment? The management plan was average. Some representation of the interconnection of tasks and the handoffs would have been useful.

- This project focuses on a single piece of equipment within a complex pretreatment process that, to date, has shown no progress toward commercialization. By the presenter's own admission, this equipment represents only 10% of the process energy consumption, so the optimization impact will likely be very small. Specific energy clearly increases with high-consistency refining, yet there was no consideration of whether lower consistency has a greater impact on energy consumption. There is no clear correlation between the reduced energy consumption and the impact on overall process performance. CFD models of disc refiners have been around for decades; this project would have strongly benefited from a survey and analysis of existing models to focus efforts. The DOE Office of Energy Efficiency and Renewable Energy (EERE) Advanced Manufacturing Office put out a Steam Tip Sheet (#21) showing how steam turbine drivers for rotating equipment can save significantly versus electrical drivers, and this should have been considered before this project was funded.

PI RESPONSE TO REVIEWER COMMENTS

- The DMR pretreatment is a newer cutting-edge technology, developed in 2012, to solve multiple issues encountered by pioneer second-generation ethanol plants. The high-temperature dilute-acid-pretreatment-based cellulosic ethanol plants struggled with the following operation challenges: (1) feeding biomass through the high-pressure boundary of the reactor, which often leads to inconsistent feeding; (2) reactor plugging due to char forming and lignin accumulation during acid pretreatment; and (3) inevitably producing inhibitors, such as acetic acid, furfural, and hydroxymethylfurfural, which significantly decrease yield in downstream biological fermentation. The DMR process is thus designed to mitigate those issues by (1) operating at atmospheric pressure to enable easy and reliable biomass feeding and discharging from a continuous reactor; (2) preventing char forming and lignin accumulation using dilute alkali pretreatment, which also reduces the material requirement for reactor constructions; and (3) avoiding inhibitor production that significantly increases sugar fermentability. By far, the DMR process has demonstrated promising and superior performance on sugar titer and yield (>270 g/L monomeric sugar, 85%–90% sugar yield), sugar fermentability (ethanol yield >90%, ethanol titer >80 g/L), and lignin reactivity. Based on NREL's sugar model, DMR sugar is approximately $0.20–$0.25/lb, which is close to the current corn starch sugar price. Disk refining is a critical step in the DMR process to improve sugar yield by increasing cellulose accessibility. Disk refining has also been used in many other biomass pretreatment processes to significantly improve the sugar yield (normally 10%–20%). J. Y. Zhu at the U.S. Department of Agriculture (USDA) used disk refining with his SPORL technology (sulfite pretreatment to overcome recalcitrance of lignocellulose) on softwood treatment and achieved

>80% sugar yield. Weiqi et al. used disk refining with hot water treatment on rice straw and increased sugar yield by almost 20%. Sunkyu Park used autohydrolysis with disk refining and improved sugar yield by up to 15% on sugarcane bagasse. Milling is also used in consolidated bioprocessing to significantly increase the butanol yield. Disk refining is also used, along with DuPont's dilute ammonia pretreatment, and significantly improved sugar yield. There are many other thermochemical pretreatment methods using disk refining to further improve sugar yields because it is cheap and efficient.

Disk refining is a critical piece of equipment that is essential for biomass deconstruction, especially for low-severity pretreatment. Our project is developing a first-principles-based computational tool to predict the energy consumption during disc refining. A thorough literature study has been done. There are two types of existing research that are similar to our work: (1) Empirical/semiempirical correlations of disc refiner power consumption with refining parameters in the pulping industry. This type of correlation is heavily dependent on the type of refiner, refiner plate type, and pulp properties. These empirical-based models are not expected to be transferrable to a different type of refiner/plate. (2) CFD models in the literature do not show predictions/validations in disc refining power consumption or do not have validations at all. These models have been developed in the pulping literatures in the past decade. They focus on the fluid flow pattern inside overly simplified plate geometries (using simple 2D/3D geometry). They rarely have rigorous experimental validations. None of this research showed power consumption prediction and validation. The key drawbacks in this research are the lack of experimentally measured rheological properties and a realistic disc refiner plate geometry (and most of the models are not well developed to be validated). In contrast, our modeling effort focuses on developing a rigorous modeling framework that uses experimentally measured rheological properties and realistic 3D-scanned refiner plate geometry to ensure high fidelity of the simulations. We also implemented power consumption calculations based on the simulation results to compare with experimental validation. Because power consumption is the metric we are interested in, we used experimental measured power consumption to benchmark our model simulations. We have successfully validated our modeling framework. The DMR process and hydrolysate sugar produced has many advantages over other pretreatment methods; however, energy consumption remains a key priority of R&D. The DMR process consists of two major GHG sources: sodium hydroxide (NaOH) usage and refining energy. Reducing disk refining energy is a must for DMR sugar to earn the U.S. Environmental Protection Agency's (EPA's) D3 renewable identification number (RIN) credit via GHG reduction. Disc refining requires 200 kWh/tonne of biomass (about $20/t) to achieve 80% sugar yield, and the refining cost is about 10% of the MFSP, producing 36% of the overall GHG emissions of DMR. Higher yields (>90%) require much more energy, near 400–500 kWh/tonne, with existing disc refiner plate designs that were intended for paper production, not biomass deconstruction. This current project is developing disc refining models to reduce the energy consumption that is absorbed by frictional losses instead of performing the desired structural and physical changes to the biomass (and/or pulp). The models enable the rapid design simulations required to optimize the disc refining process parameters and plate designs, which is not currently possible with the available iterative experimental approaches and cost/time to manufacture plate designs in an iterative fashion. Our *ab initio* modeling methods are not only applicable to herbaceous biomass but also translatable to pulp processing, where energy consumption and GHG emissions may also be reduced, and further enhancements in the process are possible.

SCIENTIFIC METHODS FOR BIOMASS REFERENCE SCENARIOS

Oak Ridge National Laboratory

PROJECT DESCRIPTION

WBS:	3.1.4.001
Presenter(s):	Keith Kline
Project Start Date:	10/01/2017
Planned Project End Date:	09/30/2020
Total DOE Funding:	$250,000

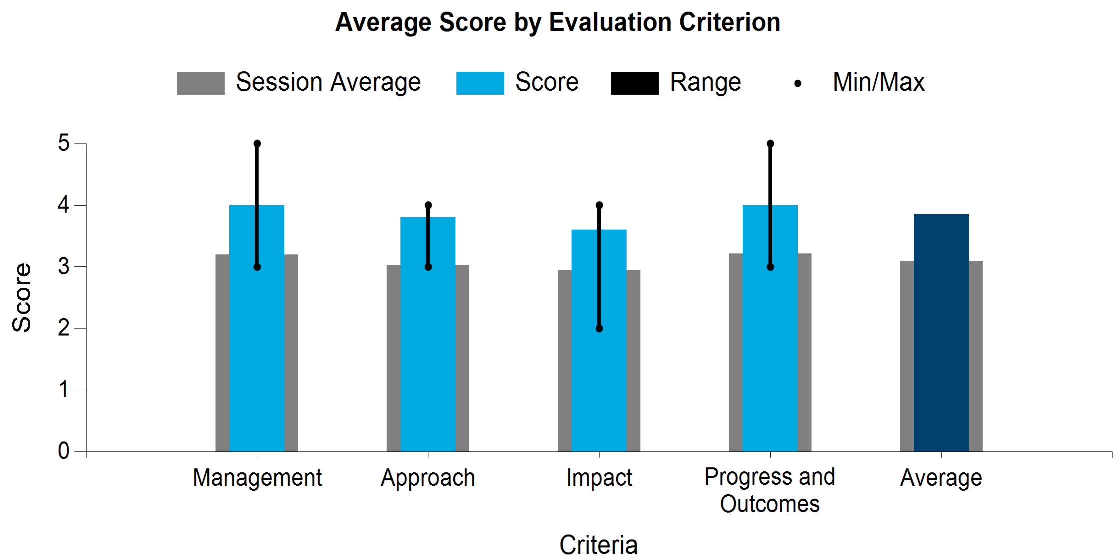
This project (concluded 9/30/2020) engaged stakeholders to develop a protocol for reference scenarios involving bio-based systems. Rationale: To quantify the effects of a bio-based product, a comparison of the bioenergy product system and a reference scenario is required. The reference scenario defines conditions in the absence of the bioenergy system with respect to the use of land, energy, and materials. Prior to the project, no protocol or standard was available, and reference scenarios were highly variable and poorly documented, resulting in conflicting and potentially biased assessments. Reference scenario assumptions should be structured and documented to permit proper analysis and interpretation of bioenergy assessments.

The project achieved goals by sharing the draft protocol and incorporating suggested improvements in two international standards (now published):

- ASTM E3256-20 - Standard Practice for Reference Scenarios When Evaluating the Relative Sustainability of Bioproducts
- ASTM E3066-20 - Standard Practice for Evaluating Relative Sustainability Involving Energy or Chemicals from Biomass.

The latter was revised and updated based on recommendations from this project.

The project addressed BETO needs for more consistent quantification and clear documentation of the net effects of advanced bio-based fuels and products and an expanding bioeconomy. The project also addressed the need for consistent industry standards and best practices.



What would happen in the absence of a bioenergy option? Images clockwise from top center: managed plantation, agriculture, urban development, wildfire, protected forest, unmanaged plantation... The innumerous possibilities complicate bioenergy analysis. New standards support transparent and consistent documentation of reference scenario assumptions.

Photo courtesy of ORNL

COMMENTS

- The development of a reference case for biomass development is a critical need for BETO and was accomplished in this project. As we move to include increasingly more "externalities" in analysis and comparison of projects, developing a basis for comparison is invaluable. Although this reference case cannot be "commercialized," it will allow investors and other funders to compare among alternative and make consistent decisions. The project team got participation and buy-in for a wide cross section of the biomass and life cycle assessment (LCA) communities, as well as acceptance by ASTM. I cannot believe this was an easy task, but it speaks well of the overall management of the project.

- The project appeared to want to solicit information from as many sources as possible. The time commitment from the group would have been helpful to understand the level of collaboration. The project may have tried too hard to involve so many stakeholders, but at the end of the project, their continued effort likely resulted in a better tool than had they made the project easier on themselves and worked with a smaller group. The standard is working as a best practice tool, which will be challenging to keep updated given the changing technology landscape. It is unclear if there is someone who will continue to keep this standard up to date following the close of the project. Consistency in the approaches on LCA/TEA evaluations would benefit the industry, but it is not clear if there are obvious errors from past projects that need to be corrected. This appears to be a tool to help those new to the industry as opposed to a tool to correct a problem. The project has produced two standards based on the work, which is what it set out to do.

- The presentation was somewhat confusing, but the final products of the project (ASTM standards) look to be very useful and necessary for the proper validation of biomass processing options.

- The slide deck itself and the presentation (too much information was presented too fast, like 90% of the talks) made it difficult to see what was (1) the point and (2) the level of progress. The structure and wording of the deck were unnecessarily abstruse. The supplementary document distributed after the talk clarified most of these points. The objective, in fact, is a useful one, and good progress has been made. The approach remains difficult to tease out in an understandable way. Progress is also somewhat hard to quantify. After reading through the deck at least twice, viewing/listening to the presentation, and reading the supplemental document, I would still find it difficult to succinctly explain what was done in this product and what the document's actual value is. Apparently presenting the actual standards is problematic, but perhaps at least they could have been described in a bit more detail.

- This project has been quite successful, producing two published standards to make biomass reference scenarios more consistent across the industry. As a result, LCA and other assessments of bioproduct impacts will become more accurate and comparable across projects.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you for the many thoughtful comments and suggestions. We appreciate the reviewers' acknowledgment of the significant achievements made by this modest initiative. We also thank the extended reviewer community, including more than 60 other individuals and organizations for their contributions to the development and drafting of the protocol, standards, and related publications. One review noted the challenges of involving so many people with disparate perspectives. We felt it was important to involve a broad range of stakeholders so that the model developers and model users, including industry and regulatory agencies, would appreciate the importance of clearly specifying reference scenarios. Our goal remains to facilitate assessments wherein reference scenarios are carefully designed and systematically documented as the bioeconomy continues to grow and evolve. The reviewers also raised excellent questions regarding the maintenance of a standard that offers "best practices" because such practices will change over time, and thus the standards will require periodic review and update in the future. We agree. Please note that the decision for this project to engage with an established international standard-setting body, ASTM, was a strategic solution to address this challenge. Rather than a report or article that is published and then remains static and dated with time, the publication of our results in the form of international standards ensures that they will grow and improve over time as living documents. All ASTM standards must undergo a formal review at least once every 5 years. The reviews provide opportunities for improvements and revisions based on input from users and committee members. The standard is then revised and re-balloted via a transparent approval process, where each review comment and any negative votes are addressed prior to final approval and publication. Finally, we also appreciate the reviewers' astute observation that the standards and outreach materials developed under the project will support more consistent approaches to LCA and other evaluations of bioenergy and thereby benefit the industry by filling "a critical need" for a more consistent basis of comparison. We wholeheartedly agree, and we thank you for contributing to this initiative.

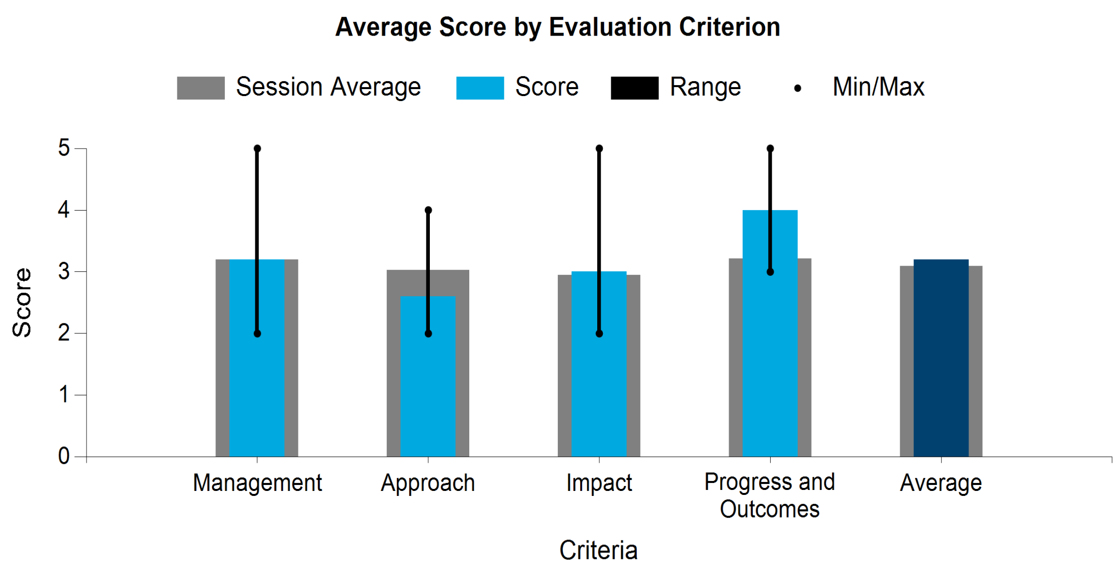
BIO-C2G MODEL FOR RAPID, AGILE ASSESSMENT OF BIOFUEL AND COPRODUCT ROUTES

Lawrence Berkeley National Laboratory

PROJECT DESCRIPTION

WBS:	3.1.4.002
Presenter(s):	Corinne Scown; Deepti Tanjore; Katy Christiansen
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$325,000

The objective of this project is to make TEA and LCA of lignocellulosic biorefinery technology options simpler and more accessible to a wide range of researchers and industry leaders. To achieve this objective, we have developed a lightweight, flexible model capable of quantifying production costs and life cycle emissions for either a hypothetical facility or a specific location with identified organic/biomass feedstocks. Our proposed project focuses on building and integrating three key components: (1) a rapid biorefinery siting and resource filtering tool; (2) a modeling framework for evaluating trade-offs within a biorefinery configuration, using basic mass and energy inputs/output; and (3) an input-output model for quickly calculating life cycle metrics of interest, such as GHG emissions. The three components of this Bio-C2G model use compatible data input/output formats and allow for quick, iterative evaluation of technology as it is developed during a research project or the early stages of a startup company. Each component is designed to generate summary result files and documentation that can easily be incorporated directly into journal papers, progress reports, and funding proposals. The result is a more rigorous, transparent framework for evaluating the economic and environmental impacts of biofuel and coproduct routes as well as a practical, useful set of tools that can be widely applied throughout the research and industry communities.



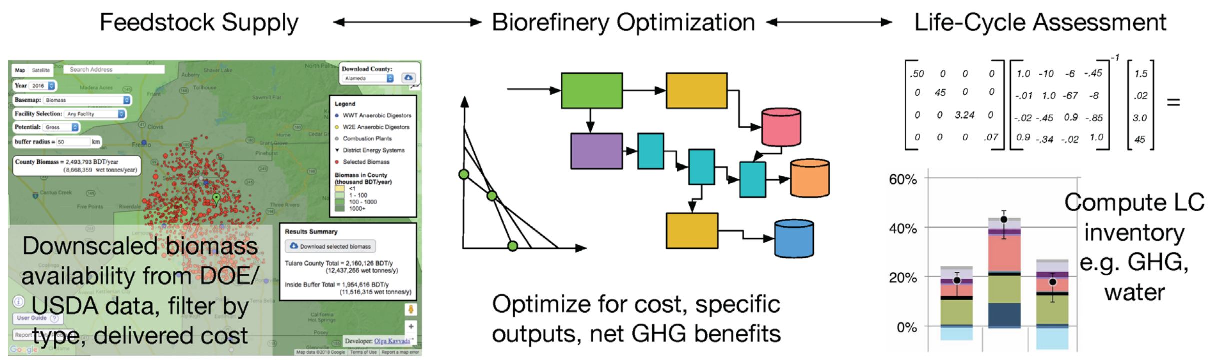


Photo courtesy of LBNL

COMMENTS

- This is another project without a clear purpose and users, and the value generation is unclear. It might be a good tool for outreach and advocacy but little else. Some of the included modeling looks overly simplistic and lacks actual industry insights. This is more of a toy than a proper technical modeling effort.

- The management plan is very superficial. It is a relatively simple project structure, to be sure. The approach was good except for the *very* narrow limits placed on feedback (Joint BioEnergy Institute, ABPDU). The value of this tool will be found in its breadth of application, so the broadest possible set of stakeholders should be surveyed for their input. The use of simulations to "train" the tool could have been better explained and defended. I believe that I understand this well, but it was clear that others did not. The "guardrails" comment on slide 7 was not sufficiently fleshed out, so there remained significant angst about nonexperts misusing the tool by ascribing too much precision to its output. Restriction to specific products perhaps is not as valuable as a parameterized description (select the most likely from a set of generic product recovery processes, etc.) as opposed to needing a fresh set of detailed simulations for each case. The focus on cellulosic sugars limits the scope to processes that will not exist for years, if ever. That said, the end product has the potential to be an extraordinary tool for a very wide range of "customers," and the progress so far has been excellent.

- This is a nice project. Tools such as this will be very helpful to the public and to the biomass startup community. Providing a tool with a consistent basis for projects to assess costs and outcomes will allow the community to compare across projects and will provide startups with a valuable tool to understand their potential impacts. This will allow the startups to apply for grants, to sell their technology to potential investors, and to better understand their overall impact. The tool should be modified to consider significant figures. Costs to the dollar are not reasonable. They should be rounded to no more precise than $1,000.

- This appears to be a very useful tool—and great progress has been made in developing it—but it is at a very high level, which limits its impact. It is understandable that to make a more powerful tool would be ridiculously complex, but the trade-off between accuracy and applicability significantly narrows the audience. It is unclear what input from industry may have driven the focus, or even if industry was approached for guidance or advice prior to the project start.

- The future plan for the tool, regarding who will update and maintain it, is unclear. It is unclear how the data in this tool are vetted. The existence of biomass in an area does not automatically mean that it is available. Transferring data between models is not as great of a challenge as the project declared in the presentation; rather, the challenge is keeping the tools updated as the project is adjusted, which this tool would help with. This tool, however, would not be worked on by a team of experts but by a nonexpert, as it states; therefore, this advantage does not really exist for what is here. There does not appear to have been any planning or evaluation of design options for the front-end user interface. It appears to be the result of one team's idea of what would make a good software platform, and the team did not plan to execute a formal customer research study. If it is targeted at the C-suite, high schools, or industry people, it would be important to know what forms and format they would like. This project is too large and broad to be achievable with impactful results if the intent is to model all conversion approaches. The use case for this project is very unclear. It is not clear whether the modeling is the equivalent of what can readily be done in an Excel file, is more in line with Aspen, or is somewhere in between. The idea of combining three different modeling tools is a good idea. Aspen will already do a TEA/LCA and process modeling, but it is expensive. The need of this tool for nonexperts is not clear. This seems to be a nice to have but not a need to have. Giving a "DOE-developed" tool to outside groups needs to have big red letters warning against relying on the data in a model, especially one with unknown accuracy. The accuracy level of the model needs to be determined and highlighted.

PI RESPONSE TO REVIEWER COMMENTS

- The project team appreciates the reviewers' time and effort in reviewing our progress. To clarify, the Bio-C2G tool is meant for use in the early stages of commercialization, to enable startup companies and researchers hoping to commercialize their technologies to better understand key cost and emissions drivers for their biofuel (and bioproduct) production routes.

  Industry partners have been engaged from the start of the project. The team also frequently discusses the model functionality with the ABPDU, whose researchers regularly work with a wide range of small and large companies and have a deep understanding of what needs those industry partners have. The emphasis on "guardrails" refers to the fact that, within the 50-plus input parameters users can alter in, for example, the sorghum-to-limonane production route, we do not allow users to enter any operating conditions or other parameters if values are far outside any reasonable range. For example, incoming feedstock moisture content is constrained between 20% and 70%.

  We disagree with the reviewer's characterization of this model as a "toy" given the 50-plus adjustable input parameters and its basis in conventional process modeling. Regarding the question on vetting, the team relies on internal validation as well as the peer review process when results are disseminated in articles.

  The points about significant figures and perception issues associated with the red warning text on the website are well taken. The team plans to remove the red warning letters, and the significant figures will also be reduced in the displayed results to reflect CapEx and OpEx to the nearest $1,000.

  Since the Peer Review presentation, the project team has added new feedstock options to Bio-C2G to capture a range of sugar feedstocks, including dextrose, beet sugar, cane sugar, etc. As noted in the presentation, the team received industry feedback expressing greater interest in sugar feedstocks relative to biomass.

FEEDSTOCK TO FUNCTION: IMPROVING BIO-BASED PRODUCT AND FUEL DEVELOPMENT THROUGH ADAPTIVE TECHNO-ECONOMIC AND PERFORMANCE MODELING

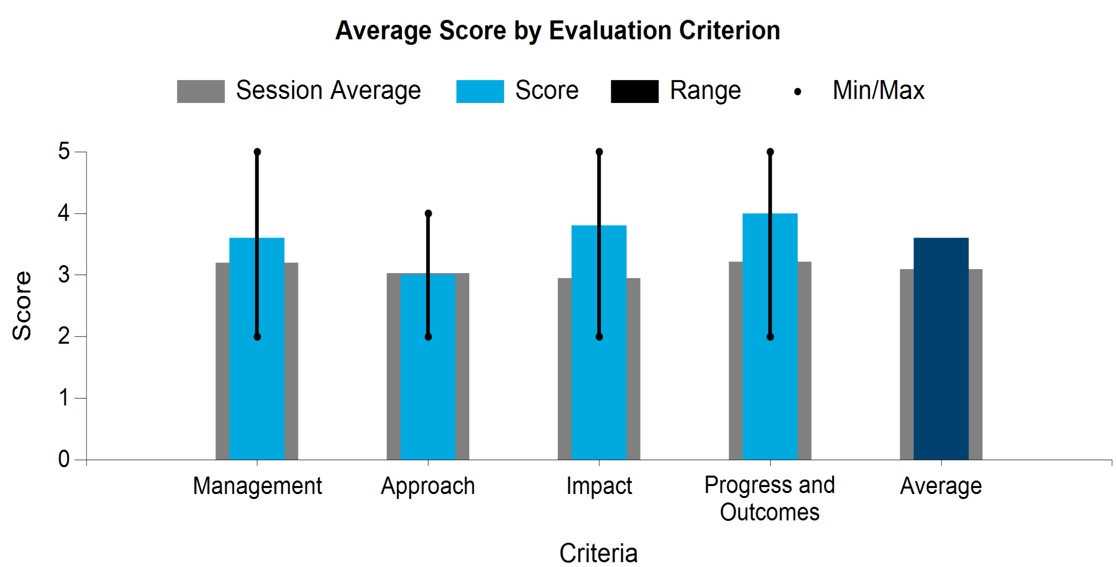
Lawrence Berkeley National Laboratory

PROJECT DESCRIPTION

WBS:	3.1.4.003
Presenter(s):	Deepti Tanjore; Vi Rapp; Katy Christiansen
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$275,000

Biological routes to fuels and products offer unparalleled flexibility in the development of novel molecules, tailored for high performance in a wide variety of applications; however, experimental property testing of these pathways is usually conducted years after initial bench-scale experiments are complete due to high experimental costs or high volume requirements. Neglecting to conduct property testing early in the pathway development cycle can lead to investments spent on scaling up production of bioproducts and biofuels that do not perform as expected.

The goal of this project is to develop an open-source "feedstock to function" tool that rapidly screens for viable bio-derived molecules to replace or substitute petrochemical intermediates, fuels, and chemicals. This web-based tool leverages machine learning to predict biomass-derived molecule properties, and it evaluates the cost, benefits, and risks of promising molecules. To establish the framework for this web tool, we first demonstrate the capability of our machine-learning-based approach to predict high-value properties of alternative jet fuel pathways. Coupled with a lightweight TEA and LCA model, the tool successfully predicts molecule properties, costs, and emissions. Overall, this tool will help reduce risk early in the R&D cycle and enable faster, less expensive bioprocess optimization and scale-up.



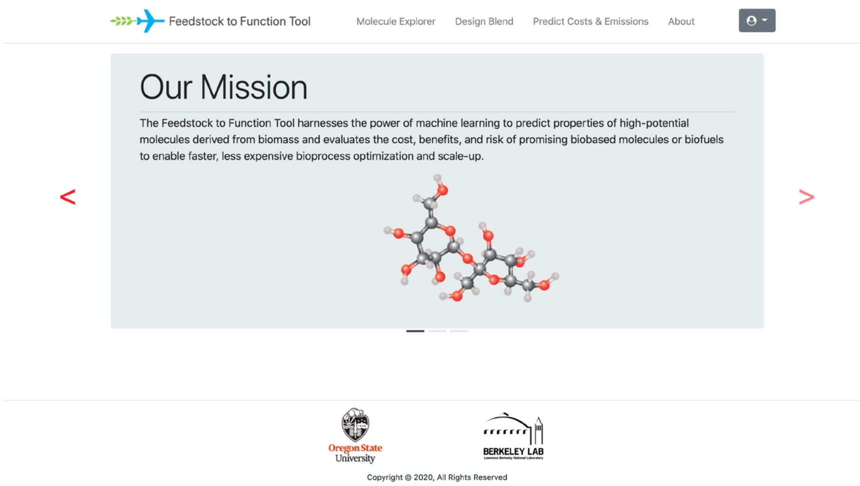


Photo courtesy of LBNL

COMMENTS

- This is another modeling project that does not seem to rely on sound understanding of the phenomena under consideration. It is unclear how any validation of the estimated properties is being done. Some of the error analysis looks appallingly amateurish!

- Blends of fuels as well as individual components are to be predicted. Blends, of course, are significantly more difficult to predict, especially for fuel blends that may have dozens of different constituents. It is not clear whether this product will be able to predict such a complex mix. It is unclear how the project determined "actual" cost data with so many data points, if, from a literature review, these data are notoriously varied in equipment type and size, making comparisons challenging. The presentation did not spend any time discussing the validation testing setup and methodology. Machine learning was to be evaluated, but it was not clear how. It is unclear whether the project withheld a known chemical from the machine-learning data set and had its properties predicted as part of the validation process. Multiple properties are being targeted to be added to this model besides combustion to increase the value of this tool to multiple processes besides fuels. The cost accuracy target was not identified. Cost estimate accuracy can be determined based on ASTM standards. The property target accuracy was noted to be 15%, which would be very valuable in planning and predicting performance. The functionality of the cost estimating tool function is not clear. It would be beneficial to understand what inputs are required and what are generated automatically—i.e., are materials of construction an input or determined by the properties? The cost estimating tool seems to distract from the overall value of the project. It seems there are enough cost prediction tools in development. It seems as if this would be a good potential tool to project potential costs during R&D as a ±50% estimate. It is not clear how this project differs from an engineering estimate based on known pathway costs, i.e., a corn-ethanol plant is $2/gallon CapEx. An open-source, publicly available cost estimating tool would be beneficial for startups and universities for investigating new ideas and to provide them valuable information that can guide their efforts. It is unclear whether the project is targeting fuels projects with a blend of chemicals or specific specialty chemicals. If the former, the companies producing these compounds do not generally understand all the structures the compounds exist in. It is not clear if this project has taken that into account. If the latter, then the reviewer is confused about which types of compounds and what properties are in question.

- This is a nice project with a great summary. I am not sure about the combination of physical properties, costs, and LCA, especially process costs. It seems like the project should focus on properties only. LCA can be included because they are primarily based on heat and material balances. The estimation of feedstock handling and hydrogenation costs are a bridge too far for me, especially because they are based on process simulations. We have no biorefinery industry, and as a long-time process modeler and experienced engineer, I don't think that we can predict the costs, and we should not try. We do not know the costs; the best that a model can do is to show relative costs, and users of the model will not know this. I am excited that the project will add properties of blends, and I think that will be a huge benefit and impact. One issue is that they should do a better job of highlighting the potential error, and I think they should cut off property projections when the error is significant. Many times, researchers are desperate for data, and they will use whatever they can find and ignore caveats. The project should assess the level of error that is acceptable and only publish those values. If this was based on products only, I would probably give it all 5s. I think we dilute its effectiveness by including everything.

- This looks to be a very useful tool for industry, with some severe caveats. It appears that the data used for machine learning were generated by process simulation, so the result is essentially both machine teaching and machine learning; validation with real-world data would go a long way toward proving efficacy and use.

- This was one of the talks where I felt that the presentation did not do justice to the potential of the product. It seemed to get caught up in the details before the underlying motivation was clearly communicated. The link to real-world value was also not made strongly, and some of the intrinsic limitations of the property prediction from structure, especially *mixture* properties, was not acknowledged. The management plan was superficial, even though the project structure is relatively simple, and it should have been given more attention. Has this been connected in any way to the "retrosynthesis" work on the Bio-JET project? The potential linkage is obvious. Aviation fuel…is then looking at *cetane number*? Why? Cetane has no real "meaning" in a turbine engine. That said, this is the beginning of what could be an extremely useful tool in the hunt for high-value biomolecules.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you for your feedback and thoughtful comments. We appreciate the detailed review of this project, and we are also excited about the potential impact of this tool to researchers, startups, and industry. Regarding the question on motivation, as stated in the presentation, the motivation for this tool is to enable users to rapidly screen for viable bio-derived molecules that could replace or substitute petrochemical intermediates, fuels, and chemicals. As a proof of concept, we focused on predicting jet fuel properties of individual molecules and blends (e.g., individual molecules with Jet A). Output from this tool will help guide biofuel development early in the R&D cycle to support more productive experimentation while reducing cost and time spent chasing dead ends.

  Concerning the amount of technical details in the presentation, we specifically targeted the level of detail DOE requested. Currently, this project has met all technical milestones, is on schedule, and is on budget. Given the purpose and length of the presentation, we did not present a detailed, scientific discussion about validating the models and calculating error. Technical details about the validation of our model are as follows: To validate the models, we split the data set and reserved 80% of the data for training and 20% for testing. These test data are not seen by the model during training. We also used cross-fold validation methods to measure the prediction uncertainty. To validate the prediction's reliability (i.e., estimate prediction error), we use absolute prediction errors that include calculating Euclidian distances of the nearest training compounds and approaches outlined by Roy et al. The prediction versus experimental data graphs shown in the presentation are a standard method for demonstrating the model's predictive capability. Thank you for the excellent comment to highlight the prediction error and the appropriate cutoff thresholds. We will explore integrating functionality to let the user set the prediction error threshold. We will also leverage the methods described above to determine thresholds for removing property predictions with significant error.

Regarding our data, as stated in the slides, all property data used for training models are experimental. We fully agree that adding property predictions of fuel blends will further increase this tool's potential impact.

The reviewer is correct that cetane number is not relevant for turbine engines. Cetane number is, however, necessary for ensuring the stable operation of compression-ignition aircraft engines (see ASTM D1655 - Standard Specification for Aviation Turbine Fuels).

Thank you for also noting the intrinsic limitations of property prediction from structure, especially mixture properties, using empirical methods. As shown in the slides, we are using machine learning to correlate experimental Fourier-transform infrared spectroscopy spectra to blend properties. This approach captures unique features of fuel mixtures and blends (e.g., with Jet A) without needing to know the exact composition of the refinery fuel. Results presented and shown in the slides demonstrate the prospect of this method for predicting blend properties.

Regarding the cost predictions, the surrogate modeling approach (machine-learning model trained on a more computationally intensive mechanistic model) is increasingly common in a variety of research fields. We absolutely agree that validation with real-world data would be excellent, and this validation is done whenever possible; however, many of the fuel production routes included in the tool have not yet been commercialized and built at scale. The team has started integrating sugar-based routes (as opposed to lignocellulosic) in the tool, which contains more real-world data points for validation.

Regarding the accuracy targets for the cost, the surrogate model accuracy can be measured, relative to the full-scale physics-based simulation, in terms of R-square and standard error. Because real-world facilities do not yet exist for many production routes, accuracy cannot be judged against those facilities.

Regarding the ASTM classifications, the tool's predictions fall somewhere in the range from Class 4 to Class 5.

DETERMINATION OF THE FEASIBILITY OF BIOFUELS IN MARINE APPLICATIONS—PART II

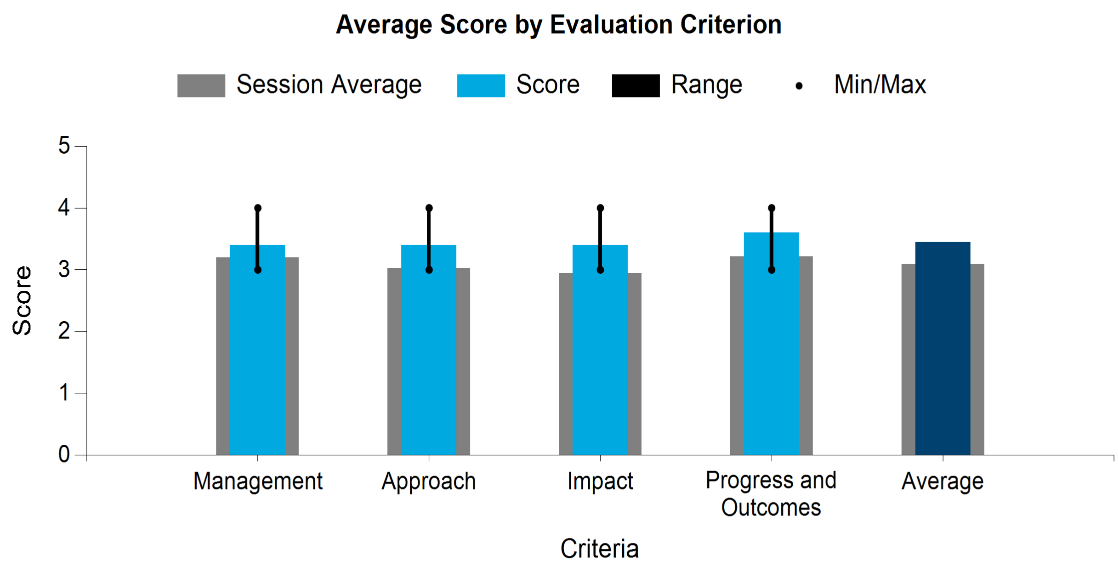
Oak Ridge National Laboratory

PROJECT DESCRIPTION

WBS:	3.1.4.012
Presenter(s):	Jim Parks; Michael Kass; Tim Theiss; Missy Miller
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2021
Total DOE Funding:	$380,000

A multilaboratory study—which includes Oak Ridge National Laboratory (ORNL), Argonne National Laboratory, NREL, and PNNL—was initiated to determine the efficacy of biofuels for the marine sector as a replacement or partial substitute for heavy fuel oil (HFO). Biofuels offer the opportunity to reduce GHG emissions and the carbon intensity of marine shipping, which current contributes approximately 2% of global carbon dioxide (CO_2) production. The International Maritime Organization has set an ambitious target of reducing GHG emissions by 50% in 2050, and biofuels offer a solid approach to achieving that goal.

The approach combines TEA and LCA with the technical feasibility of promising biofuels that exist within the BETO portfolio. Preliminary studies have been highly encouraging because bio-intermediates have demonstrated good compatibility, lower viscosity, and excellent combustion characteristics when blended with HFO at low levels. LCA shows positive benefits in reducing GHG emissions of biofuels for many production pathways. Preliminary TEA work is also encouraging. Industry stakeholders have been responding positively and are strongly supportive of a DOE BETO program on biofuels for the marine sector.



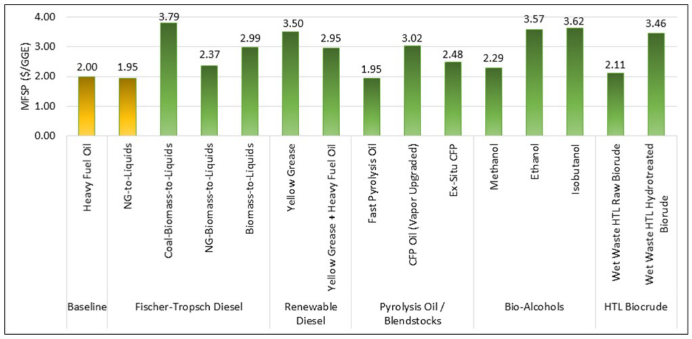


Photo courtesy of ORNL

COMMENTS

- This is an interesting project looking at the feasible use of biofuels for marine applications. It is a well-managed project with a coherent and clear approach. It seems like the cost of logistics and the establishment of a supply chain, as well as preferred feedstocks per targeted location, should be emphasized and prioritized. Some of the commercial targets being pointed out (slide 16) look to be high for what is currently a commercially marginal fuel (HFO). Seeking advice from the commercial side of fuel/refining companies should be very helpful here. Connections and differentiation between this project and project 3.2.1.001 should be clarified.

- Great amount of stakeholder feedback! Engine manufacturer, shipper, oil, and gas. This is the type of information that is critical for these types of projects. The management of this large task appears to be on point and using the strengths of multiple national labs effectively. The project should be collaborating with other NREL and FCIC projects to better incorporate project planning and lessons learned. The merits of biofuels for marine applications were reviewed, but those merits were not discussed in the presentation. It is unclear which, if any, pathways or fuels were eliminated from the study based on the work done. TEAs for all these processes have been done multiple times. It is not clear what work was leveraged and what work was new. There is a material compatibility project discussed in this Peer Review. The work between these two projects does not appear to be correlated. The project appears to provide a single repository for bio-oil information. This information could also be provided to Task 8 of the FCIC to support that project. The makeup of the bio-oil(s) chosen for this study is critical in its relation to the process and feedstock variables. How these bio-oils are chosen and how their differences impact the project results is important to plan, document, and understand.

- The management plan was weak because there is no schedule or defined interaction by the tasks. It appears to be seven independent tasks. Also, there were numerous repeated slides between this and the first marine fuel project, but neither project addressed their relationship and interaction. This project has similar issues to the previous project. The management plan is insufficient because there does not appear to be traceability to the pathway and characteristics (pH, oxygen, etc.) of the bio-oil. It is not even clear whether all the bio-oil tests are conducted on the same type of bio-oil within this project and compared to the other marine fuel projects. Also, it is unclear whether the acceptable blending levels (e.g., 15% in combustion) will meet the 0.5 wt % sulfur specification. So, although there are encouraging results, it is unclear whether the blending strategy can meet specs, even at the overall goal of the sulfur level. It is good that the fuel is being tested using industry standard ASTM tests; however, there does not seem to be any consideration of impurities in the bio-oil (e.g., inorganics) that may not appear on an ASTM specification because they are not found in petroleum but nonetheless could affect long term-engine performance. How is the project proposing to address these? I would not think that modeling would be sufficient, and longer-term engine testing may be more appropriate. The impact could be significant, but the path to commercialization is not totally clear. The stakeholder feedback slide was indicative of this because the feedback was just a bulleted list without any apparent organization or identification of key takeaways. It was also not apparent how this feedback was helping to guide the project. It appeared that the project needed stakeholder input, so it checked the box. The approach seems reasonable and technically sound, and good progress has been made toward goals. The overriding question that this reviewer has is why is the project comparing itself to HFO instead of very-low-sulfur fuel oil (VLSFO)? It seems that VLSFO is the current fuel standard, and any improvement should have been measured against this. The overall objective of the project is excellent because the commercialization of bio-oil-based processes and fuels is impossible without understanding material requirements; however, I found the management plan lacking. It was simply a listing of who is on the project, without a clear outline of tasks, milestones, risks, or mitigation strategies. In addition, there was no description or specification of the "bio-oil." A standard bio-oil should be used and specified, or the results are not useable.

- This is one of three projects with the same general goal, yet none appear to be communicating with each other. Combined, there is no clear critical path, nor a pathway to the fastest implementation. Several of the findings in this project seem worth pursuing to gain a foothold in the industry for biofuels (e.g., viscosity impact), and there are good preliminary TEA findings.
- This was a solid project across the board. The major concern, which is probably not the fault of the performers, was that this study should have *preceded* significant experimental, modeling, or standards development. It provides an excellent guide for the most promising directions in bio-derived marine fuels, though it is still far short of a comprehensive assessment. Only certain bio-liquids were considered, or at least only some were considered in depth. It was not clear precisely what the selection/downselection criteria were. There can be a great deal of variation in the liquids from one process to another, even within the same "family"—the impacts of known variations could have been better addressed. The number/density of the slides represented *far* too much information for the time available, and it meant that many topics were passed over far too quickly to be understood. The text and graphic density were far too great on some slides to be at all useful in a presentation format. The final product appears to be something of great use to the industry, and it is much needed considering pressures on sulfur levels and carbon intensity.

PI RESPONSE TO REVIEWER COMMENTS

- In hindsight, we should have done a better job detailing the relationships and leveraging the individual projects and the differences between this study (3.1.4.010-013), which looked at multiple biofuels and pathways, and the complementary effort (3.2.1.001) that focused solely on bio-oil compatibility with marine residual oils. The bio-oil compatibility study began 4 years ago and was instrumental in setting up the current multi-lab effort. Note that the bio-oil study (3.2.1.001) is concluding this fiscal year, and we are going forward as a single effort with the marine biofuel feasibility study (3.1.4.010-013). The tasks within the larger project were designed to be highly interrelated and dependent on each other. For example, the results from the experimental work are used by the research teams conducting the TEA and LCA work to better define and improve their models. This interrelationship should have been clearer in the presentation. We did include details on tasks, milestones, etc., but, in hindsight, we should have provided more information, perhaps as a backup slide or two. This project does come across as too complex, and we will work on simplifying and clarifying the roles for future presentations. We also failed to mention that the bio-oil used in 3.2.1.001 was not (CFP) oil provided by NREL, and the feedstock was mostly pine. This bio-oil was provided to us in quantities (approximately 10 gallons) that allowed us to conduct several compatibility studies, both in neat form and as a blend with VLSFO. No other bio-oil was used in that activity. Because of the large quantity available, we were also able to conduct compatibility studies with relevant metals as part of the 3.2.1.001 activity. The bio-oils that we are receiving as part of this study (3.1.4.010-013) have only just recently started arriving, and we have not yet completed the planned stability, rheology, and combustion experiments. We wanted to include a comparison of bio-oil with the HTL oils we had received earlier in the Peer Review presentation because there was valuable information related to the compositional differences that we felt were inherent between pyrolysis oil and HTL oil. Specifically, HTL oils comprise much longer and heavier molecular weight hydrocarbons than the pine-based bio-oil considered in 3.2.1.001. This finding influences the polarity and, hence, the compatibility of the oil. We realize that we should have made it clearer that we had leveraged the results from 3.2.1.001.

We fully agree with the reviewer on the importance of the logistics. We had a late start on the logistics task, but it is now progressing at full speed. Our team has had discussions with U.S. and international port authorities and is currently collecting data. The logistics and feedstock supply teams are the same that have successfully evaluated these factors for aviation biofuels. This is important because the BETO program seeks to evaluate the use of separating the light-molecular-weight hydrocarbons for aviation from the heavier-molecular-weight cuts suitable for marine use. The reviewer makes a good point about collaborating with the FCIC. I confess that I was not familiar with the FCIC, but I have made inquiries and discovered that some members of the research team are involved with the FCIC. Also, NREL staff working in the FCIC space are also part of the marine biofuels research team; however, a more formal working relationship would allow a better exchange of information and issues.

Yes, pathways have been discounted based on cost. We did show that some pathways are not cost-effective, and these will not be pursued. Perhaps we should have highlighted this better. At first glance, the TEAs might appear repetitive, but they are continually being updated and revised as new data are received. The preliminary TEA and LCA activities were instrumental in identifying important properties and variables that need to be considered. At the same time, experiments and modeling activities are critical inputs necessary to perform these analyses. We agree that the study is not fully comprehensive because we are still in an early stage of development. We prioritized the pathways and feedstocks that have the most potential within the BETO portfolio for consideration in these analyses within available resources. Established biofuels, such as biodiesel and ethanol, have already been extensively analyzed for TEAs and were not reanalyzed here. We recognize that there is a great deal of variation in a biofuel family, and we are starting to look at compositional factors for their impacts on marine performance. We agree that probably too much information was packed into the presentation, but we wanted it to be well understood that a large amount of work was conducted in this effort to meet the stated project goals. Note that the TEA and LCA results have been reused and modified quite a bit as new information was received. This information included new cost data, pathways, stakeholder feedback, and technical findings related to biofuel performances. We fully anticipate that as the experimental work continues to progress, the TEA and LCA efforts will be improved.

The reviewer is correct that bio-oil makeup significantly impacts its performance as a marine fuel. To date, we had received limited quantities and conducted experiments with the bio-oils we had on hand. We are getting newer bio-oils with varying processes, and we are understanding processing impacts on their performance as a marine fuel. Three types of pyrolysis-based bio-oils were selected for marine fuel evaluation: non-CFP oil, catalytic fast pyrolysis produced over Pt/TiO_2 catalyst (bifunctional hydrodeoxygenation catalyst), and CFP produced over ZSM-5 catalyst (zeolite catalyst). For each, the whole bio-oil and residue fractions after the removal of the light components will be evaluated, resulting in a total of five to eight bio-oil samples. Non-catalytic pyrolysis oil was prepared from clean pine in NREL's 2-inch fluidized bed reactor. For CFP oil over ZSM-5, oil was produced in NREL's pilot facility. Based on these very recent results, we are now identifying compositional variables (such as oxygen content) that are important. Another comment addressed the lack of the traceability of the pathway and characteristics (pH, oxygen, etc.) of the bio-oil. Our response is that this information is available, though it was not included in the slides. For instance, we found CFP oils to be more compatible with VLSFO than the non-catalytic pyrolysis oils because they have lower oxygen contents and, hence, will be more miscible with hydrocarbon compounds. The two oils that behaved the best so far are CFP oils prepared over the Pt/TiO_2 catalyst (7195-077, which is whole oil, and 7070-034, which is the high-boiling fractions of that type of oil). The other oils that were less compatible were catalytic oils prepared over a zeolite catalyst (ZSM-5), which was less effective at upgrading than those prepared over Pt/TiO_2. We are now examining bio-oils produced via different pathways and determining the compositional effects. Note that we have the bio-oil specs and included these in recent publications. We agree that using both HFO and VLSFO terminology is confusing, and we apologize for the inconsistent terminology. The work in this study is using VLSFO as the baseline, not high-sulfur HFO, and this should have been made clearer. Biofuels are not needed to reduce the sulfur content, but they have significant potential for cutting the overall life cycle GHG and other emissions and might offer an additional efficiency benefit.

Regarding our lack of consideration of the impurities in bio-oil, we intend to evaluate impurities through compositional analysis. We have not yet considered the impurity impacts on engine performance. The biggest concern will be filter plugging, which is important, and yes, we need to consider potential negative impacts due to impurities. We fully agree that engine testing is necessary to obtain more accurate performance and emissions data. The LCA activity, in particular, needs experimental validation to accurately assess the true GHG profiles. Setting up engine experiments is time-consuming and expensive, and we could not accomplish this during the current fiscal year. We are planning on future engine-based experimentation, and we are exploring four-stroke and two-stroke options. This project is fulfilling a key step in the pathway to commercialization by providing information to the maritime sector. Our industry stakeholders have made it clear to us that they do not want to see us favoring one fuel type over another; rather, they need for us to provide them with information they can use to decide on and develop strategies to reduce GHG emissions. This is a role well suited for DOE labs. As noted by one reviewer, we did not provide a complete listing of all our stakeholder interactions and, in hindsight, should have included the full non-abbreviated listing as a backup slide. We have had a number of discussions with the stakeholder community (in both group and individual settings), and they have been important in directing us toward biofuels of interest and those that are not, including baseline fuels such as natural gas. The feedback slide was, in fact, a listing of key takeaways. We should have made this clearer in the presentation.

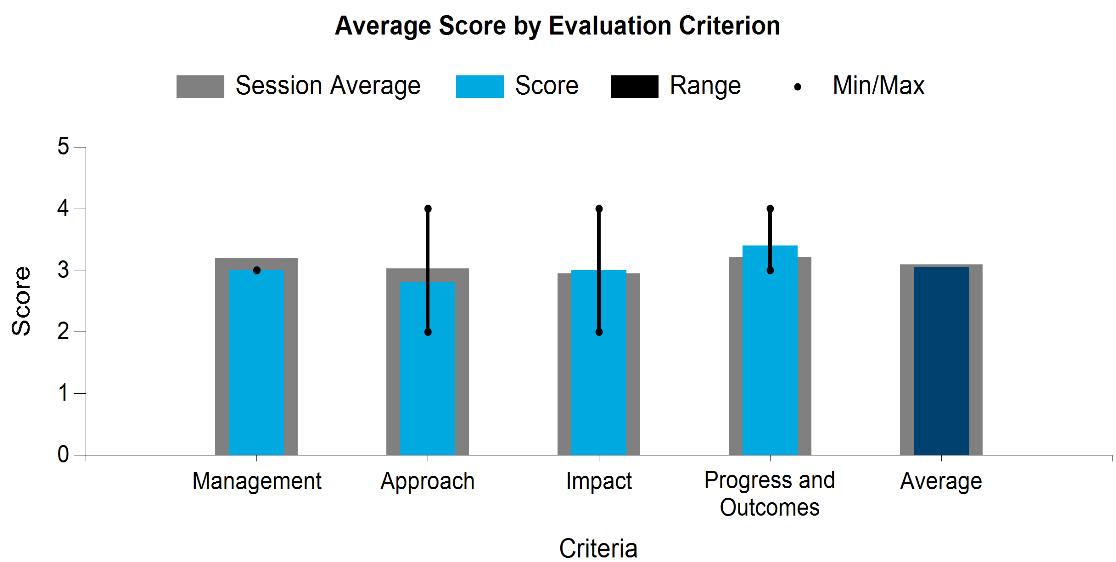
EVALUATION OF BIO-OILS FOR USE IN MARINE ENGINES

Oak Ridge National Laboratory

PROJECT DESCRIPTION

WBS:	3.2.1.001
Presenter(s):	Jim Parks; Michael Kass; Tim Theiss; Missy Miller; Brian Kaul
Project Start Date:	10/01/2017
Planned Project End Date:	09/30/2021
Total DOE Funding:	$722,873

The maritime sector represents a large potential market for biofuels, which are naturally low in sulfur and significantly lower in global GHG emissions. This task aims to determine the technical feasibility of using biofuels, particularly minimally upgraded bio-oils, in marine engines in place of current HFOs. Results indicate good blending compatibility with market fuels, resulting in stable blends that do not precipitate asphaltenes. Blend viscosity was favorable, offering potential efficiency gains through reduced heating requirements. Blends of up to 15% bio-oil indicate acceptable ignition properties, though higher blend percentages will likely require engine/process modifications to avoid polymerization of the bio-oils at high temperatures. To evaluate expected efficiency and emissions impacts in the slow-speed two-stroke engines comprising approximately two-thirds of the global fuel market, a digital twin model of a 1:10-scale two-stroke research engine at ORNL was developed. This capability can be used for screening candidate biofuels in the future. Options for obtaining efficiency and emissions impact data for medium- and high-speed four-stroke engines—which comprise approximately one-third of global marine fuel use but the majority of the inland, naval, and cruise fleets—are being scoped.



COMMENTS

- This project is on the evaluation of bio-oil use in marine applications. It focuses on the technical feasibility of "some" bio-oils from a clearly experimental and detailed modeling perspective. Connections and differentiation between this project and project 3.1.4.012 should be clarified.

- I appreciated how the team is approaching the challenge of testing unavailable fuels in large unavailable engines. This does not remove the overall requirement, however, that this be done at some point as part of another project to validate the results provided here. The business strategy and implementation for marine engines is nearly as important as the technology. The overall plan for the implementation was not fully discussed. It is difficult for the reviewer to understand where this project is in the overall project (i.e., fuel in ships) being complete. The lack of industry support for this project troubles this reviewer. If this is a challenge in the industry with a current new standard to meet, then industry should be pouring in dollars and time to meet this challenge; however, they seem rather silent, leading to the obvious question of whether this is a problem or not. It is not clear how the international maritime rules are to be enforced or in which countries. This is a great example of a project within DOE that is attempting to make inroads into a new market that could support multiple companies nationally. The project does not address whether the 15% blend helps the industry meet the standard specified. The oxygen content of the bio-oil should be consistent and realistic for the multiple technologies that are being evaluated. The project did not specify which bio-oils they were using in this project and did not appear to believe that the selection of these bio-oils and their pathways was a critical evaluation metric for the project. It would have been a very helpful to understand what range of fuels were under study in this project because not all bio-oils are the same, and the specific makeup of the bio-oils is important to distinguish. Additional work is needed on logistics to determine the correct feedstock(s) that can be used in the multiple ports that will provide the industry and consistent fuel. The overall plan of this project and its relationship to the overarching plan to develop this industry were not clear. Project metrics are lacking. The end result of this project is unclear. There is a lot of potential impact to make bio-based marine fuels viable, but how far this project will bring this into fruition is unclear. The U.S. Department of Defense also utilizes four-stroke engines in parts of its feet and should be included in this work as a stakeholder.

- The management plan is adequate for a single-lab project, but some procedures, such as the selection of bio-oils for testing, are not laid out. The fact that a limited range of oils were considered from the spectrum of liquefied biomass, with few/no samples of other bio-liquids, limits the impact. The project will serve as a reasonable example for further work, less than a truly standard set of certification tests. Even VLSFO, for example, varies somewhat from one batch to another and from one supplier to another. The stability of bio-oils was considered to some degree, but it was not fully addressed. Property changes over time in the context of onboard storage could effect significant changes in the results. It was not clear that the level of certainty about potential bio-based marine fuels justified the level of model development seen here. Fuel selection, blending, property, and blending tests probably should be more extensive before much modeling is done. There were more than a few points of confusion concerning exactly what was done in each of the three ORNL projects related to this and to what degree they were fully integrated. Perhaps there was (or needed to be) a management plan one level up.

- The project needs to be clear about the bio-oil specification and how this project coordinates with the other project. It is not clear that the management plan is considering these significant handoffs. Bio-oil should be specified, at a minimum, by feedstock, process, acid content, oxygen content, pH, and oxygen speciation. NREL, or whoever is supplying the bio-oil, should have some type of naming convention, and, if possible, all tests should be run with the same lot or at least the same methodology. When this is not done, we cannot be sure that our comparisons are appropriate. This is a management issue. It seems that VLSFO should be the standard for TEA, not HFO, because this would be the fuel that any blend would need to compete against. I do not understand why everything seems to compare to HFO. The project should evaluate the impact of the drop-in viscosity on the heating requirements and/or any other process improvements. The impact could be high, but it was not clear how the results of the study and the model development were received by the stakeholders and what next steps may be. The path to commercialization should be made more clear.

- This is a very ambitious project in that it attempts to model all combustion kinetics for a huge number of components and a large number of feedstocks. In addition, it appears to assume that bio-oils will remain consistent with the original source. The efficiency improvement seems superfluous in this project; the goal should be to determine the compatibility to facilitate replacement, not complicate commercialization by requiring biofuels to perform better than those they replace.

PI RESPONSE TO REVIEWER COMMENTS

- We apologize for the lack of clarity on the connections and differentiation between this project and the multi-lab projects 3.1.4.010–013. This task (3.2.1.001) began 4 years ago with a focus on initial feasibility studies considering the compatibility of bio-oils with marine engine applications and was instrumental in setting up the current multi-lab project, which has a broader scope, including other barriers to commercialization. It will be ending this fiscal year, with future work being conducted within the larger multi-lab collaboration. Stakeholder engagement and the evaluation of the big-picture path to commercialization will continue to be a focus of that project going forward. Blends of, e.g., 15% bio-oil are considered a necessary pathway to the widespread use of biofuels as they become increasingly available over time. Even with 100% biofuel usage as the future target, lower blend levels will be needed in the transition period, and thus a good understanding of compatibility with current market fuels is required. When this task was initiated, the switch from HFO to VLSFO was still several years in the future, and the baseline terminology was set accordingly, with a focus on sulfur reduction. As the industry has navigated that transition and its focus has turned to CO_2 reduction, the terminology for the baseline market fuel has shifted accordingly. Blends considered here were conducted with VLSFO rather than high-sulfur HFO; we apologize for the inconsistent terminology. TEA is being conducted under the multi-lab collaboration in 3.1.4.010–013 rather than as part of this task. We agree that engine testing will certainly be necessary to fully address the knowledge gaps around bio-oil impacts, to develop better combustion kinetic mechanisms, and to validate modeling results. We are working to identify the best means to generate relevant engine data for these purposes going forward. Long-term stability will also be important, as noted by the reviewer. Plans for evaluating this are being developed for proposed future work within the multi-lab collaboration. Consideration of a larger variety of biofuel compositions is also planned.

EVALUATE NEW BIOMASS-DERIVED LIQUID FUELS FOR MATERIALS COMPATIBILITY

Oak Ridge National Laboratory

PROJECT DESCRIPTION

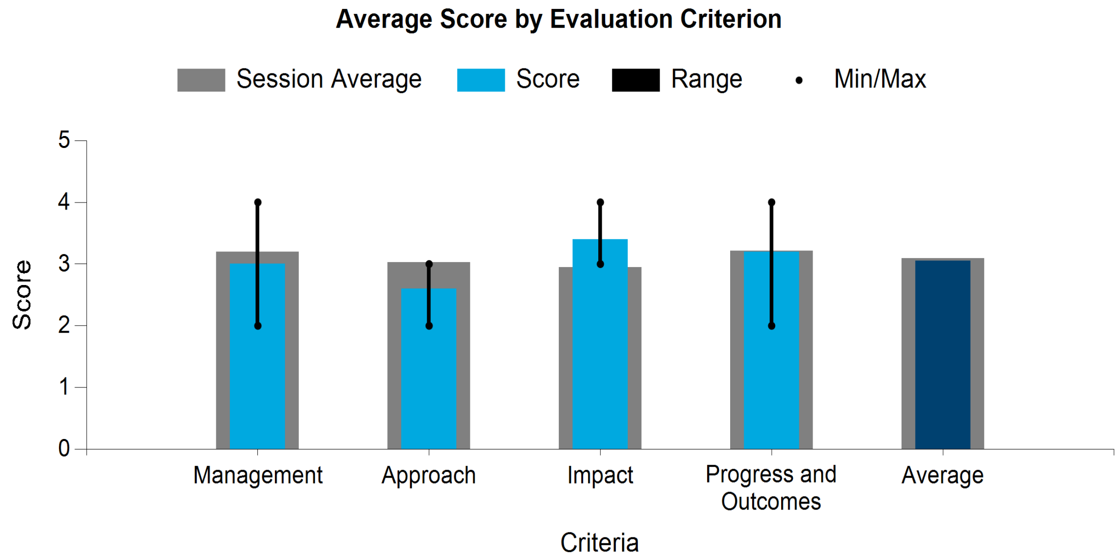
WBS:	3.2.1.003
Presenter(s):	Jim Keiser; Jim Parks; Tim Theiss; Missy Miller
Project Start Date:	06/23/2009
Planned Project End Date:	09/30/2018
Total DOE Funding:	$1,452,500

The ultimate objective of this project is to identify the components of bio-oils that cause degradation of metallic and nonmetallic materials, to determine the degradation mechanisms, and then to acquire sufficient information so that materials with acceptable corrosion resistance can be identified. By achieving these goals, we should be able to provide guidance to system designers and operators so that materials issues should not prevent the successful commercialization of any biomass liquefaction technology.

We have conducted and continue to conduct short- and long-term exposures of metallic and nonmetallic samples in bio-oils to identify materials suitable for storage and transport of bio-oils We have identified formic acid as a major contributor to the corrosion of metallic materials under storage conditions, but there may be other acids and potential chelating agents that contribute to the degradation of alloys with less than 10%–14% chromium—depending on the acidity of the bio-oil. For nonmetallic materials, the ketones and possibly aldehydes cause rapid degradation of some materials, and fundamental studies are underway to better understand the mechanism.

We have provided and are continuing to provide samples to national laboratories, universities, and commercial organizations for exposure under operating conditions. We know that under short-term exposures, coking is an issue, and we are investigating whether there are alloys that might be more resistant to coking. For longer-term exposures under operating conditions, we know that the oxide layer that forms on the surface of stainless steels is often porous and does not provide sufficient protection, leaving the alloy susceptible to intergranular corrosion. We suspect that minor elements in biomass hinder the formation of a protective oxide layer on the stainless steel. Further studies are needed to better define the corrosion mechanism and to identify more resistant materials.

The final result of this project will be the identification of corrosion-resistant, cost-effective materials such that materials issues do not prevent the successful commercialization of any biomass liquefaction technology.



COMMENTS

- This is an evaluation of the effects of bio-oils in materials. There is some confusion in targeted alloys (it is unclear how common some of them are). Some important questions remain unanswered in terms of the cost of these alloys beyond their metal content. How available and ready to source are they?

- Slide 14: It was unclear whether factors were studied other than volume (swelling?) before concluding that all the plastics were acceptable for bio-oil/biocrude. The work plan for this project did not appear to collaborate with the FCIC team that is also conducting MOC studies. Techniques or lessons learned could have resulted from this collaboration. It is unclear whether welding material is a separate part of the study. I really liked the approach to obtaining several pieces of equipment that were used in operation without creating your own hydrotreating unit. The process differences between the three different places would have been good to address. The goal of this project should be to identify not only whether ash is responsible for corrosion, but also which species. Because bio-oils can vary greatly depending on the feedstock and process, the mechanism of corrosion should be understood before concluding the effort. The application in hammer mills and heater tubes appears to be premature to the overall question of MOC compatibility. Why are we looking at hammer mills and heater tubes when we have not answered the fundamental question on this project, which is what materials are suitable for bio-oils production? The answer cannot be some noncommercial alloy.

- The technical approach is very strong on the technology and testing methodologies; however, I was struck by the lack of standard test specifications and some type of overall outline of which tests would be required for commercial use. Are there no ASTM standards or other standards that materials must meet for storage or transport? This seems to be critical. Further, I was surprised that the team was developing new materials. Is there enough budget and time to get this done? Is this the best use of funds? The impacts should also be strengthened. It was great to see that the team took note of previous reviews and are disseminating their findings. Perhaps instead of developing new materials, the team could focus on developing standards and recommendations for storage and the transport of fuel bio-oils. It is not clear that the avenues selected for disseminating the findings are the most relevant. The progress and outcomes are the best part of the project. It is clear that good work is being conducted and many helpful things are being learned. Having a clearer plan and a more narrow approach with stronger input from industry would significantly improve the project.

- There are a number of issues, none serious, but together, they seem to make this project less useful than it might have been. Alternate or exotic materials were not clearly of value. The MOC evaluation seem to have been part of the motivation, but why not study these in the context of material that might be used, or better yet, that *are* already used in equipment where bio-oils might be handled? In terms of staff employed and equipment utilized, some were more obviously of value than others, and it begs the question: Were people and facilities used "because they were there" or out of clear justification? The latter is not clear in all cases. In some cases, the more sophisticated testing might be justified for materials selection for an actual project, but with only sample evaluation versus a handful of bio-oils, may be too much. It was disappointing to hear that facilities were not available for high-temperature studies. This put exposure testing in the hands of third parties, and no doubt into more potentially variable and/or inadequately characterized conditions. It seems like Ensyn and NREL are the only bio-oil sources being used at ORNL, and this is certainly not a broad enough spectrum. At least a handful of comparison tests should be carried out using other oils. (It should be a requirement of BETO funding that samples be made available, under nondisclosure agreement, for testing of this sort.)
- This project directly supports two others studying bio-oils for marine fuels use, but it does not appear to be communicating with those other projects; although the data and conclusions being generated are important, there is no clear pathway toward commercialization. The purpose behind the addition of solid-phase processing to the scope is unclear and appears to be a distraction from the timely completion of the work needed to support the use of bio-oils as fuels.

PI RESPONSE TO REVIEWER COMMENTS

- Response to all reviewers: This is a very large project with seven separate tasks, and covering all of it in 20 minutes was impossible. In hindsight, it would have been better if there had been time to provide more background, but our presentation, for the most part, built on what we have reported in previous reviews. Because this is all new material to the reviewers, we apologize for the lack of background information.

  Regarding the comment, "Slide 14: It was unclear whether factors were studied other than volume (swelling?) before concluding that all the plastics were acceptable for bio-oil/biocrude": Our studies of nonmetallic materials have considered many other materials (elastomers and polymers) and other properties, including wet and dry hardness. We have also looked at structural changes using dynamic mechanical analysis to determine whether there are any changes in the glass-to-rubber transition temperature. This is an expensive test, so we are selective in its use. In the past, we have also conducted tensile tests, but, again, these are expensive to run, so we must be more selective. The volume and hardness changes are much more readily applied to large numbers of specimens.

  Regarding the comment, "The work plan for this project did not appear to collaborate with the FCIC team that is also conducting MOC studies. Techniques or lessons learned could have resulted from this collaboration": In fact, we have close collaboration with the participants in the materials task of the FCIC project. Several of us are participating in both projects, and we definitely work together. The FCIC project is addressing the initial processing of biomass, whereas this project is considering the effect on materials for biomass liquefaction and gasification and the subsequent storage and transport of bio-oil.

  "It is unclear whether welding material is a separate part of the study." We are not separately addressing welding materials, but we do consider the effect on welds when we examine welded components that have been exposed in operating systems. "I really liked the approach to obtaining several pieces of equipment that were used in operation without creating your own hydrotreating unit. The process differences between the three different places would have been good to address." We realize it would have been more informative to you if we had defined the differences between the exposure conditions, but, in fact, we have examined samples from more than a dozen exposure conditions. We should have provided a better description of the samples we reported on.

Regarding the comment, “The goal of this project should be to identify not only whether ash is responsible for corrosion but also which species”: In unreported studies, we have not found ash to be a major factor in corrosion—it is more the carboxylic acids for metals and ketones for some elastomers. The bio-oil composition seems more determined by process technique and processing conditions.

Regarding the comment, “Because bio-oils can vary greatly, depending on the feedstock and process, the mechanism of corrosion should be understood before concluding the effort”: As noted, understanding the degradation mechanism(s) is necessary before we can make competent recommendations of structural materials. By analyzing corrosion products and conducting detailed examinations of corroded components, we expect to be able to define the degradation mechanisms in more detail than we currently can.

Regarding the comment, “The application in hammer mills and heater tubes appears to be premature to the overall question of MOC compatibility. Why are we looking at hammer mills and heater tubes when we have not answered the fundamental question on this project, which is what materials are suitable for bio-oils production?”: The solid-phase processing task specifically calls for us to identify alternate materials to those currently in use for selected “challenge areas” in the corn ethanol production process and the MSW gasification process. Wastage of hammers in the milling of corn and the degradation of pulse heater tubes were identified by the industry organizations as areas where they would like help in identifying alternate materials.

Regarding the comment, “The answer cannot be some noncommercial alloy”: We agree that the noncommercial “model” alloys are not the solution, but they allow us to determine the effect of compositional variations on corrosion in specific environments. Once we can define the optimal composition of alloying elements, we can recommend commercial alloys that are similar in composition.

Regarding the comment, “This is an evaluation of the effects of bio-oils in materials. There is some confusion in targeted alloys (it is unclear how common some of them are)”: In a few cases, we are using model alloys to determine the effect of variations in alloy compositions, but we will always relate the results to commercially available alloys when we make recommendations for structural materials for specific applications. “Some important questions remain unanswered in terms of the cost of these alloys beyond their metal content. How available and ready to source are they?” One primary consideration in our recommendations will be to identify the most cost-effective alloys—we will consider corrosion resistance, availability, and cost.

Regarding the comment, “This project directly supports two others studying bio-oils for marine fuels use, but it does not appear to be communicating with those other projects; although the data and conclusions being generated are important, there is no clear pathway toward commercialization”: Again, this is a situation where we should have provided more information. In fact, there is good communication; the leader of the marine fuel studies is the leader of our task on the degradation of nonmetallic materials. Several of us are involved in both projects, and we apologize for not making that clear.

Regarding the comment, “The purpose behind the addition of solid-phase processing to the scope is unclear and appears to be a distraction from timely completion of the work needed to support the use of bio-oils as fuels”: The solid-phase processing task is addressing alternate materials for “challenge areas” identified by the process operators, and we will consider certain coating process and friction stir welding. We are also including alternate conventional materials in our testing as well as processing conditions, such as carburizing and nitriding, to address fouling and wear issues.

Regarding the comment, “The technical approach is very strong on the technology and testing methodologies; however, I was struck by the lack of standard test specifications and some type of overall outline of which tests would be required for commercial use”: There is a separate project addressing alternate testing methods and the development of testing procedures. As in other projects, two of our team members with strong chemistry backgrounds are participants in the project on test specifications and procedures. There is some consideration to incorporating the standards and procedures task in our materials degradation project for FY 2022.

Regarding the comment, "Are there no ASTM standards or other standards that materials must meet for storage or transport?": There are standards for transport and storage of petroleum-derived oils and fuels, but, as we discovered for acidity measurements, those standards and procedures are not always suitable for biomass-derived oils and fuels. For FY 2022, we are proposing to add a task to specifically address whether the standards and procedures for petroleum-derived products are suitable for biomass-derived fuels—particularly jet, marine, and diesel fuels. This seems to be critical.

Regarding the comment, "Further, I was surprised that the team was developing new materials. Is there enough budget and time to get this done? Is this the best use of funds?": Our presentation must have been misleading; we are not developing new materials. We have made model alloys specifically to help us determine the effect of small compositional variations on corrosion resistance, but these are not expected to be developed commercially or actually used in operating systems.

Regarding the comment, "The impacts should also be strengthened. It was great to see that the team took note of previous reviews and are disseminating their findings. Perhaps instead of developing new materials, the team could focus on developing standards and recommendations for storage and the transport of fuel bio-oils": As just noted, we are not developing new alloys, and we agree that attention needs to be given to the evaluation of existing standards and procedures developed for petroleum-derived fuels to determine their suitability for biomass-derived fuels.

Regarding the comment, "It is not clear that the avenues selected for disseminating the findings are the most relevant": We would welcome any recommendations on other methods of disseminating our results. We can reach other researchers and the operators of existing systems, but we would appreciate advice on how to reach process designers.

Regarding the comment, "The progress and outcomes is the best part of the project. It is clear that good work is being conducted and many helpful things are being learned": We appreciate the positive comments about the project, and we believe we are acquiring some useful information that will be of value for those responsible for selecting structural materials.

Regarding the comment, "Having a clearer plan and a more narrow approach with stronger input from industry would significantly improve the project": We are working with a few industries/commercial system operators, but a lot of the process developers are very secretive about their processes. We have nondisclosure agreements with a number of organizations, and those have enabled us to get some information and access to facilities; however, we would certainly welcome any advice you can offer on how to get our results more widely disseminated.

Regarding the comment, "There are a number of issues, none serious, but together, they seem to make this project less useful than it might have been. Alternate or exotic materials were not clearly of value. The MOC evaluation seems to have been part of the motivation, but why not study these in the context of material that might be used, or better yet, that *are* already used in equipment where bio-oils might be handled?": We apologize that the impression we gave was that exotic materials are of more interest than the determination of mechanisms. Our studies of degraded components from operating systems are helping us identify mechanisms and are providing guidance on the selection of alternate materials that might perform better than currently used materials. The operating systems are using conventional materials, and any exposures we conduct in the operating systems utilize commercially available materials. Apparently, our presentation mistakenly gave the impression that exotic and model alloys are major parts of the program, but that is not at all the case.

Regarding the comment, “In terms of staff employed and equipment utilized, some were more obviously of value than others, and it begs the question: Were people and facilities used ‘because they were there’ or out of clear justification? The latter is not clear in all cases. In some cases, the more sophisticated testing might be justified for materials selection for an actual project, but with just sample evaluation versus a handful of bio-oils, may be too much”: Certainly, some tasks have higher visibility than others, but the chemical characterization of bio-oils is essential, whereas corrosion testing of metallic and nonmetallic materials is at the heart of the project. Characterization of degraded samples is a critical follow-up of the corrosion testing. There are a couple tasks that are more fundamental in nature, but they are providing information to help us understand corrosion mechanisms. We believe all the tasks are justified, and the tasks included in the project have evolved over time as we see a need for an additional study.

Regarding the comment, “It was disappointing to hear that facilities were not available for high-temperature studies. This put exposure testing in the hands of third parties, and no doubt into more potentially variable and/or inadequately characterized conditions”: High-temperature pyrolysis environments cannot be adequately simulated in lab conditions for corrosion testing (by us or anyone else we are aware of). Instead, we utilize *in situ* exposure of alloys in pilot-scale pyrolysis systems. We are very interested in working with other entities to have a pilot-scale system run long term under controlled operation conditions devoted to corrosion studies. We have proposed such a new task, and we have, so far unsuccessfully, investigated the possibility of long-term exposure studies in commercial-scale pyrolysis systems in North America and Europe.

Regarding the comment, “It seems like Ensyn and NREL are the only bio-oil sources being used at ORNL, and this is certainly not a broad enough spectrum. At least a handful of comparison tests should be carried out using other oils. (It should be a requirement of BETO funding that samples be made available, under nondisclosure agreement, for testing of this sort.)”: Again, we had too little time to provide as much background information as would have been appropriate. In fact, we have gotten bio-oils from both domestic and foreign sources. Other domestic sources include PNNL, Iowa State, the University of Massachusetts, Virent, and others, and international sources include CanmetENERGY and Ensyn in Canada and VTT in Finland.

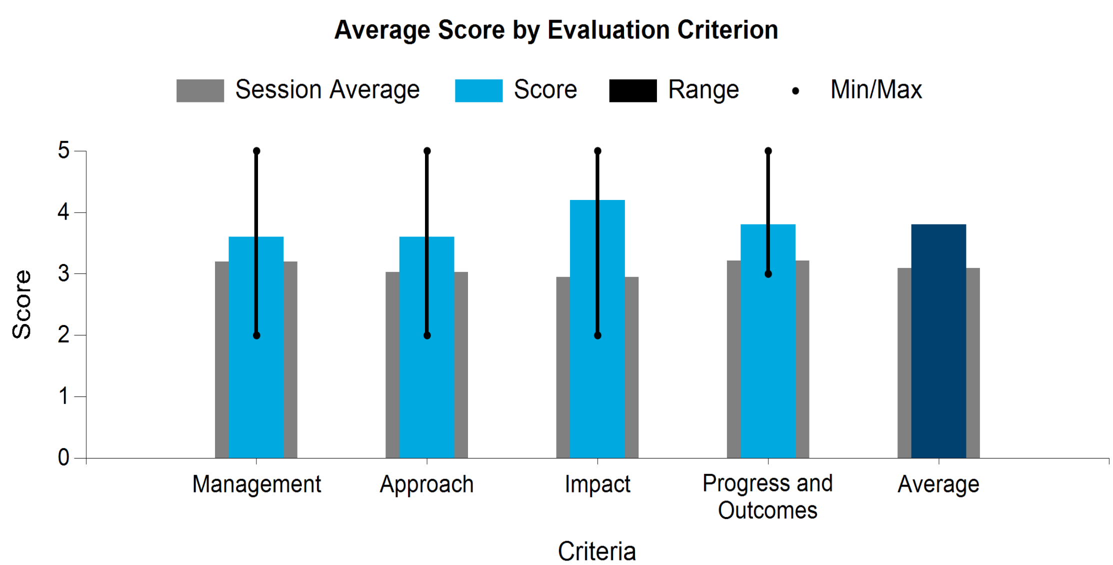
THE ENGINEERING OF CATALYST SCALE-UP

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.3.2.701
Presenter(s):	Fred Baddour
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$373,614

The goal of this project is to create a flexible, engineering-scale catalyst synthesis capability within BETO to develop the critical scientific basis of catalyst scale-up required to translate emerging biomass conversion materials from the laboratory to commercial relevance. The utilization and performance verification of next-generation catalyst materials at the engineering scale requires the development of strategies for preparing complex technical bodies suitable for large-scale operation. Moreover, the impact of translating the syntheses of these catalysts from the laboratory scale to the engineering scale on the key catalyst physical properties is nontrivial and remains largely unexplored for research catalysts being developed in BETO's conversion portfolio. The establishment of a robust technical catalyst development cycle is critical to enabling the evaluation of advanced catalytic materials and to reducing the risks associated with the commercial adoption of these technologies. At its onset, this project focused on scaling up SOT catalysts for the CFP and methanol to high-octane gasoline pathways while concurrently developing a capability that is broadly applicable to the catalysts developed across BETO's portfolio. This presentation will highlight the unique capabilities and scale-up methodologies developed by this project that are specifically tailored to the demands of BETO's biomass conversion pathways.



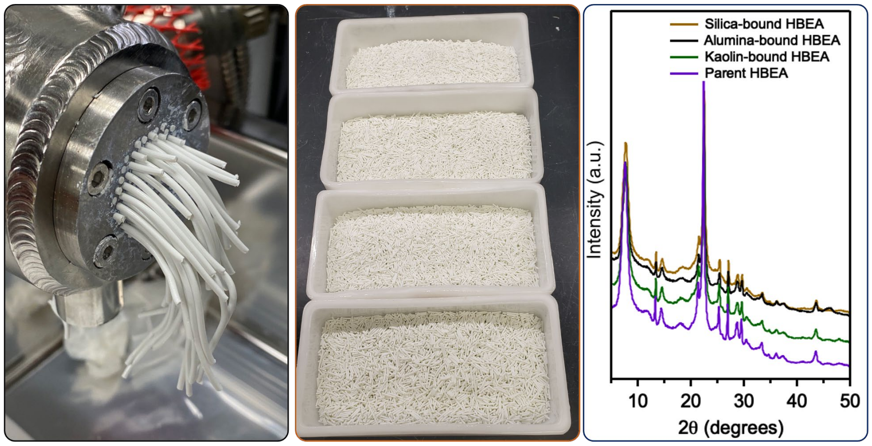


Photo courtesy of NREL

COMMENTS

- This is an interesting project and a good idea for NREL to look into. It is questionable whether the team has enough industry knowledge and/or enough industry input. Input should be along the whole life cycle of catalysts, not only the design/manufacture but also use and end-of-life questions. I have the usual questions about precious and rare metals as part of the catalyst composition.

- The project is much needed because being able to scale up catalysts for biomass technologies is critical, and it has the potential to have significant impacts. The approach used is fantastic, and it was great to see that the project team followed previous reviewers' recommendations. The description of the overall management plan could have been more detailed, but it is noted that there is an industry advisory board (IAB) with representatives from across critical industries.

- This is a great project that is directly addressing one of the major issues for the scale-up of thermochemical processes. It has an excellent IAB, and using an industry-guided approach to process development will go a long way toward bridging the gap to commercial-scale operations. It is unclear how much the result of this project will be available to industry startups; additional information around post-project implementation would be helpful.

- This is a poorly chosen direction for a project. Catalyst innovation is perfectly reasonable as an activity for BETO and in the labs under BETO's support. Catalyst scale-up would be akin to getting involved in the detailed mechanical design and fabrication of airlift fermenters. It is a step beyond the R&D range of TRLs, and there are plenty of commercial firms that do it very well. Even refining and chemical companies with revenues in the tens or hundreds of billions of dollars, active in internal catalyst R&D, often go to external catalyst vendors for commercial catalyst development and scale-up. It is far too broad and complex a craft to be developed within the national labs. Within the DOE EERE Advanced Manufacturing Office, perhaps, one could imagine an effort to advance the underlying technology for catalyst scale-up, but for BETO, there is no need for such a capability simply to advance its aims, and to advance the art of catalyst scale-up itself is outside its mission.

- What better project to have than one that highlights the challenges going from the lab to commercial and provides tools to ease those challenges? The problem addressed by this project is a great example of providing the industry with tools they need to be successful. Demonstration of catalyst is often done from tolling producers who can provide initial batches for testing from their own pilot plants. The equipment in those plants is not flexible, and certain decisions are made that may not be ideal for catalyst production based on what is available. It would be beneficial to understand which company offered which type of manufacturing method and where it was located. Great job defining "engineering-scale quantities," slide 14. Good effort working on two known DOE catalysts to review this process. The assumption is that the work is not finished with these initial results and that the team will evaluate the recipe and equipment used to make the catalyst and keep progressing toward acceptable results. A list of target catalysts developed by DOE should be put through this process to increase their value to industry. Are existing pilot trial runs (such as that at PNNL) being swapped out with catalyst made by this equipment? It would be of benefit to survey which catalyst production processes are possible within the national labs and which processes are used in the commercial industry to highlight any gaps. It looks like some form of this has been done, but the full breadth of the survey was not clear.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thorough and insightful comments into the state of the project and the scope of the challenges it seeks to address. We appreciate the reviewers' feedback on the importance and need for industry input for this project, and we will seek to increase industry involvement and engagement within this project.

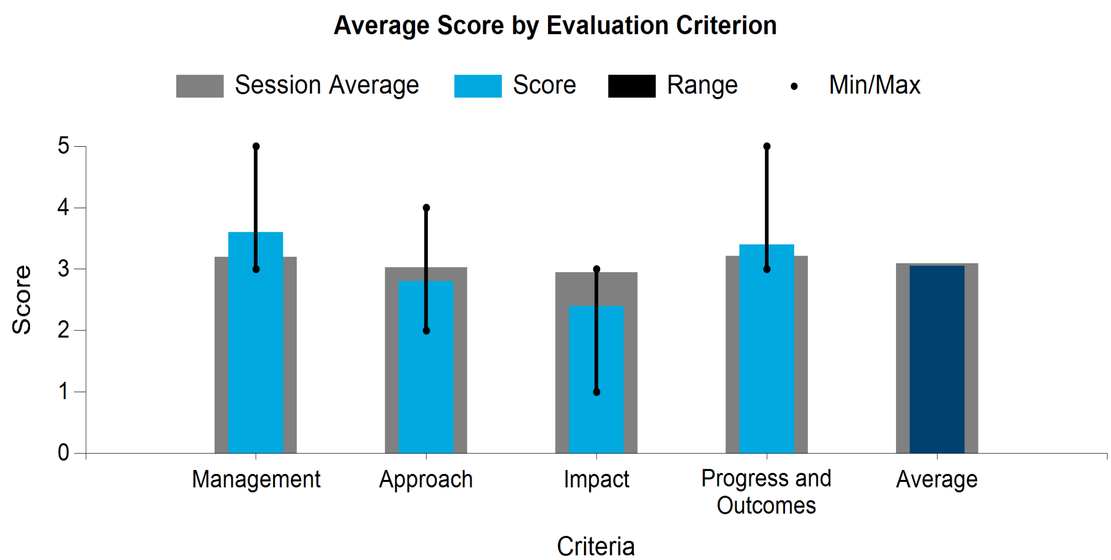
SOLID LIGNIN RECOVERY

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.3.4.601
Presenter(s):	Dan Schell
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$430,000

Valorizing the lignin residue remaining after the enzymatic hydrolysis of pretreated biomass is necessary for realizing cost-effective biofuels/bioproducts from a biochemical pathway. But no clear options existed at the start of this project for achieving high recovery of dewatered and washed lignin solids at low water usage rates using commercially available, solid-liquid separation equipment, particularly for lignin derived from the deacetylation and mechanical refining process or caustic-based pretreatment. This separation is challenging due to the lignin's small particle size (10-µm mean) and low particle settling velocities. Our goal is to find an economic solution for recovering solid lignin by first investigating non-flocculated separation processes and then a flocculated process if needed. In FY 2020, we reviewed commercial separation techniques and then tested several processes that seemed most able to meet the goals. The work generated data for TEA for comparison to a baseline model using flocculation. Decantation (decanter centrifuge) with multiple-stage washing and cross-flow filtration both produced an MFSP below the baseline value by $0.21/GGE and $0.03/GGE, respectively, generating a decision to further explore and optimize the performance of these processes. Work in FY 2021 will explore the scale-up performance of cross-flow filtration, decantation, and dynamic cross-flow filtration at higher solids loadings, generating more rigorous pilot-scale data sets.



COMMENTS

- This project is interesting, but it is unclear in the scope and goals. Why is it included here (SDI)? Shouldn't it be part of the biochemical technology development?

- Immense funding has been given specifically to the DMR process, but none of that funding appears to be going toward promoting this process within industry. It is not clear whether there is a special advantage of DMR-derived lignin or how it compares to other recovered lignin from other processes. The presentation did not delve into other current lignin-producing technique advantages or disadvantages compared to DMR. Additionally, the economics of the options studied were indeed provided, but the technology advantages and disadvantages of the processes were not discussed. The approach (slide 8) shows the desire for investigating more non-flocculating options, but the TEA shows only a flocculating path. It is unclear if the TEA was developed within this group or by another team. The concern is that the team may make the TEA lean toward the direction that they prefer to investigate. It is unclear what the price point of lignin or its application in the TEA is based on. The baseline model really should be burning the lignin or perhaps discarding the lignin without any additional processing. In this way, the value of any additional processing is made clear. The team provided data from three different processes but did not provide an explanation of what was learned by the data presented or whether the data were simply used to inform the TEA. If this was a unique or new way of utilizing this equipment, there should have been some lessons learned in its operation. It is not clear if the OEMs were involved in this study or whether the equipment has been optimized for the process. Metso was notably quoted in the presentation, but it is not clear what role they had in the project. The project provided a good review of the different options tested as part of the project. It is not clear how long these tests were run or what other process information was acquired, if any. Coordination with the FCIC may have provided additional factors to measure that may have impacted performance.

- It is extremely difficult to accept the dollars/prices quoted here. The number of pieces of equipment required—including multiple, complex, solids-processing pieces of rotation machinery—and the idea of even considering dynamic cross-flow filtration for products of such values make the costs quoted not credible. The scale at which lignocellulosic biomass plants will need to operate makes this multiplicity of exceptionally costly unit operations extremely unlikely to produce fuels at anything like the quoted price. A solid-liquid separator, then a screw feeder, then a disc refiner, then a secondary mill, then the separation of very fine lignin solids…it just goes on and on. I would not spend one more penny on this technology without an objective third-party assessment of the economics. This technology looks closer to pharmaceutical processing than fuels, and the product prices would likely need to be more like pharma as well.
- The project is well managed and has a well-thought-out approach that is on target. The only area of concern is the overall impact of the project. Although the DMR process is used internally and the team members shared their experience with the excellent fermentability of the substrate, it is unclear if the DMR process is supported by industry and will be scaled up.
- This project is focused on DMR-derived lignin, and, as such, it seems like it should be supported by that project and not SDI, which targets the commercialization of technologies. Additional detail around the TEA and the size of the market for lignin derived via this methodology would have been greatly appreciated; it is unclear whether the market would support a significant primary product quantity.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the reviewers' comments and their efforts reviewing this work. This project's primary goal is to ascertain if commercially available solid-liquid separation technology can effectively recover solid lignin generated after the enzymatic hydrolysis of treated biomass. Although the focus has been on DMR-derived biomass, the results should generally be applicable to any aqueous-phase pretreatment process; however, we have found that DMR-derived lignin is the most difficult to separate, and for this reason, this material was used in this work. Until now, only flocculation has produced an acceptable separation, but flocculants are costly, and there are unknown downstream impacts; therefore, the specific objective is to find an alternative and more cost-effective separation option using pilot-scale test results for TEA. This is high-TRL work that we believe is well aligned with the SDI's mission to facilitate commercialization. TEA was performed by the NREL process analysis team using previously established models. These models include DMR and lignin utilization process design and economics as documented in NREL's 2018 design report (https://www.nrel.gov/docs/fy19osti/71949.pdf), which has been reviewed and vetted by industry and other external reviewers. We felt it best to start from an existing model framework for this project rather than to develop a new model, particularly because the goal is to assess the relative performance of the different separation technologies. Different process designs and economics could certainly change the relative comparisons, but that is beyond the scope of this exploratory project (i.e., upstream DMR operations are outside the scope of this project's focus). Rather, the intent was to (1) recognize that the process configuration as originally laid out in the 2018 design report is likely overly optimistic, specifically with respect to the use of a lignin pressure filter downstream of whole-slurry fermentation, and, accordingly, establish a new base case for comparison by moving that separation step upstream of fermentation and switching to a flocculant-assisted vacuum belt filter (which has been demonstrated experimentally, albeit at higher costs than the simpler, non-flocculated pressure filter); and (2) compare this base case model against the alternative non-flocculation options investigated in this study. For dynamic cross-flow filtration specifically, we agree that this is an earlier-stage conceptual technology, and, accordingly, we noted that this option currently carries a higher degree of uncertainty than the others based on extrapolating a vendor cost quotation to an equipment size that has never been operated commercially. We plan to further investigate and refine the economics for that case moving forward.

IMPROVED FEEDING AND RESIDUAL SOLIDS RECOVERY SYSTEM FOR INTEGRATED BIOREFINERY

ThermoChem Recovery International, Inc.

PROJECT DESCRIPTION

WBS:	3.4.1.201
Presenter(s):	Ravi Chandran
Project Start Date:	10/01/2017
Planned Project End Date:	06/30/2022
Total DOE Funding:	$3,230,520

This project aims to enhance the versatility and economic viability of IBR technologies. More specifically, this project will enable IBRs to employ a greater variety of non-pristine feedstocks that differ in geographic source, age, composition, size, energy content, and moisture content. It also incorporates improved solids-handling systems to selectively remove inert solids and discharge residual fine solids (ash) from the reactor more reliably, efficiently, and safely. These will increase annual feedstock throughput, decrease energy costs, decrease GHG emissions, and accelerate IBR deployment. These improvements may be offered together or individually and will catapult the SOA technology available to all the IBRs. These will also help meet the DOE/EERE/BETO objectives to dramatically reduce dependence on imported oil and spur the development of the domestic bioindustry.

This project will leverage the existing commercial, technical, and operational capabilities of TRI to reliably introduce a variety of feedstocks into a reactor and remove process residuals safely and economically. Aligned to accommodate the FOA's intent, the present project will utilize TRI's existing 4-ton/day PDU at the TRI Advanced Development Center in Durham, North Carolina, with modifications to its first-generation feed system, residual fine solids discharge system, and the addition of a classifier system for the selective removal of inert solids and agglomerates from the reactor. The project will be validated by performing a continuous, long-duration trial with forest residuals, agricultural waste, and sorted MSW feedstock in the 4-ton/day PDU and by evaluating the benefits for a reference 500-ton/day biomass-to-diesel commercial plant. The anticipated benefits at this scale are:

- A 30% increase in feedstock annual throughput per feeder.
- Energy savings of 3,500 MWh/year.
- Reduction in GHG emissions of >2.5 g CO_2 equivalent/MJ diesel or >3,000 tons CO_2 equivalent/year.

Phase 1 involved tasks related to process and data verification (BP-1A) and component design (BP-1B). Most of these tasks were completed prior to the 2019 BETO Peer Review meeting, and the details were presented in that meeting. Subsequently, we prepared and compiled the budget and found it to exceed the original budget due to the longer duration, the multiple feedstock testing, and the higher component costs. We discussed this issue with DOE and the independent engineers and proposed combining this project with the small-scale biorefinery project (WBS 3.5.2.204) for Phase 2, which was accepted by DOE. Due to (1) the requirement in the small-scale biorefinery project for a contingency cash reserve of 25% of the Phase 2 budget and (2) the TRI revenue impairment due to the COVID-19 pandemic-related delays, both projects have been on hold since 2020 with the consent of DOE. Note that the total expenditure to date in Phase 1 has been a very small proportion (on the order of 5%) of the total budget. From a macro perspective, the legislative requirement that a small startup company such as TRI place more than $2 million in escrow has disrupted progress. We are thankful to BETO for giving us more time to clear this big hurdle, but it has been difficult, especially with the COVID headwinds.

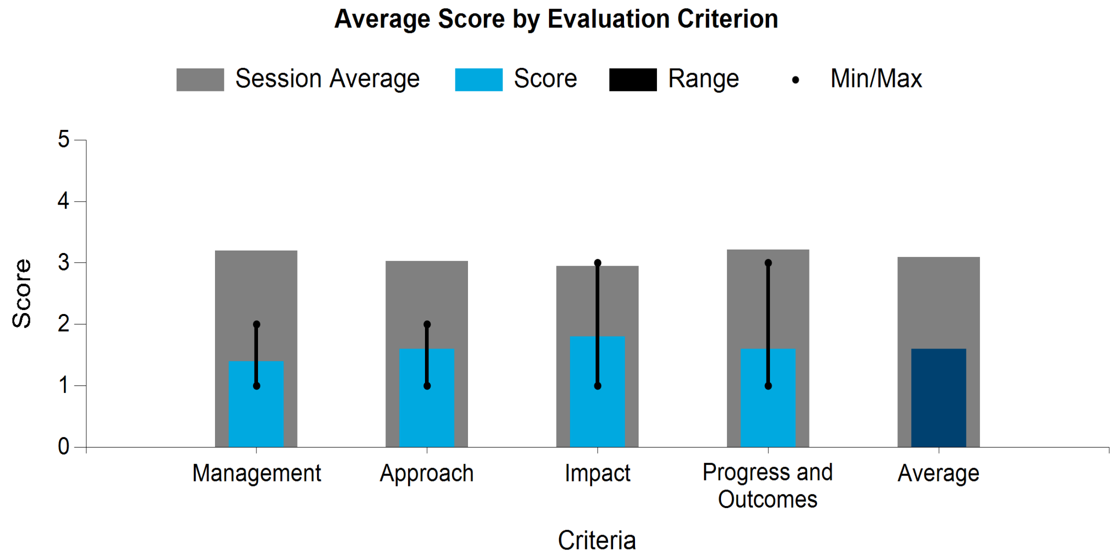


Photo courtesy of TRI

COMMENTS

- This was an extremely generic presentation, especially the management and approach section. There was some insight into the partnership, but I was underwhelmed by the review. The project team needs to take these peer reviews seriously and understand that they are part of the necessities for publicly financed projects. I understand that COVID has had big effects on the work, but this should be explained and justified in the slides.
- The issue of feeding biomass directly into reactors under pressure has been a significant source of trouble for the industry for years, and several BETO-funded projects are studying/addressing this issue. Apparently, this project does as well, but it is not clear what specific work is being completed, what

progress has been made, whether there is communication among these projects, or even whether publications or other dissemination of information has been considered. The presenter may have assumed that the Peer Review Panel had information they did not; the lack of information makes it very difficult to provide a meaningful review. The project management plan is weak, especially the risk assessment and mitigation plan. Risks are not adequately described, and the mitigation responses are often poor; the response to "premature filter blinding" should not be "additional tests"; it should be a description of activities to be performed to alleviate the potential problem. The use of OpEx only to indicate meeting BETO's dollar-per-GGE goal is disingenuous at best.

- The presentation does not discuss the challenges of the first system or how the second system is designed to address those challenges. The risks presented did not appear to represent any sort of challenges that could not have been addressed in the first design. If the solution to a plugged drain port is a cage, that does not require a grant to fix. Modeling the inert gas to determine the proper amount is a complex way of throttling the valve and seeing what happens. The project did not present CapEx or OpEx cost-saving strategies. The project did not address how close they were to the target cost of $2/GGE (OpEx) or how it could be obtained. The feedstocks selected (i.e., wood, corn stover) will not necessarily result in the problems that they are trying to address (e.g., tramp metal)). It is not clear what ash levels were a challenge with the existing unit. Although the project states that they have achieved their goals, no data were provided to support that claim. Fire safety does not appear to have been considered with the trash/tramp removal system. The hot material will drop into an oxygen-rich environment, and any carbonaceous materials will burn. A project plan with a logical testing sequence to help ensure success was not presented. The management section did not provide the reviewer confidence that a sound approach to resolving these issues was being taken. The challenges/risks presented did not address how the original design ended up as a design that required modifications in the first place. The project is attempting to address known challenges with their feed system and the biomass preparation, but there was no metric to measure performance against it.

- There is very little here for a project that began 3.5 years ago. What is going on? The only actual tests appear to have been on the first-generation feeder, but one assumes the first-generation feeder would have been tested already. This is nothing but a few schematics. The BFD (slide 16) seems unrealistically complicated for a lignocellulosic biomass process. It also shows "GAS" and "O_2" inlets—three for GAS and two for O_2. Are we using fossil natural gas here? Do we need an air separation plant to provide oxygen?

- This project completed no work in FY 2020, but there was no discussion of this or an overall summary of achievements. The presenter claimed that several milestones were achieved, but there was no attempt to show the reviewers this. The feeder drawing was interesting and helpful. It is unfortunate that the reviewer chose not to provide information for a critical review and basically wasted the reviewers' time. The presentation was not received on time, and what was received was subpar.

PI RESPONSE TO REVIEWER COMMENTS

- Phase 1 involved tasks related to process and data verification (BP-1A) and component design (BP-1B). Most of these tasks were completed prior to the 2019 BETO Peer Review meeting, and the details were presented in that meeting. Subsequently, we prepared and compiled the budget and found it to exceed the original budget due to the longer duration, the multiple feedstock testing, and the higher component costs. We discussed this issue with DOE and the independent engineers and proposed combining this project with the small-scale biorefinery project (WBS 3.5.2.204) for Phase 2, which was accepted by DOE. Due to (1) the requirement in the small-scale biorefinery project for a contingency cash reserve of 25% of the Phase 2 budget and (2) the TRI revenue impairment due to COVID-related delays, both projects have been on hold since 2020 with the consent of DOE. Note that the total expenditure to date in Phase 1 has been a very small proportion (on the order of 5%) of the total budget. Our understanding was that we were to provide an update since that 2019 meeting, so we did not include a list of tasks and milestones and the details for work accomplished prior to that date. We did request permission from DOE and prepared and submitted a more detailed version of the presentation, but it appears that version did not get distributed to the reviewers. From a macro perspective, the legislative requirement that a small startup company such as TRI place more than $2 million in escrow has disrupted progress. We are thankful to BETO for giving us more time to clear this big hurdle, but it has been difficult, especially with the COVID headwinds.

The feeder system has three main functions: (1) pressurize the feedstock from atmospheric pressure to the reactor operating pressure, (2) transport the feedstock and inject it into the reactor, and (3) create a gastight seal between the reactor and the atmospheric feedstock day bin. The last two functions are essential because an imperfect seal would risk backflow of the reactor contents into the day bin, compromising safety and operability. TRI has proven the first-generation feeder design in the PDU, achieving more than 13,000 hours of operation, and during that period, TRI never experienced a blowback through the feeder system. Based on that experience, we identified three areas of improvement to reduce energy consumption and improve uptime, throughput, operability, reliability, and ease of maintenance. These led to the incorporation of opposing brake, press-type housing and rapid advance pistons in the second-generation feeder design. The changes were detailed in the proposal, and we have subsequently tested these modifications and addressed these risks in an internal TRI program not related to this funding. So, the main risk was in incorporating these in the existing feeder at the PDU, and this was the only one identified in the risk registry for the feed system.

The target for the selective solids removal was the classifier design and not the cage. The cage was intended to prevent the blockage of the drain port in case of oversized tramp particles or accidental formation of large agglomerates or clinkers. Due to the classifier facilitating active bed inventory management, the formation of a large agglomerate is considered highly unlikely. As the classifier cold flow video indicated, the selective solids removal is a batch process performed cyclically and involves several steps. Both by experimentation and fluid dynamic modeling, we have investigated the inert gas flow rate and time duration for the relevant steps to minimize the total gas usage per cycle. As indicated in the summary, we have estimated the following for a commercial 500-dry ton/day IBR due to the feeder, classifier, and ash discharge improvements: >30% increase in feedstock throughput per feeder, >3,500-MWh/year savings in power input, and >2.5 g CO_2 equivalent/MJ diesel reduction in GHG emissions.

The TEA and LCA are planned at the completion of the PDU trial in Phase 2, and hence CapEx and OpEx savings will be quantified at that time. As mentioned in the presentation, three feedstocks—forest residuals, MSW, and corn stover—with a broad range of moisture content, ash content, tramp content, bulk density, and Sauter mean diameter are targeted. A statistical design of experiments comprising a total of 20 tests has been formulated. Ash content of up to 25 wt % on a dry basis has been included in the matrix.

We concur with the reviewer's observation that there is potential for char to burn if it were to enter hot into the ambient atmosphere. In the TRI classifier system, the char and bed material are separated from the tramp and returned to the reformer vapor space, and the tramp is in contact with warm CO_2 for most of the cycle time, so it should drain after being cooled to 450°F or less and being made inert in CO_2. Second, the tramp drains into a catch pot that is sealed, thereby providing opportunity for additional cooling prior to ambient exposure. This addresses the fire safety concern. We have included formal hazard and operability study reviews at the beginning of Phase 2 to further review and alleviate safety concerns, if any.

The GAS in the BFD refers to inert gas (not natural gas), and typically recycled CO_2 is used (captured downstream from the syngas and partially recycled).

Yes, the gasification process does use oxygen for partial oxidation; this may be supplied in a commercial plant either from an air separation plant in-house or over the fence from a third party on a lease/contract basis. For the PDU trial, we use cryogenic oxygen.

A TEA is planned for Phase 2 and will account for both CapEx and OpEx.

BIOMASS FEEDSTOCK USER FACILITY—IMPROVING BALE DECONSTRUCTION AND MATERIAL FLOW

Idaho National Laboratory

PROJECT DESCRIPTION

WBS:	3.4.1.202
Presenter(s):	Neal Yancey
Project Start Date:	07/03/2008
Planned Project End Date:	09/30/2021
Total DOE Funding:	$6,000,000

BETO has recognized an INL core competency in the scale-up and integration of biomass preprocessing technologies and process design. The foundation of this core competency is the biomass feedstock PDU, which is an integrated pilot-scale preprocessing system. This core competency is further supported by the EERE designation as a national user facility in FY 2013. The user facility designation has expanded the use of the PDU in supporting collaborative projects with industry, universities, and other federal agencies. During the past 6 years, the PDU has been used extensively for preprocessing R&D and demonstration, process development, toll processing (for feedstock supply) for both BETO- and industry-funded projects, third-party testing, and validation. The project is intended to transform the PDU to new and innovative uses in system-level research that enables and informs early-stage R&D in biomass preprocessing and handling.

This project has both technical and programmatic objectives. The technical objective of this project is to eliminate the slugging caused by the first-stage grinder that is perpetuated through the preprocessing of baled biomass, resulting in the inconsistent flow of biomass during the size reduction process. This will be achieved by decoupling the first-stage grinding and bale deconstruction. The project will replace the high-speed, energy-intensive bale grinder with a low-speed bale processor designed to use low speed and high torque to convert baled biomass into a flowable loose feedstock. The system will be able to process both round and square bales.

Another technical objective of this project is to equip the PDU with visualization tools and real-time measurement capabilities that allow in-depth characterization of the interaction of material and machine. The use and benefit of these tools will be demonstrated with a specific study of the mechanics of deconstruction and conveyance of biomass materials. Process visualization and in-line sensor applications will inform early-stage R&D and define operational boundaries. The data generated will be collected and stored in a data collection system that is consistent with and accessible by other DOE labs.

The programmatic objective is to increase PDU utilization. PDU utilization during the last 6 years has ranged from 30%–40% (the ratio of the amount of days the PDU was in use to the amount of days the PDU was available for use). PDU utilization is a combination of internal use, support of national lab AOP projects, and external industry collaborations. The end-of-project goal for this programmatic objective is to increase user facility utilization to 60% (from the current baseline of 30%–40%) with tactical upgrades and improvements and demonstrated examples and successes of the use of the PDU and associated capabilities for system-level R&D.

Accomplishing the technical (segmented bale deconstruction) and programmatic (increase BFNUF utilization) objectives will involve an approach that combines (1) testing new bale deconstruction methods that utilize low-speed, deliberate bale deconstruction methods specifically developed for square or round bales; (2) developing and implementing in-line sensors and visualization tools that will enable the study of basic material and airflow properties within equipment (grinders and mills, conveyors, and other processing equipment) that will lead to more even flow, reduce equipment wear, and enhance separation capabilities; (3) developing data management tools that will increase access of PDU data to the FCIC, other labs, and industry; (4) continuing to adapt the PDU to include improvements identified through the FCIC, INL, and industry research and interactions; and (5) applying the system-level research capabilities (developed in 1–4) to study the biomass deconstruction and conveyance process in the PDU.

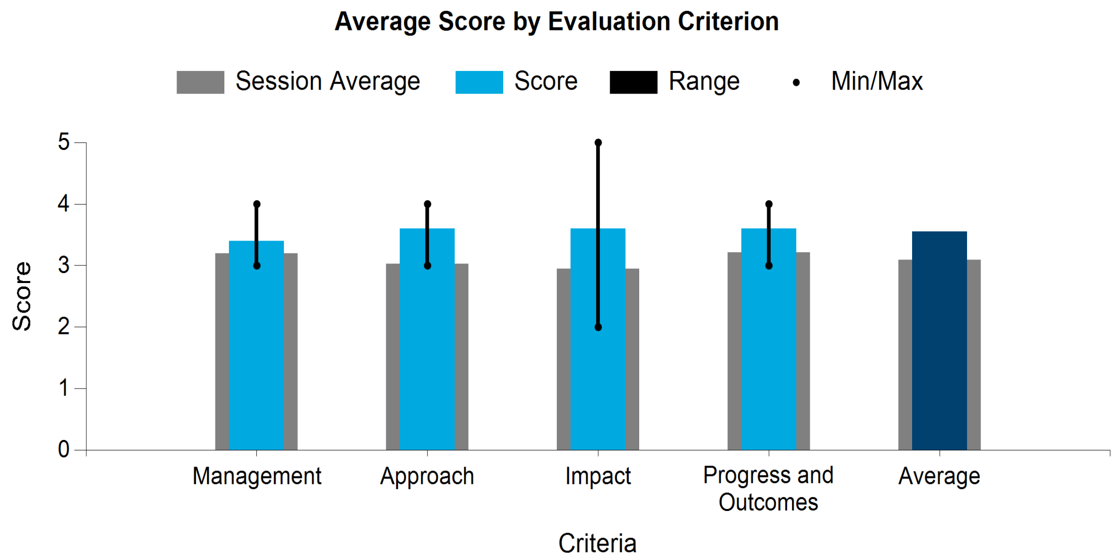


Photo courtesy of INL

COMMENTS

- This is a good and interesting project on bale deconstruction and feeding. Low versus high speed is unclear. What are the throughput effects? They have the same throughput, but it is confusing. Overlap with FCIC projects appears large: There is lots of interaction, and BFNUF is developing a complete process, not just individual steps.

- The management plan is a bit cursory but adequate. The approach is, in one sense, ideal in that it moves the feedstock uniformity and quality control upstream, where it belongs. In another sense, it departs from the idea of a uniform feedstock format. If every feedstock is custom milled and custom treated to meet specifications for a particular process or even a particular plant, biomass will never become a true commodity, and it will never be able to be moved very far. That said, all the approaches to the *stated* objective are logical and likely to be effective. The metrics are sensible. Fractionation and fines control will be helpful in maintaining plant reliability and on-specification performance. Progress on milling and fractionation is good so far. Is there a connection to the FCIC?

- The choice of approach was not made clear in the project. The project should have discussed how machine learning and automation equipment were arrived upon as the appropriate tools for this problem. The current SOT and the disadvantages of those technologies to these processes was not made clear. The current facilities do look at conveyor heights and control them—what is wrong with these systems? The project noted that they are trading information back and forth between the FCIC and that this project is distinct from those projects by its look at the whole process. In the presentation, however, the economics of the approach were not covered; rather, the process was being worked on. The project is attempting to achieve a more consistent product for downstream process. This has shown to be necessary in other past projects. The economic baseline of a process with a clean stream of chips but burning or otherwise discarding the other streams should be presented because a facility is unlikely to be built with three different processes that can utilize the three streams noted differently and economically. It is unclear if there were any activities to modify any of the mills shown or just to operate at slower speeds; it appears the latter was done to gain data. What data are lacking and how close is the project to gathering sufficient data? Lower throughput requires additional parallel or larger units to be operated. It was not clear whether the project expected a high CapEx, nor were the predicted operational benefits of the project. By reducing the non-white wood, you reduce a larger percentage of the incoming feed. The resulting per-ton cost of biomass from this process and the application/disposal plan for the remaining feedstock were not made clear in the project plan. This is a good example of consistency in the approach between BETO groups (FCIC and SDI). The impact of a 25% energy savings on the front-end hammer mill is not an obvious internal rate of return driver for overall operations. "Slow processing" can be confused with throughput, and the project should make sure its audience is aware of what it intends. The dissemination schedule of a best practice for a front-end system was not provided. This appears to be the overall goal of the work being done, but it is not clear when this task is planned.

- The project has great objectives to improve the variability in feedstocks, and the equipment testing plan has achieved good results in identifying and testing equipment to achieve more consistent feedstock. I found that the management plan should be better outlined. Risks are identified, but they are not fully addressed. A detailed work plan would have been a good addition and increased industry involvement. A cooperative research and development agreement (CRADA) with Warren & Baerg Manufacturing, Inc., would be an excellent addition, as would other industry partnerships. Finally, I found it surprising that the addition of screening on the mills was considered an improvement. This is industry standard, and it is unfortunate that this needed to be tested and is not standard in biomass projects. The amount of industry involvement appears lower than necessary.

- This is a good quality-by-design project and has the potential to have significant impact on the bioconversion industry as a whole. Although it does seem to implement things as new that have been in practical application for years (e.g., screening, recycling overs), it clearly demonstrates the value of these practices. Slower processing for more consistent feed is clearly demonstrated as well, but the presentation would have benefited from showing the impacts/costs associated with doing so (e.g., equipment size or quantity and subsequent impact on project CapEx).

PI RESPONSE TO REVIEWER COMMENTS

- I want to thank the reviewers for their comments. It is always helpful and important to get the perspective of others through these Peer Review presentations.

Bale deconstruction: There was an overall interpretation that lower-speed milling meant lower throughput. Let me address this first and change some terminology as well. I will start by using low intensity rather than low speed. The new debaling approach is taking a scientific approach to bale deconstruction. Bales are put together in balers that accumulate a section of biomass, then compress that into a wafer or leaf of the bale. Consecutive sections are then compressed into a bale. The approach now is to break apart bale sections systematically without size reduction to create a flowable stream of bulk biomass. Because bale deconstruction does not include size reduction, it requires much less energy. As opposed to using a high-impact approach to break the bale apart, we use a combination of bars and cutters (if necessary) to break apart and delaminate the bale sections. This low-intensity debaling is equal in throughput to high-speed bale grinding but uses much less energy. The reasons for these changes are to (1) reduce energy; (2) decrease the generation of fines; (3) enable downstream separation and sorting, including contaminant removal; (4) reduce wear; and (5) achieve equivalent throughput.

Advanced milling and fractionation: Another frequent comment was associated with cost and the reason for the additional customized processes to the milling approach. For instance, "We can customize a process for every different feedstock and condition but at what cost and what is the payoff?" This scientific methodology is not a customized approach to each feedstock, but rather developing a process with end conversion in mind. The methodology being used is:

- Identify the properties of the feedstock—baled, whole logs, chips, moisture, etc.—and anticipated contaminants that need to be removed.
- Using a quality-by-design approach, apply specific tools to reach the final goal for conversion. For example, high-moisture bales require different milling approaches than dry bales, so we must ask, how do we process high-moisture bales in a manner that most benefits the conversion process?
- Use screening and sorting to maximize advantages by (1) screening early to prevent overprocessing; (2) using mechanical methods to eliminate inorganic contamination as early as possible in the process, thus reducing wear on equipment (it benefits nothing to carry it to the end and then get rid of it); (3) sorting fractions that can be treated more efficiently from the rest—i.e., separate needles and bark from white wood or leaves from stalks and cobs in stover; and (4) creating as consistent and accurate as possible a particle size for all fractions that will result in more efficient conversion.
- Use milling approaches that match the material. Use impact milling only when it serves a purpose, such as dislodging contaminants. Use knife milling or crumbling to generate 3D particles that result in higher efficiency in conversion processes.
- Consider densification to improve flowability, consistent conversion, and transportation. This methodology is applied in all cases, but only unit operations that will result in increased value and performance at the reactor should be considered. The cost of air classification adds $0.85/ton to the preprocessing. The cost of screening adds approximately $0.30/ton to the processing costs. These costs must be compared to the increase in value observed at conversion. The outcome should be lower conversion costs, increased throughput, less energy use, consistent performance, consistent properties—physical and chemical, minimizing losses, fines or other—and maximized efficiency and performance during conversion.
- Historical processing generally consisted of: [bale grinding]>[fine grinding]>[possible screening out fines]>[metering or storage]>[conversion]. Advanced milling and fractionation: [debaling]>[screening to remove contaminants and separate on-spec material or specific anatomical fractions]>[specific milling to minimize losses and achieve optimal shape]>[screening to reach specific particle size and remove fines if needed]>[density separation if needed to sort tissue or chemical fraction when needed]>[metering or storage]>[conversion].

- Low-speed bale processing reduces the generation of fines, uses less energy, maintains throughput, provides even flow, and produces a much more consistent particle size and chemical composition to the conversion process. There is a lot of synergy between the FCIC and this project, but the FCIC projects tend to focus more on unit operations, specific material breakage understanding, and other detailed information, whereas this project focuses on operations at scale.

Real-time monitoring and control: With respect to comments on the material flow in the conveyors, mass flow in processing is generally controlled through feed rates and can be and is often monitored in the conveyors by depth or mass flow. I brought up the way we monitor material depth as just one example of real-time monitoring that we conduct. Specifically, we were tracking variations that occur as a result of uneven flow from the bale grinder and identifying means to adjust on the fly to prevent a surge from impacting downstream processes. Still, that was only one example of real-time controls. The BFNUF monitors flow, temperature, moisture, amperage, overcurrent events, pressure, and other things that allow us to adjust on the fly, and we are developing software to automate those responses. We are also developing controls based on particle size or fine generation, which use variable-frequency drives to control mill speed—not to control throughput, but to control quality or particle size of the feedstock. Ultimately, we are developing a methodology to increase the quality of both physical and chemical composition at reduced energy costs. We expect improved efficiency in conversion and high retention of quality material from the feedstock being used. Finally, as we move forward, we are developing industry partners such as Warren & Baerg. Specifically, we have current projects with Forest Concepts, Idaho Forest Group, Enerkem, Titus, Fulcrum, GreenGold, and others. I should have made this clearer.

Thank you for the comment on screens. For many industries, screening is a standard operation. We have been trying to add screening to our processing facility for several years, but funding has only been available in the recent BFNUF upgrade.

BIOCHEMICAL PILOT-SCALE SUPPORT AND PROCESS INTEGRATIONS

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.201
Presenter(s):	Dan Schell
Project Start Date:	10/01/2003
Planned Project End Date:	09/30/2017
Total DOE Funding:	$1,048,000

The Biochemical Pilot-Scale Support and Process Integration project's high-level goal is to help transition technology to the marketplace by providing a facility for pilot-scale performance testing and verification. To facilitate this goal, we maintain the functionality and operational readiness of the biochemical pilot plant located at NREL, and we evolve its capability to perform process-relevant integration work for BETO and industry clients. We also encounter and solve unknown scale-up issues that usually only manifest at the pilot scale prior to technology deployment; however, processing biomass feedstocks remains a challenge at the pilot scale, particularly in handling a variety of raw biomass materials. In the past 2 years, we have completed modernizing the pilot plant's control software with a new automation software product that is cheaper to maintain, easier to learn, and has enhanced capabilities—i.e., continuous automated data storage to an SQL database. We have also developed and implemented a data management system that effectively captures and logs all pilot plant sensor data associated with experimental runs or plant operations into an easily retrievable format. Finally, our plant documentation and management programs have been improved and better automated during the last few years. The pilot plant continues to be used by BETO projects as well as by industry clients, with nine new industry-based projects that began in FY 2019/2020.

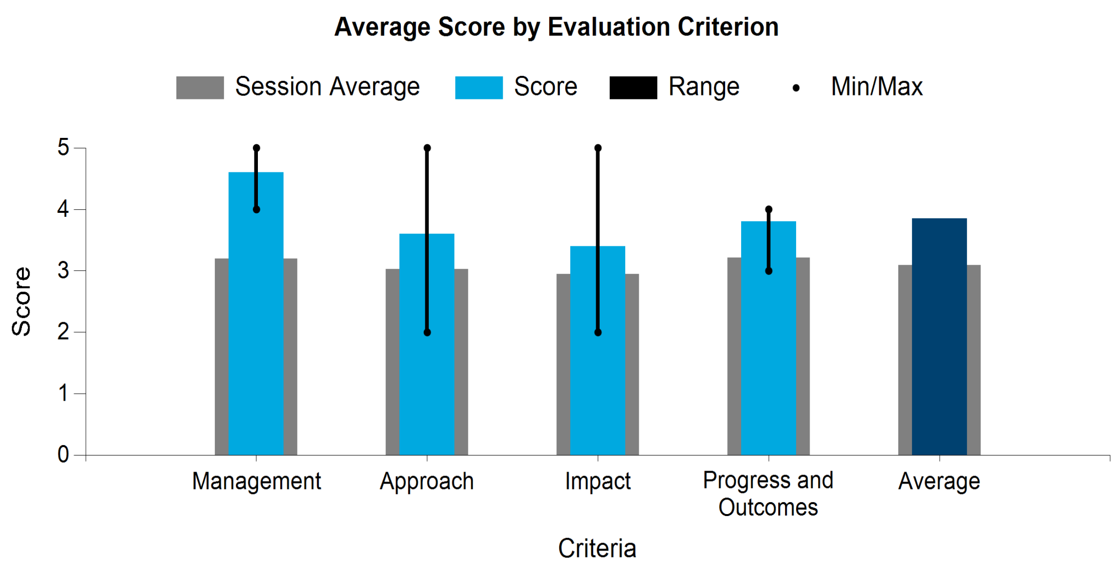


Photo courtesy of NREL

COMMENTS

- This is an interesting update of the biochemical pilots at NREL. Industry interaction and prioritization remains unclear. How are partnerships arrived at? FOAs? Industrial clients? It sounds quite informal, and it could benefit from a more strategic approach to equally benefit all stakeholders and not only those that are more connected with the current lab activities and personnel. It is unclear what is driving the current focus on the DMR. In general, these types of programs should be following a wider approach of options and less focused on one or two single technologies, especially when they are specific to a supplier.

- It is not clear what from the 35-year-old original facility is still in operation and is still relative to industry and research. The project does not appear to have full control of what equipment is purchased and installed at the facility—i.e., the disc refiner. It would be beneficial to understand how the pilot plant approaches new clients in the assessment of their technology using the lessons learned from past projects. The utilization of specific equipment within the facility would be beneficial to understand and how this ties into the out-of-service program. The potential for larger-scale unit operations or the history of longer-term reliability testing at the facility is not clear. On the opposite end of the spectrum, it is not clear how the PDU communicates its lessons learned to other bench-scale R&D within BETO and to industry partners to share the lessons learned. Although the presentation does not make clear what equipment exists, it makes it clear that the equipment is being utilized by industry. It was encouraging to read a review of process equipment relevancy in industry. This should be an annual task with an advisory board, however. Although this facility does not do any business, development has begun to include industry outreach to have its capabilities assessed and refined by others so that in the future it can maintain its critical status in DOE and the industry. The process in determining what new equipment is purchased by the PDU was not discussed. There is a risk not mentioned in the presentation that the equipment at the PDU will not be of interest to industry. It is not clear if and when the data management system will be integrated with FCIC Task 8.

- The Integrated Biorefinery Research Facility has been an invaluable resource for industry for many years and continues to play an important role for many projects. The presentation shows an excellent management plan, including significant communications with other projects and with industry. As a source for clean cellulosic sugars and solids lignin for research, DMR makes sense, but the focus on expanding capacity and the optimization of DMR appears to be internally driven, with no clear support for the commercialization of the technology from industry.

- This reviewer likes the way the project divided the tasks into routine, pilot plant operations and new capabilities. This is an excellent way to organize, and the management plan is sound. This reviewer also really likes the way that the PDU is used to help demonstrate technologies for the program along with other partners. Continuous operation of an integrated process is a critical need in the scale-up and commercialization of any technology and one that is generally downplayed, minimized, or even skipped. It is generally very hard to get funding for these in the private sector. The strategy of using the PDU to close this gap is a great use of taxpayer funds. The team appears well coordinated and focused on their goals and has been meeting their goals.

- Unlike the BFNUF and the ABPDU, it is not clear that this facility is flexible outside of cellulosic sugars/lignin and the DMR process, both of which are of lesser interest in industry these days. It would be helpful to see a more thorough study, by year, of the external clients and the sort of work they did there. Has interest remained as strong over the years? Are the customers using the DMR capabilities, or are the projects more stand-alone fermentation with noncellulosic sugars? It is impossible to answer these questions from the slides or the presentation, but I am concerned that much of the equipment and activity are less timely than they once were. Otherwise, this is basic blocking and tackling to maintain and upgrade a user facility.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the reviewers' comments and their assessment of this work, and we provide some clarifications. This project's goal is to maintain a safe and process-relevant biochemical-based pilot plant that is made available to others to use, including industry partnerships and BETO research projects. We understand the concerns regarding some of the older equipment systems that are not routinely used, but roughly three-quarters of this facility is used for research. Industry projects performed in the plant usually arrive via inquiries from industry or individual researchers' industry contacts, and work is executed using work-for-others agreements or CRADAs entirely funded by the partner. Other industry collaborations resulting in facility use are from awarded FOA projects, which are roughly one-third of our industry partnerships. We can usually execute all projects without the need for prioritization or downselection, including BETO research projects. Capabilities being used by industry projects range from pretreatment, enzymatic hydrolysis, bioconversion, and separations either as individual unit operations or multiple operations at a scope and scale depending on the needs of the client. Nevertheless, there is an opportunity to improve our strategic approach to partnerships and facility use, and we are currently working to develop this plan for both NREL pilot plants within the directorate. Also, we hope to acquire new research equipment to better align with new low-carbon-intensive technologies for producing biofuels and bioproducts. Because many of the BETO research projects are executed in close collaboration with personnel doing the bench-scale research, we have a good path forward for communicating lessons learned within NREL; however, there is opportunity to improve and more widely distribute findings when possible. With respect to our efforts to yearly update our capabilities, this work is generally focused on small, low-cost efforts that enhance the safety or our ability to support future BETO R&D directions and the potential needs of industry clients. But the funding for this effort comes from our supply, maintenance, and repair budget, and the available funds are highly variable depending on other needs throughout the year. This year, we are adding vent condensers on the 160-L bioreactors, and next year, we will likely need high-pressure, steam piping upgrades. These are examples of the types of minor upgrades we can do with funds from this project. Major equipment additions require an alternative funding source, and, in this case, more input is sought from technical experts within and outside of NREL.

ADVANCED BIOFUELS AND BIOPRODUCTS PROCESS DEVELOPMENT UNIT OPERATIONS

Lawrence Berkeley National Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.202
Presenter(s):	Deepti Tanjore
Project Start Date:	07/13/2010
Planned Project End Date:	09/30/2021
Total DOE Funding:	$7,300,000

The ABPDU was authorized in 2009–2010 and commissioned in late 2012 as a shared community resource to provide process optimization, prototyping, development, and piloting and scale-up services to the biofuels and bioproducts community, including industry, academia, and the national labs. This AOP covers expenses related to (1) partnership and project development, (2) facility readiness, (3) process benchmarking, and (4) teaming with other BETO PDUs. Although ABPDU collaborators and sponsors are required to fund “cost recovery” associated with project work at this facility, this base ABPDU operations budget is required to maintain and operate the facility in a nonprofit model consistent with cost recovery. The partnerships enabled by this BETO collaboration facility allow the advancement of key technologies from early-stage TRL in the 2–3 range to prototypes at the mid-TRL range from 4–5. The ABPDU does not directly commercialize or provide financial support to deployment by industry partners; rather, the process research and optimization the ABPDU team and facility engage in brings value to the entire biofuels and bioproducts community and provide high-visibility examples relevant to the BETO mission.

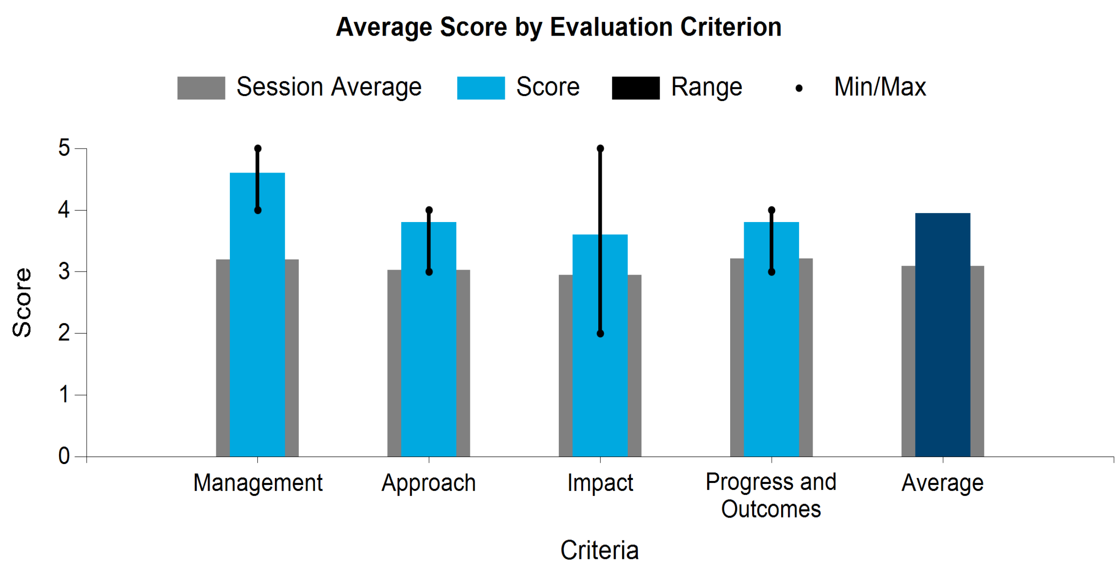


Photo courtesy of LBNL

COMMENTS

- This is a good overview of the management and activities and the ABPDU. It would be good to have a more strategic plan on how to reach out to external collaborators, besides word of mouth and personal connections, to maximize the impact of the ABPDU facilities in the overall industry and to avoid preferences with better connected groups, etc. How to best benefit the BETO and the broad DOE community from the work being done is key. Right now, it feels like it is mostly through supporting new companies and training activities. The benefits back should be maximized and well thought through. Likewise on how to address intellectual property (IP) and related issues. Supporting new private IP is okay, but the goals of a public facility, no matter how the current funding is, should look to broader benefits for the taxpayer.

- The ABPDU is a terrific resource for industry and has proven to be proactive in identifying skills and capabilities that can help with commercialization efforts. Although word of mouth appears to be more than sufficient for advertising, additional effort should be made to reach out to industry and look to identify additional opportunities. It is unclear how much findings from completed projects are/can be shared with the industry as a whole, but this is an area in which the ABPDU can extend its sphere of influence.

- This is less of a project and more of a baseline maintenance funding for a PDU. As such, it is money extremely well spent. The ABPDU provides capabilities that are otherwise difficult to find at this scale, and I have been involved in multiple projects in the past that encountered problems or had to face high costs and construction delays to provide similar capabilities in-house, only to then use those capabilities rarely or even never in the future. By being there when needed for industry, lab, and even academic clients, the ABPDU relives them of those costs, delays, and problems. Their amazing list of partner companies and high percentage of full-time employee utilization are testaments to their success. Ideally, they should have a process for periodically adding new capabilities—not a regular capital budget, but perhaps an AOP cycle process for proposing and defending new equipment suggested by their many interactions with biotechnology developers.

- This is not really a project; it is an ongoing function. Although it appears that they are meeting their stated goals, I question whether this is the best use of taxpayer funds to help companies without getting anything in return—there is no IP and little to no information sharing. I do not think the impacts outweigh the costs.

- This project has had a tremendous level of impact in 10 years in its ability to assist in obtaining funding for so many clients. The project reports that they are aware of around six pieces of equipment necessary for new industries. Budgets range from $10,000 to $150,000, which allow small and large companies to work with the ABPDU, either with subject matter experts or with equipment. The lessons learned on these projects do not appear to have a home within BETO. Additional information would be appreciated. Strategic partnership project/CRADA conversion percentage versus target would have been beneficial to understand. The process in determining what new equipment is purchased by the PDU was not discussed. There is a risk not mentioned in the presentation that the equipment at the PDU will not be of interest to industry. The project demonstrated a well-defined approach to its work, including details on its outreach, its safety program, and its contracting program. The presentation could have provided more information on what processes they do support specifically and how they are improving or advancing these processing through new acquisitions or projects to advance the SOA. It is not clear if and when the data management system will be integrated with FCIC Task 8.

PI RESPONSE TO REVIEWER COMMENTS

- The ABPDU team thanks the reviewer for the feedback. The team is leveraging its track record of having helped well over 65 companies in scaling their bioprocess technologies to reach out to small and big companies. In an effort to continue to expand the ABPDU's reach and visibility, last year the team dramatically augmented content through case studies on industry collaborations, alumni successes, and female entrepreneurs. These studies were shared via our recently updated website, our new quarterly newsletter, and multiple social media channels. We are now periodically benchmarking the performance of these platforms to compare figures against earlier performance indicators, prior to these upgrades. As an indicator, we are also keeping track of how companies become aware of us. Along with the information collected during Industry Listening Day, we look forward to maximizing and reporting the value of these communication tools in the context of a larger strategy of outreach. The ABPDU has three granted patents submitted jointly with industry collaborators and several outstanding patent applications that should be awarded in the next few years. Continued collaboration with BETO consortia and CRADA-based projects provide the ABPDU staff with more opportunities for expanding the LBNL/BETO IP portfolio, and these research efforts often leverage industry interactions to address generalizable challenges in biomanufacturing As an example, ABPDU researchers have recently filed records of invention (ROIs) covering novel process integration strategies for hydrogen (H_2) fermentation and for the capture of volatile fermentation products; both ROIs were informed by interactions with multiple industry partners facing technical challenges in these areas.

  Thank you for the detailed comments. The lessons learned from these projects are packaged into proposals pursued via consortia, AOPs, or directed funded opportunity projects funded by BETO. For example, BETO invited ABPDU PIs to submit four full AOP proposals last year, one of which was funded. Similarly, the ABPDU shares much of our know-how through the training we offer to our employees and the students of the master's program at the University of California, Berkeley. These alumni often join companies that further BETO's mission (e.g., ZymoChem, Visolis, LanzaTech). The ABPDU uses an end-to-end collaborator onboarding process that has allowed the team to understand the strategic partnership project/CRADA conversion rate. The data have thus far demonstrated an approximate 9% conversion rate of prospects to projects. Last year, the collaboration development team interacted with approximately 83 groups, leading to 8 contracted projects. We are keen to understand and minimize drop-off points along the process, and we have identified the need to convert more draft statements of work into strategic partnership project agreements. The ABPDU, alongside LBNL's IP Office and Strategic Partnerships Office, have implemented a number of improvements to the process, increasing the speed of nondisclosure agreement drafting and execution, shortening communication turnaround times, and monitoring the process flow for all opportunities of continuous improvement. Of course, the necessary brevity of the presentation led us to omit many details of our technical and collaboration development operations. CRADA conversion has been typically around 7% and is often based on public funding opportunities. As such, our success rate varies substantially with the content of the funding call. Thank you for the feedback on equipment and utilization. BETO requires its PDU facilities to monitor utilization for the purposes of strategic facility development. Our rent-to-buy approach, which allows our collaborators to contribute during the rental phase, demonstrates industry interest in the specific equipment. We also conduct industry listening days where the industry expresses interest in specific equipment with both ABPDU leadership and BETO management.

The brevity of the reviewer's comments renders them difficult to interpret. Given the many scientific functions that the ABPDU AOP supports, we strongly believe that we serve the DOE and BETO missions and deliver substantial economic and technology development impact from taxpayer funds. Companies piloting primarily with the ABPDU have raised nearly a billion dollars of private funds compared to approximately $40 million in public investment to the ABPDU, representing a >20-times return on investment. Access to the ABPDU has accelerated time to market for numerous commercial products, helping catalyze the once nascent U.S. biomanufacturing industry and thereby remaining highly responsive to the BETO mission. This private funding has generated over 1,000 direct jobs and many thousands of indirect jobs. Offering a very much-needed pilot bioprocess development function has also resulted in augmented value to existing IP in both the private sector as well as the LBNL/BETO portfolio. For example, HelioBioSys developed their cyanobacterial polysaccharide production and separation technology with the ABPDU, developing joint IP under a CRADA agreement. Based on our interactions with industry, we are in a good position to identify industrywide issues that no one company is incentivized to solve. We leverage this knowledge to inform BETO AOPs and consortia research programs, generating IP that will benefit the entire industry. As an example, the BETO Separations Consortium was created as a response to a lack of a dedicated separation focus in the BETO portfolio—a research gap informed directly by ABPDU interactions with industry partners. The ABPDU team also actively connects the private sector to BETO's relevant program managers or consortium PIs, bridging industry with BETO programs or other national labs.

The ABPDU team thanks the reviewer for the generous comments. The team strives to provide unique value to the biomanufacturing community for the conversion of feedstocks to sustainable fuels, coproducts, or bioproducts more generally. All these areas provide inroads for greater economic and technological growth and competition so that all facets of the bioeconomy innovate and flourish. With evolving technologies and industry needs comes the real need for additional capabilities, of which the BETO team is actively aware. The ABPDU staff has identified several new capabilities—running the gamut from data capture to downstream processing unit operations. Moreover, they arise from both industry demand as well as alignment with the evolving BETO mission. The reviewers' suggestions will be further broached by the team. Again, we appreciate the helpful comments.

The ABPDU team thanks the reviewer for the comments and suggestions regarding outreach. In an effort to continue to expand the ABPDU's outreach and visibility, last year the team undertook an upgrade to the website's look and feel and has dramatically augmented the useful content available through the website, quarterly newsletter, and multiple social media channels. We are now periodically benchmarking the performance of these platforms to compare figures against earlier performance indicators, prior to these upgrades. We look forward to maximizing and reporting the value of these communication tools in the context of a larger strategy of outreach. The reuse of data and project learnings has required careful consideration. If information is in the public domain, through peer-reviewed publications and other channels, then it is available for supporting the industry as a whole. With more than 30 publications, more than 10 invention disclosures, more than 10 annual presentations, more than 5 standard operating procedure videos, master's-level coursework, and more than 90 well-trained alumni, the ABPDU has offered a variety of ways in which it generates an outsized influence; however, and perhaps more to the reviewer's point, we would also welcome ways in which anonymized and collated experimental data from multiple projects could be used for advanced modeling and meta-learning purposes. The ABPDU submitted a full proposal to BETO, "Decision Support and Knowledge Representation in Bioprocessing," which focused on enabling community sharing of data, as well as knowledge, in bioprocessing. We proposed deploying knowledge representation, reasoning-based systems, and other artificial intelligence on community-generated data to further *in silico* bioreactor experiments and narrow the parameter space for lab experiments, saving substantial resources and reducing time to commercialization. We look forward to working on such projects to enable data reuse at the ABPDU.

PACIFIC NORTHWEST NATIONAL LABORATORY HYDROTHERMAL PROCESS DEVELOPMENT UNITS

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.301
Presenter(s):	Dan Anderson
Project Start Date:	10/01/2015
Planned Project End Date:	09/30/2018
Total DOE Funding:	$2,600,000.00

The PNNL hydrothermal PDU project is focused on adapting and applying hydrothermal PDU capabilities (HTL, catalytic upgrading, catalytic hydrothermal gasification) to produce biofuels and coproducts from wet-waste feedstocks. The project has four major objectives: (1) conduct process development R&D to enable the scale-up of hydrothermal processing unit operations; (2) scale up the testing and production of fuels and coproducts from wet-waste feedstocks; (3) PDU systems capability management supporting operations, maintenance, and system modifications; and (4) PDU utilization and development of industry partnerships. The PDU project is addressing engineering scale-up challenges that must be resolved to move forward with later-stage integrated pilot testing and commercialization. This has resulted in several industry collaborations, two CRADAs, the development of IP for improved HTL processing and upgrading, and licensing agreements with commercialization partners.

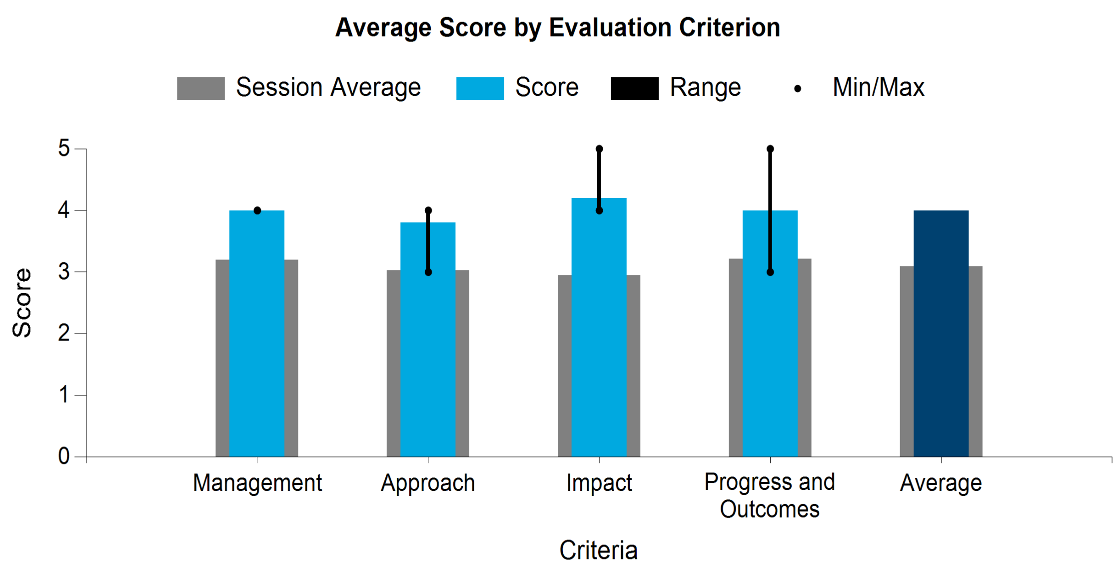


Photo courtesy of PNNL

COMMENTS

- This is good, interesting work, but maybe a bit overcomplicated. It is a bit confusing in terms of equipment versus process development. It provides great insights into HTL advantages over anaerobic digestion—sludge reduction, perfluoroalkyl and polyfluoroalkyl substance (PFAS) reduction, liquid fuel over renewable natural gas (RNG), etc. There are possible issues with manure "cleanup" for processing. This is a very distributed approach with many units in scope, so CapEx is a serious concern. The hub-and-spoke approach is probably best (biocrude to centralized hydrotreating).

- This is a great, well-managed project with well-defined goals and excellent achievements, including stretch goals. The project team should be proud of their accomplishments. Having several scales available for testing is invaluable and looks to be well used. Understanding how these units are managed, how the work is prioritized, and how modifications are made would have been useful. The impact of these efforts could be significant because processing wet waste is a huge need, and although RNG may be an option for many of these wastes, having a dense liquid fuel is a good alternative and, in some cases, more valuable.

- HTL, in particular, is a promising technology, especially for those feedstocks that are fundamentally very high in moisture as received. Hydrotreating is an important upgrading operation. The jury is still out on compressed natural gas, but it remains worthy of further research at this point; therefore, a facility covering these operations is of value to BETO, its grantees, and potentially industry partners as well. The management structure seems adequate to the complexity of the task, which, though substantial, is not highly variable on a short timescale, and therefore close to routing even if the actual study being conducted is anything but. The risk mitigation approach shows a clear understanding of the most likely trouble spots, although one needs to watch for the unlikely ones as well when doing early-stage R&D. There are multiple promising and ambitious but reasonable lines of R&D underway. Progress on the ongoing projects toward the stated objectives is good.

- It is not clear how or how long the PDU can achieve a 1,000-ton/day scale on the HTL feed so that even steady-state operations can be achieved. The strategy to specifically sell the HTL process to industry is unclear. Does PNNL intend to scale up this technology themselves to the commercial scale? What is the strategy to do that? PNNL stated that project partners want to scale the technology and do pilot-scale studies. At this stage, and with the work already done at the pilot scale at PNNL, scaling the technology needs to mean something beyond the pilot scale. The project reported that dairy manure plugged their upfront equipment. The project did not discuss why their front-end system could not handle this feedstock or its root cause. General guidance on the risk mitigation plan during the years (number of risks/number accepted/number outstanding/number new risks in last 2 years) was immensely beneficial to understand how the project is progressing. The approach covers a well-defined list of tasks with appropriate success metrics. The assumption is that these tasks can be tied directly to risks, requirements, or the strategic plan. On the approach, it would be good to understand the new target versus a realistic target needed for commercialization. The dollar-per-GGE target on slide 8 did not seem to match the graphic on slide 10. PNNL noted in their comments that the target is 8,000 hours for commercialization. It was not clear if the 2,000-hour run was sufficient to provide this *pro forma* target. It is unclear if PNNL has settled on a catalyst formulation and begun to produce commercial catalyst to further validate the abilities of this process. The project continues to demonstrate knowledge and the ability to reduce CapEx and OpEx and to increase the value of this technology. Industry interest appears to be coming from wastewater sources, and PNNL is responding by improving their feedstock handling equipment for this industry.

- The focus of the SDI portfolio has been on the demonstration and commercialization of technologies that can directly impact BETO's goals; this project clearly supports that focus with process development, scale-up, and partnership activities that directly impact the commercialization of HTL projects, including the development of other pilot plants. In the future, it seems that a terrific opportunity would be collaboration with modeling projects that assume biocrude as a feedstock—a sensitivity analysis around the feedstock variation impact on biocrude properties could provide much-needed data for the prediction of impact on downstream upgrading processes and final product properties.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful and constructive comments and questions. We will address key questions and areas that need further clarification.

  Regarding the comment, "It is a bit confusing in terms of equipment versus process development": Yes, this project has an element of both components. The project is responsible for maintaining and updating hydrothermal processing systems and capabilities for use to support DOE and industry research. In addition, the project also has a major process development R&D component to address key technical issues to enable scale-up and commercialization.

  Regarding the comment, "What is the scale of testing at PNNL and in scale-up efforts relative to the 1,000-ton/day goal case?": PNNL has bench- and engineering-scale HTL test systems (2–18-L/hour slurry, or a little less than 100 kg solids/day). The 1,000-ton/day plant is the envisioned scale for a commercial unit that draws on sludge; food; fats, oils, and greases; and manure within a geographic region. Several projects are underway to build and operate pilot plants that will process on the order of 3–5 tons/day.

  Regarding the comment, "Does PNNL intend to scale up this technology themselves to the commercial scale? What is the strategy to do that?": PNNL's strategy is to work with both technology end users/adopters and commercialization partners to scale up and commercialize the technology. We have established strategic partnerships with users that are generating and managing wet-waste feedstocks, and we have licensing agreements with commercialization partners that are raising capital for scale-up and commercialization.

  Regarding the reviewer's recommendation on the pursuit of modeling to understand the impacts of feedstock composition on the upgrading process and final product properties, we agree that being able to systematically correlate incoming biomass composition with the upgraded fuel blendstock product properties is of great value. Toward this effort, we have developed reduced-order models based on PNNL's extensive library of continuous HTL processing data to predict biocrude yield and quality. Extending the models to predict the upgraded fuel properties based on biocrude quality is the next logical next step that should be worked into our future plans.

Regarding the reviewer's comment on why the PDU upfront equipment could not handle manure feed when this stream is successfully handled at anaerobic digestion facilities around the country, manure feedstock to anaerobic digestion generally consists of settled particulate that is pumped from lagoons through large pipes/hoses at 2 to 4 wt % solids. To achieve high yields to biocrude and efficient use of reactor size, HTL feedstocks should be between 15 and 25 wt % solids. HTL reactors at PNNL are fabricated from ½-inch tubing or smaller. We attempt to collect manure that will be typical of larger-scale aggregation efforts (i.e., to avoid unrealistic hygrading). Some of the manure collected in this manner contains more than 50% ash (e.g., rocks, grit, dirt). It is this tramp material that creates upfront issues for formatting and processing at our scale.

Regarding the comment, "Understanding how these units are managed, how the work is prioritized, and how modifications are made would have been useful": The PDU team holds a large meeting every month in which all task elements are discussed, including interactions with other projects. Milestones (internal and external), test needs and equipment issues, and utilization are included in this meeting. With the entire team present, setting resource priorities is straightforward.

Regarding the comment, "The dollar-per-GGE target on slide 8 does not seem to match the graphic on slide 10": As the reviewer noted, there are small differences in the individual cost savings associated with the various improvements between slides 8 and 10, whereas the total cost savings is consistent. The modeled cost savings from the various improvements are a function of the order in which improvements are realized (an improvement implemented earlier [or later] generates a larger [or smaller] cost reduction) and the realized magnitude of the improvement. These cost savings are consistently refined based on our continuously updated model development efforts using the latest experimental data and anticipated implemented timeline.

Regarding the comment, "PNNL noted in their comments that the target is 8,000 hours for commercialization. It was not clear if the 2,000-hour run was sufficient to provide this *pro forma* target": Yes, the goal is to achieve a modeled hydrotreater catalyst life of 1 year (>8,000 hours). To achieve a modeled hydrotreater catalyst life of 1 year, we plan to do long-term catalyst lifetime testing for 2,000 hours or more runs. We plan to use the long runs and look at the deactivation of the catalyst as a function of position as well as learn about the deactivation rate based on the change in activity with time. Based on the slope of deactivation and the local deactivation rates (top versus the main section of the catalyst bed), we believe we can achieve a modeled catalyst life of >1 hour. In a 2,000-hour run, we did not change hydrotreating operation conditions for the first 1,500 hours. During that period, the deactivation is not measurable based on product quality. We are optimistic that this along with future 2,000-hour-plus hydrotreater experiments will enable us to estimate a catalyst life over 1 year.

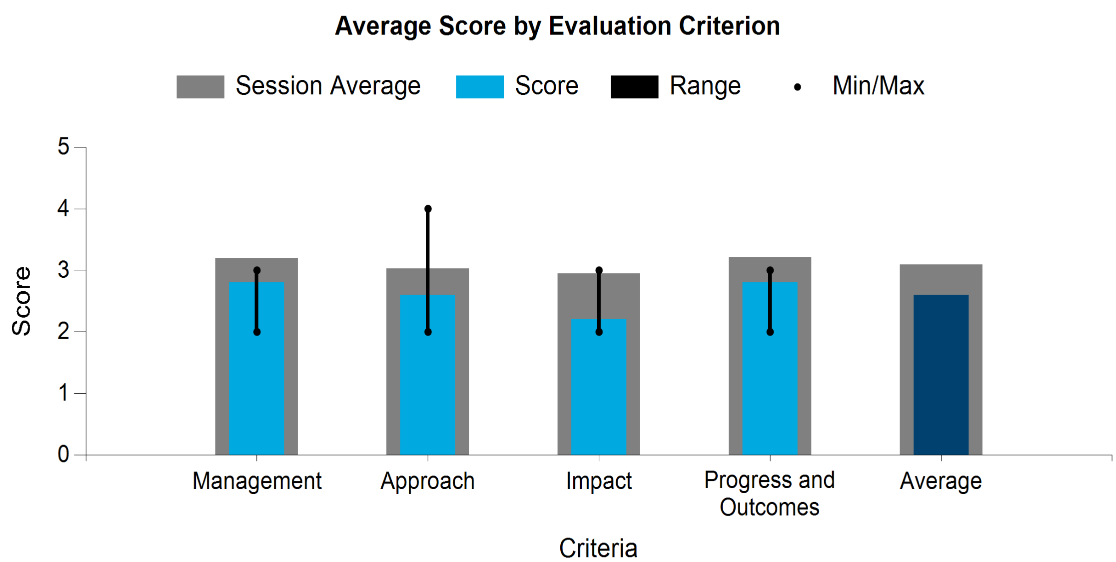
PROCESS SCALE-UP TO PRODUCTION ENVIRONMENTS

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.302
Presenter(s):	David Robichaud
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2021
Total DOE Funding:	$5,250,000

This project supports BETO's mission of transitioning bioenergy technologies to market by de-risking integration, developing scaling relations and modeling that de-risks scale-up, and providing a feedback loop with lower-TRL projects to understand process and technology fundamentals. Two objectives were pursued during this merit cycle. First, the Thermal and Catalytic Process Development Unit (TCPDU), a 0.5-ton/day pilot plant, was used to validate kinetic models developed by the CCPC. Validating the models to accurately predict product yields and composition is a first step toward de-risking a common industry failure—taking too large steps between scales. In addition, these models help with the design and troubleshooting of new unit operations for the TCPDU. The second objective was to conduct the FY 2022 verification campaign around *ex situ* CFP. The primary challenge of this effort was the coordination of multiple national labs and projects. This was overcome by a dedicated leadership role and effective communication strategy between the projects. Currently, the project is undergoing a pivot based on a stage-gate decision to not conduct the verification campaign in the TCPDU, and it is focused on closing out the CFP technology at a smaller scale by the end of the current fiscal year.



COMMENTS

- It is very unclear what is going on. Whatever it is, the presentation does not do anything for it. It is very confusing and does not really address the project itself. I think the presentation assumed way too much context that we might not have. The project might be very clear for those in it, but not to us. I struggle with the presentation more than with what I'm starting to get is the project's status.

- This is an excellent example of the risk management tool being used to identify a personnel need in a risk area and addressing that risk. The PDU works with lower-level R&D groups (routinely) and industry groups (at least on an infrequent basis). It is not clear whether the group pushes back on R&D to steer their research toward more commercially available equipment. This can be more valuable than listening to what they need and finding or designing new equipment. It is not clear how this team is selling itself to other groups or outside industry. The impact of this PDU appears to be minimal within BETO and did not report any significant projects that are active. There is strong collaboration between BETO entities but no external collaboration for this project other than Particulate Solid Research, Inc., which was mentioned for design assistance. A cold flow unit would be of assistance to catalyst developers and modelers trying to understand how their particles will behave in a bubbling bed. Modeling efforts discussed in the SDI panel have not included any cold flow experimentation. It is great involvement of the modelers to be physically in the field to understand data points and which data were being collected and how. It would have been interesting to hear how the data were collected differently based on the modelers' feedback or how the modelers had to change their model based on how it was in the field. This is a good example of using go/no-go criteria to stop a project prior to additional funds being spent on something that otherwise would not work. It is great to see that although the project is being delayed, it has a higher chance for success. The plan for multiscale modeling was unclear, such as what information was available at the start of the project and who else was consulted doing similar models; the FCIC is noted to be collaborating, but the specific task or group was not mentioned.

- The presentation for this project was unclear as to what specifically is being done, possibly because it was assumed that the reviewers had prior knowledge of the activities/approach. Several of the concepts introduced (e.g., "How do you make sure data are relevant to the next scale?") are excellent but lacked details as to the implementation. The comment, "Successful application of the risk mitigation strategy to inform a proactive verification pivot" sounds very much like, "We couldn't do CFP at the pilot scale, but we found a way to keep the funding." More information should be shared about this: What was the issue, and can the success be shared with industry to prevent similar issues for others?

- The project seems focused on incremental improvements to a fairly narrow technology that is not necessarily ever going to be a winner. It seems more like a generic set of tasks to maintain and improve an existing pilot plant. Where is the evidence that this should be done in preference to abandoning this line of research and spending the money elsewhere? In particular, it seems that the comment to "consider alternatives" on slide 6 will be very narrowly drawn. The sidebar on H_2 safety was not very well integrated or explained. Was there a serious incident in this facility? The modeling work is not well connected to the pilot plant upgrade, other than to add sample points. Where is the technology going, and what is the justification for going there? There is too much attention to what/how, not enough to why. It is also not clear exactly how they "disrupted the story." What actually happened? The failure/pivot was not really explained. There should be a more serious review of the value and purpose of this facility before significant additional sums are spent on its maintenance/upgrade.

- This reviewer found the overall goal of the project nebulous and ill-defined. It seems to be a catchall for problems that are not solved elsewhere; however, it seems that these issues should be solved within those projects. The impact of the project was noted that poor performance led to pivoting away from piloting. I do not see how this is an impact. This should always be present as a go/no-go decision before piloting, so it is unclear why piloting was included in this project if bench-scale results were not promising or if they had not yet been conducted. This project assumes that the reviewers have information not in evidence to the reviewers.

PI RESPONSE TO REVIEWER COMMENTS

- A primary comment from the reviewers of this project was that there was an over-assumption of context provided prior to the presentation. This is true. We assumed that the details of the verification effort and the CFP technology would have been provided in advance, and we apologize for the oversight. The purpose of this project was to prepare for and conduct a pilot-scale campaign of the CFP technology. This included modifications, including safety, to the pilot facility; participating in a multi-project stage gate of the CFP technology and its readiness for scale-up; and culminating in the execution of the campaign. Although many of the modification designs were in progress or have been completed, the stage-gate process demonstrated that the technology was not ready for scale-up. Part of the pivot for this project was to develop methods/procedures to help catch issues raised earlier in the stage gate and to provide support to the early-to-fail paradigm going forward.

The comments regarding the modeling are well received. Very little modeling was available at the outset of this project in relation to the verification technology and piloting. The modeling support that was provided was the result of collaboration among this project, the FCIC, the Chemical Catalysis for Bioenergy Consortium, and the CCPC. Although we do not have cold flow units of our pilot capabilities, the National Energy Technology Laboratory does have a variety of cold flow setups that they use extensively to support modeling work, including verification of flowability parameters (e.g., drag coefficients) of our catalysts and biomass feedstocks. The use of their capabilities, though not exactly related to our systems, greatly improves their ability to accurately model our systems. It is our intent to continue to collaborate with the CCPC, which provides the modeling support across a variety of BETO-funded efforts. As part of that continued collaboration, we will work with the CCPC to evaluate the added value of cold flow capabilities to supporting the design, operation, and de-risking of the facility.

The focus on H_2 safety during this project was not due to an incident in the facility or one associated with the technology at other scales. The underlying technology that we were being tasked with piloting required substantial quantities of H_2; however, our facility was not designed to operate under H_2 conditions. Given the age of the facility and the potential severity of an incident (as established in a precampaign process hazard review), we spent considerable time and effort to design safety controls and procedures to ensure an incident would not happen. The H_2 safety designs that we developed were not incorporated into the pilot plant due to the no-go stage-gate decision; however, those designs were utilized by at least one other project and provided a good deal of insight into how we might remodel our facility to support future technologies that BETO will invest in.

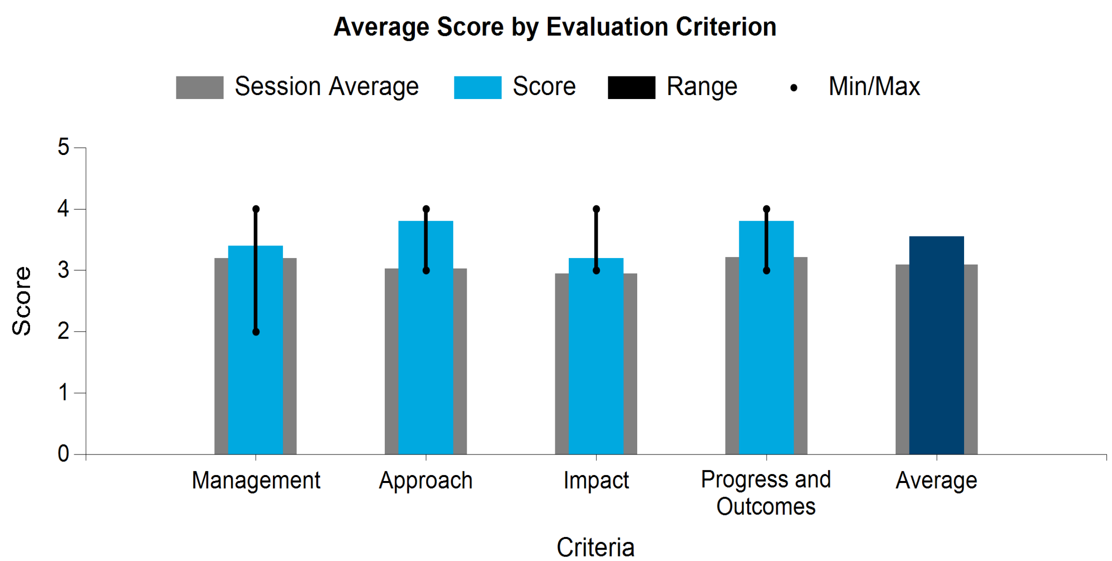
UPGRADING OF STILLAGE SYRUP INTO SINGLE-CELL PROTEIN FOR AQUACULTURE FEED

White Dog Labs, Inc.

PROJECT DESCRIPTION

WBS:	3.4.3.201
Presenter(s):	Carrissa Wiedel
Project Start Date:	01/01/2018
Planned Project End Date:	12/31/2021
Total DOE Funding:	$3,307,290

In this project, the fermentation streams from a cellulosic ethanol plant will be upgraded into a high-value single-cell protein (SCP) product that is enhanced with butyrate for broiler feed applications. Currently, after the cellulosic fermentation, the ethanol is distilled, and the solids containing protein, lignin, and other non-fermentables are dehydrated to produce a low-fiber, high-protein dried distillers' grains with solubles (DDGS). White Dog Labs, Inc., proposes performing a quick fermentation on the beer, before distillation and dehydration, to generate an SCP that can boost the protein content of the DDGS already being produced by the cellulosic ethanol plant. In addition to the increased protein, the fermentation would generate butyrate salts in the form of ammonium butyrate, which can be blended with other DDGS to deliver an efficacious dose of butyrate to broiler chickens. In the proposed project, led by White Dog Labs research scientist Carrissa Wiedel, we will produce SCP enhanced with butyrate from cellulosic streams and conduct a broiler chicken feeding study to validate the nutritional value of the SCP. Inclusion of the proposed SCP process will increase the value of the plant's current DDGS that are suitable for monogastric animals, including swine and poultry.



COMMENTS

- This is a great project and idea. It is unclear if any work is being done at the ethanol facility or if all of it is being done at the lab with shipped feed. There are some questions on the variability of the feed, etc. The plan to adapt strain to each feed could work but has some potential downsides if it is too costly or too much work. How is the product acceptable to animal growers?

- This project is clearly being managed with appropriate tools and metrics. The team is working with previous partner companies, which will facilitate success. The project demonstrated a great ability to identify problems and pivot to alternate technical and market solutions. This project is a great demonstration of project management and approach. The project has a strain library that they select from to find the best strain for a specific stillage stream, and the team has not found a particular technical challenge in adapting their strains to this process. It would have been of benefit to better understand the strain selection process, the challenges, and the risks associated with new process feed streams in the future. The schedule for this activity was 6 months, which is a long time for a task without technical challenges or risks. The value proposition to a potential cellulosic facility not demonstrated at $25–$50/ton is not clear without the associated CapEx. It is unclear what the internal rate of return impact to a facility would be. It is unclear whether the butyrate or SCP would be impacted going from wet distillers' grains with solubles to DDGS. Based on the location of the ethanol plants, the DDGS would need to be dried prior to shipment as chicken feed. The project appears to have made strides in the technical goals, showing reasonable fermentation times on unfiltered material. The project would not have been successful without pivoting in the manners they have had to. The project schedule appears to have been severely impacted by the loss of their feedstock supplier for this project. The project did not have any engineering design-related tasks in the schedule. It would have been good to understand the overall schedule for the design of the system (front-end design package, etc.). Their design partner is noted to have only 1% of the total project costs.
- It is unclear how big of an impact this project can/would have on the existing (huge) SCP market; piggybacking on existing ethanol facilities will provide limited growth opportunity. It would be very interesting to see tests on clean cellulosic sugars and how much of an impact this technology could have on the TEA of a cellulosic biofuels company using this SCP as a coproduct to improve financial viability.
- The connection to cellulosic sugars is unclear. On slide 4, the team shows the process working on a cellulosic stream within a corn ethanol plant and with their feed product simply blended with DDGS from the corn. A true cellulosic ethanol plant would not have an animal feed product available for blending, so at least some of the process/product integration shown would be absent. In fact, despite the project title, there does not seem to be any real synergy with cellulosic ethanol; the team could as easily ferment a slipstream of corn-based sugars to make their SCP with butyrate. Not much attention was given to the management or approach. Course correction in the face of adversity looks like it turned out well. The progress is reasonable given the timing and spend and allowing for both the project disruption and COVID.
- This project is well managed and appears to have executed a well-thought-out pivot to producing food for chickens. It is hard to assess the impact of the project because no information was provided regarding the value of the additional protein. We all know that protein is important in animal feed, and we have learned that butyric acid is also important, but just how valuable was not provided. It is also unclear why chickens were selected. Cattle is the largest market for DDGS, so some sort of justification for focusing on chickens should be provided. Finally, more discussion on how specific the culture of organisms would be to the specific waste stream would have been helpful, although the presenter briefly addressed it during the question-and-answer period. It appears that the team has made good progress toward their goals, and I commend them for recognizing an issue with their initial approach and developing a nice, technically sound, and well-managed pivot to a more promising technology.

PI RESPONSE TO REVIEWER COMMENTS

- All the work is currently being done by White Dog Labs using cellulosic streams being shipped to us by Ace Ethanol, LLC. Thus far, all the material we have received has been relatively uniform, with only slight variabilities. Because of this, each time we have been able to adapt Strain 8 to the feed during the seed train, which is not costly or time-consuming. The DDGS product is accepted by animal growers because the butyrate in the final product helps with gut health, weight gain, and feed efficiency.

For the strain selection process, we screened our library to see which strains could consume the highest amount of the remaining sugar and the acids in the feed but not consume any of the ethanol, which would have the fastest doubling time, and which would require the least number of transfers for adapting the strain to the feed. Also, note that there is no indication today of any additional CapEx needed. We would incorporate this fermentation into their existing process, therefore using equipment that is already at the plant as part of the standard D3MAX process. Because no additional CapEx is required, we can easily estimate the internal-rate-of-return impact based on the original model with the added benefit of the butyrate in the DDGS. We can estimate that the inclusion level of 1,500 ppm would generate a premium DDGS with butyrate worth $50/ton more than traditional DDGS. Based on the pounds/hour of solids generated at Ace Ethanol, we can estimate that they would be able to generate 30% more revenue from the DDGS with butyrate. The butyrate and SCP should not be impacted going from wet distillers' grains with solubles to DDGS, and the butyrate should not be volatile with the ethanol because it will be in salt form. The increase in feed value will come from the addition of the butyrate in the feed, not because of the slight boost in protein.

Although cattle represent a large market for DDGS, the United States has the largest broiler chicken industry in the world, with 9.18 billion broiler chickens produced in 2019. Cost, timelines, and the amount of DDGS with butyrate needed for feed trials were also deciding factors with how to move forward with this grant. Ultimately, based on our results with broiler chickens, we would like to provide this to a more diverse market to include cattle and swine. If we were to separate out an SCP product, it would be in such small quantities that we agree it would not have much of an impact at all in an SCP market; thus, it does not seem to warrant this approach. Instead, we are taking a modified approach and allowing the cell mass to go through the process into the final DDGS. Regarding testing on clean cellulosic sugars, you are right—it makes a lot of sense that, in addition to making ethanol, you could take a portion of that clean cellulosic sugar to make an SCP product. We have good indications from using corn dextrose that a stand-alone plant by itself—not even making a biofuel—can be very attractive; however, at this point, we have not assessed its value in the context of an integrated cellulosic biofuel plant. Thank you to the reviewers for all the comments and insights.

OPTIMIZATION OF CARBON EFFICIENCY FOR CATALYTIC FAST PYROLYSIS AND HYDROTREATING

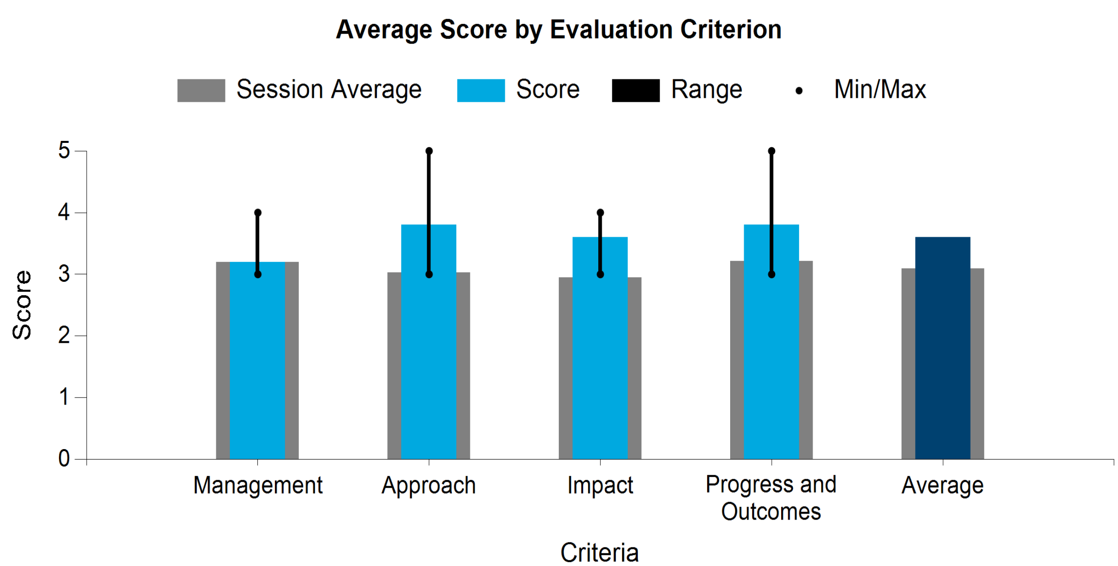
National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.4.3.304
Presenter(s):	Kristiina Iisa
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$500,000

The overall goal of this work is to support the development of the CFP platform by addressing knowledge gaps in the integration of the CFP process and hydrotreating. Hydrotreating of the product from the CFP process (CFP oil) is required to produce hydrocarbon fuels. Co-hydrotreating of CFP oil with petroleum feeds reduces the MFSP of the bio-based fuel via utilization of the economies of the large scale of petroleum refineries and introduces biogenic carbon directly into petroleum refineries. The challenges include ensuring that the introduction of CFP oil does not negatively impact the quality or the operability of the petroleum process and maintaining good deoxygenation of the CFP oil at the operating conditions of the petrochemical process. The objectives of the work are to demonstrate the production of quality fuel via co-hydrotreating, identify compound groups in CFP oils that negatively impact co-hydrotreating performance, and develop critical material attributes for CFP oils.

Co-hydrotreating with straight-run diesel was chosen for this work due to the predicted continued high demand for middle distillate fuels. The results to date have shown that a fuel with good properties—a low oxygen content and acceptable cetane number—can be produced via co-hydrotreating. NiMo was found to be the preferred catalyst for co-hydrotreating due to its high hydrogenation activity and the corresponding high cetane number of the diesel product.



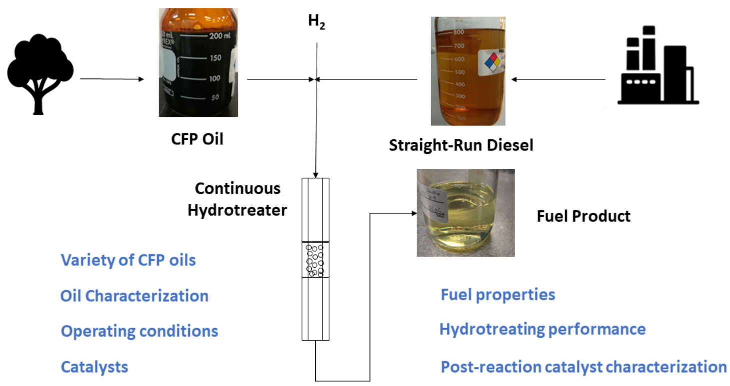


Photo courtesy of NREL

COMMENTS

- This presentation provided good insights into the newest developments for CFP. It could have provided a bit more detail on how the proposed integration into refinery hydrotreaters is to be accomplished because different refinery configurations and hydrotreating options are very varied. Which intermediate streams in existing refineries are targeted? How about the known issues with adding bio-oils to refineries (the presence of oxygen given rise to extra water production, N compounds, etc.)? Testing at 20/80 when targeting 5% mixtures does not seem relevant.

- This project has a reasonable management plan and identification/mitigation plans for risks. It is not clear that the CFP oils being studied are representative of a sufficiently broad class of candidates. Also, is it clear that they are stable in shipping and storage? The fractionation of CFP oil should be the primary plan rather than the backup plan based on past experience, though this may somewhat depend on the nature of the CFP oils selected. But *some* such oils certainly ought to be fractionated, and it would be nice to include at least one of those for comparison. The team should also consider industry standard "accelerated catalyst aging tests" as a backup to "no negative impacts." One concern in hydrotreating oxygenated oils is the very large exotherm that can be generated, but these are typically damped out in lab-scale equipment operating more nearly isothermally than adiabatically. Will per-pass conversions and reactor construction be suitable for observing any exotherms and their effects on catalysts?

  The U.S. average refinery size is a bit misleading at 140,000 barrels/day. There are 10 refineries 2.5–5.5 times that size; these are the most sophisticated ones, and obviously they process a significant fraction of the crude by themselves. There are a couple dozen more approximately two times that size, and there are quite a few that are much smaller, and all of those are far less sophisticated. So although 140,000 barrels/day may be average, it is not typical, and most crude by volume gets processed in larger refineries.

  Without the analysis of the CFP oils, it is difficult to say for sure, but the H_2 consumption number seems *very* low—one was even listed at 0.0%. It does not seem like much hydrotreating at all is going on. But with a CFP oil C-efficiency of 94%–95% (slide 12), it seems like more H_2 than that must be used just to cap that lost carbon? On slide 14, the apparent compositions of the bio-oils include *high* concentrations of oxygenated species. This seems inconsistent with the very low H_2 consumption and the low final oxygen content of the hydrotreated oils. Are all the atoms getting accounted for here? Low-temperature pre-hydrogenation is pretty well known (slide 14). Was it a surprise that might be required?

- The presentation did not provide adequate information on whether industry involvement from refiners (operators and engineers) was gathered, especially during the creation of the risk management program. Refinery buy-in is absolutely critical for this path, and it is not clear if refiners are being brought in to monitor the progress of this technology. Additional tasks or measurements may be required for a refiner to incorporate this technology into their system. It is not clear if NREL has settled on a catalyst formulation and begun to produce commercial catalyst to further validate the abilities of this process. "No negative impacts observed" is a great risk to have covered, along with the quality resolution of "make it fail." Too often projects do not see anything bad and falsely conclude nothing is wrong. There was a long delay (March–December) between characterization and testing. The composition of the CFP should have been taken right before testing; it was not clear if it was. The results did not appear to distinguish between the feedstocks or the process conditions used to make them. It is unclear if this project can understand the causes of the differences in the process results in this project. The overall goal of the project is excellent. I would like to have the project discuss the benchmarks for success—for example, how many hours of operation and at what scale would be required for industry to accept this technology? This does not mean it has to be done at this stage, but the overall plan should work toward that goal. The project is producing real results and is looking deeper into problems beyond oxygen content to understand the impact of what form the oxygen is in to understand the root causes.

- The project is making great progress with respect to its goals. The management plan is lacking in detail, and this reviewer found it very concerning that the provenance of the bio-oils was not documented or explained. Bio-oil was used as a specific technical term, when, in general, bio-oil is anything but specific. Understanding and ensuring that all the original bio-oils were similar seemed to be glossed over, but this is critical to the success of the project and in interpreting and comparing results. It is great that the project is looking at coprocessing because although it introduces considerable risk to refiners, it is unlikely that separate processing will be cost-effective due to economies of scale. The impact of the project is good, but it could be improved. The impact was noted as risk reduction for industry adoption, which aligns well with the project. It would be great if instead of only suggesting mitigation strategies, these strategies were tested, or at least a high-level plan for testing these mitigation strategies was developed.

- This is a good project that explores a potentially viable pathway to getting biofuels into the market. Given the ultimate goal, it would be good to see industry advisors (from the companies that own the hydrotreaters) providing feedback and guidance. It has been unclear whether coprocessing is a truly viable option for refineries, in part because there is often not enough focus on bio-oil variation. This project directly addresses the impact that varying compositions could have on refinery operations.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their detailed comments and constructive suggestions. We are in discussions with refiners and will seek additional industry feedback as suggested, including information on additional measurements desired by refiners. This will also aid in defining the metrics of success for commercial success as recommended by the reviewers. This project evaluates refinery coprocessing strategies together with 2.3.1.314 Catalytic Upgrading of Pyrolysis Products and 3.4.3.307 Bio-Oil Coprocessing in Refineries. We currently target hydrotreating with straight-run diesel refinery stream, but, as pointed out by the reviewers, there are several refinery strategies and hydrotreating options. Another potentially promising option would be FCC feed hydrotreater together with vacuum gas oil. Testing at the level of 20% of the CFP oil mixed with the petroleum stream was chosen because that level allows for a more accurate evaluation of the impacts, and although blends at the level of 5% CFP oil likely represent the first commercial-scale processes, the goal is to increase the blend ratio. As commented by one of the reviewers, in order to produce meaningful reductions in GHG emissions, full replacement of fossil fuels is the ultimate goal.

The bio-oils in this study were provided by NREL under BETO-funded projects; we have full information on their provenance—including biomass feeds, reactor configurations, operating conditions, and details on CFP catalyst formulations—and we will include that information in future presentations. Experimentation time required (2 weeks per experiment) and the availability of CFP oils limit our ability to perform experiments. Instead, our goal is to identify compound groups that negatively impact hydrotreating by testing a smaller number of oils and spiking oils with suspected detrimental compound types. This will allow us to determine critical material attributes for CFP oils, which can then be applied to oils from different feedstocks and processes. The base oil (Pt/TiO_2 oil with 17% oxygen on a dry basis) in our experiments is similar to BETO's 2019 SOT CFP oil and is thus relevant to BETO. Since the Peer Review, we have also hydrotreated BETO's 2020 SOT CFP oil. We closely collaborate with the project 2.3.1.314 Catalytic Upgrading of Pyrolysis Products, and we plan to test new types of CFP oils they produce. Fractionation of CFP oils via fractional condensation is currently being evaluated in that project, and we plan to assess the hydrotreating of those fractions. In this project, we concentrate on the impacts of CFP oil compounds on commercial-type catalysts and hydrotreating processes, and we do not currently develop catalysts or processes. Initial comparisons between two basic types of catalysts were performed, as shown in the presentation, to select a catalyst for further experimentation. As noted by the reviewers, CFP oil hydrotreating produces water, which could be detrimental to catalysts, but some refiners already process fats, oils, and greases for renewable diesel; these feedstocks also contain oxygen and form water, and the information from these processes can be leveraged here. The nitrogen contents of many CFP oils—particularly those from woody biomass sources, which are likely to be the first to be commercialized—are low compared to petroleum streams, and petroleum refineries are set for hydrodenitrification. A potential problem is CFP oil interfering with the capability of the catalyst to reduce nitrogen contents, and that is one of the attributes we are evaluating.

In addition to the processability of the CFP oils during hydrotreating, the stability of these oils during shipping and storing are important considerations, and the project 2.5.2.301 Development and Standardization of Techniques for Bio-Oil Characterization, with which we closely collaborate, is involved in developing methods for assessing storage stability. The timetable had been modified in the beginning of FY 2021 (October 2020). The long delay between analysis and testing (March to December) was due to delays caused by the pivot in BETO's CFP program and COVID-related restrictions to laboratory access. Initially, the experiments were scheduled to be completed in June 2020.

Hydrotreating CFP oils gives rise to exotherms, as pointed out the reviewers. We have up to six thermocouples in the catalyst bed to measure temperatures and evaluate exotherms. In addition, we assess the magnitude of the exotherms by thermodynamics and heat transfer calculations. The exotherms will also be significantly smaller for co-hydrotreating than for stand-alone hydrotreating. Low-temperature hydrogenation, sometimes in two stages, is a well-known strategy for the mitigation of bed plugging in the hydrotreating of non-CFP oils. Because of the upgrading during the catalytic pyrolysis step, the properties of the resulting bio-oil are improved, and single-stage hydrotreating without prior hydrogenation has been utilized. Our current research aims to identify potential problems caused by the variety of catalytic pyrolysis oils and suggest mitigation strategies, and we wish to be able to test them in a continuation of this project.

Thank you also for the opportunity to clear some misunderstandings that arose from the short presentation. The low H_2 consumption values on slide 12 were for hydrotreating of the petroleum stream alone; the values for co-hydrotreating were 1.4%–1.5% of the combined feed. With 20% CFP oil in the mixture, this translates to approximately 7% of the CFP oil mass, similar to values for the stand-alone hydrotreating of CFP oils and well in excess of the H_2 required for hydrodeoxygenation (2% or 0.02 g/g of oil is required for our base oil with 17% oxygen). The U.S. average refinery size was used for illustrative purposes only to demonstrate the difference in scales, and no decisions were made based on the types or sizes of refineries.

BIO-OIL COPROCESSING WITH REFINERY STREAMS

National Renewable Energy Laboratory

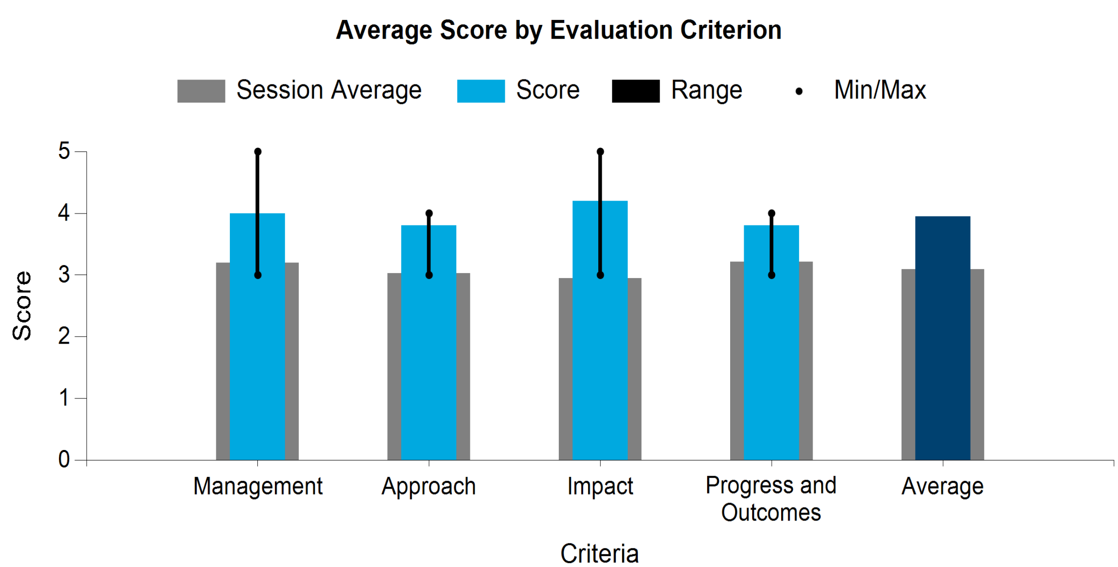
PROJECT DESCRIPTION

WBS:	3.4.3.307
Presenter(s):	Kim Magrini
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2021
Total DOE Funding:	$750,000

The objective of this three-laboratory project is to accelerate the adoption of coprocessing biomass-derived feedstocks with petroleum streams in petroleum refineries by developing and publishing data for processing renewable intermediates and offering coprocessing strategies. This project leverages unique national laboratory capabilities in catalysis, process development, isotope tracking, and TEA and LCA to conduct basic research through applied R&D to address major technical gaps in coprocessing and to reduce technology uncertainties to refiners. The first 3 project years demonstrated bio-oil coprocessing using continuous FCC and hydrotreating/hydrocracking systems with real bio-oils and industrial catalysts, tracing biogenic carbon incorporation using ^{13}C-labeled biomass, and developing carbon isotope measurement methods.

Accelerating refiner adoption is achieved in the next 3 project years by reducing risk around three critical needs identified by the project's IAB: (1) an operability risk for process stability via catalyst deactivation; (2) a regulatory risk around rapidly measuring process biogenic carbon and oxygenates; and (3) a knowledge risk centered on the lack of coprocessing data, including feedstock compositions and contaminants, product compositions, reaction kinetics of biocompounds, and pathway TEA/LCA.

Project metrics include assessing catalyst performance losses, causes and mitigation for both pathways, measuring biogenic carbon at <1% levels in coprocessing fuels, and generating process data for accurate TEA and LCA. A public database of feedstocks, coprocessing conditions, and biofuels will be available for refiner use, including TEA- and LCA-determined process cost and GHG impacts per pathway.



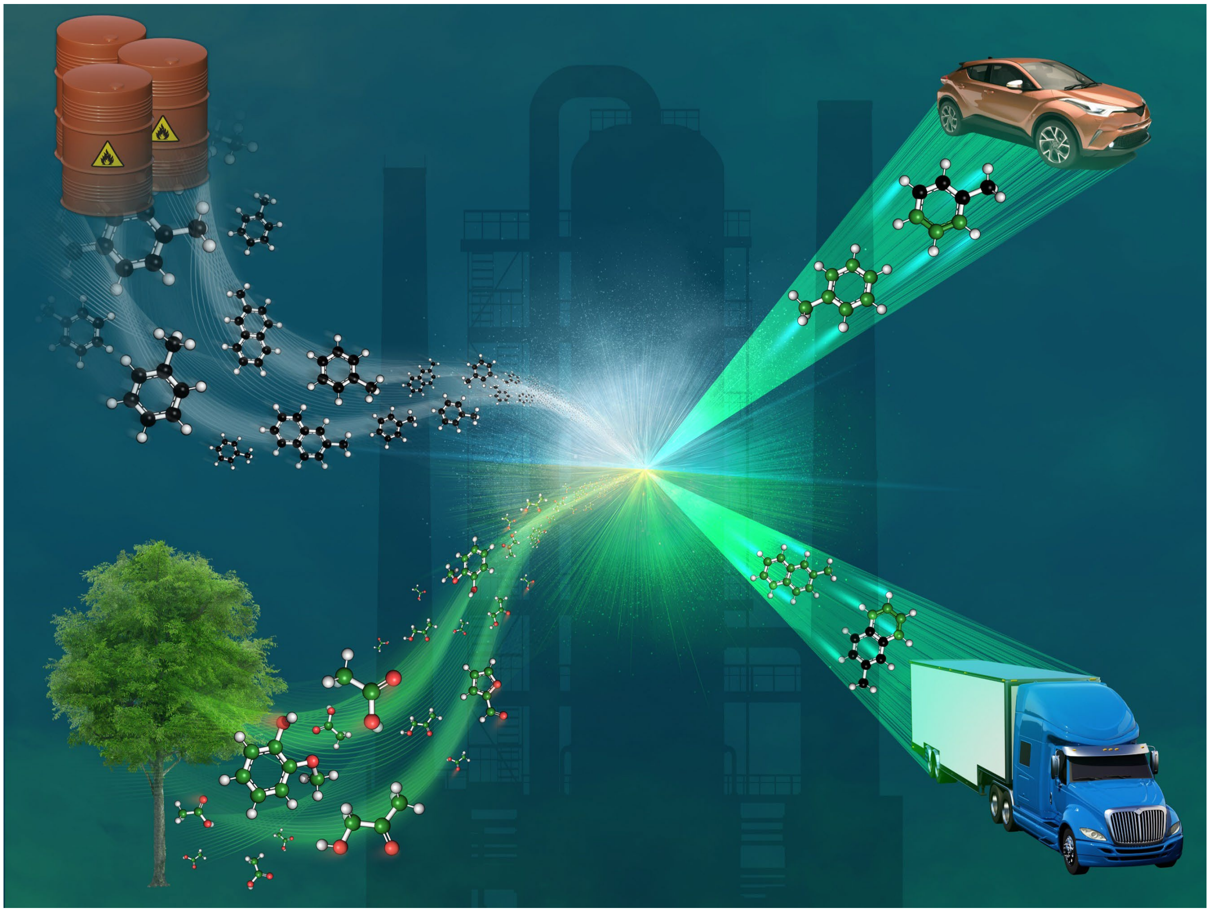


Photo courtesy of NREL

COMMENTS

- This presentation was good, but it needs more refinery insight and operations experience. Is hydrotreating/hydrocracking and FCC possible in one refinery? There is a need to clearly understand the value (advanced optimization is needed). Why is biogenic carbon tracking needed? Should not a simple carbon accounting balance be enough? What is the value of added bio-oils, the value created? How was TEA performed? Should be calculating the cost of an external (bio-) stream to achieve fuel costs. That is a different way to look at it.

- The tasks of the refineries were not clear. It seems they were involved in an advisor role only. It would be of benefit if NREL could entice these entities into a greater participatory role. It would be beneficial to know what refineries have told BETO regarding the willingness to adopt a new catalyst recipe. Refinery buy-in is critical for this path, and it is not clear if refiners are being brought in to monitor the progress of this technology. The project is aware of the further challenges in refinery adoption, but there are not any further plans to do this work at a pilot scale. The 8% displacement is massive in industry, even if it is a small number. The corn ethanol industry displaces 10% of petroleum and supports thousands of jobs and billions of dollars in gross domestic product. It would be good to understand the non-RIN value of the blend versus the standard FCC output (slide 12). The project has done a good job of providing tasks to each of the known risks of this technology blend and is clearly working toward eliminating roadblocks to the development of bio-oil and FCC blending. The project discusses the long-term catalyst stability risk, but the presentation is not clear on how this is being measured experimentally. The reviewers would like to know how the project has assessed performance, how frequently it has regenerated its catalyst, and how it projects performance. Potassium and sulfur are mentioned as elements under study for catalyst deactivation; however, the impact of other more minor elements, or those that are known to easily be resolved through regeneration, do not appear to be under study. If the catalyst needs to be regenerated more frequently, that, too, would have a serious impact on the refinery.

The metrics of the demonstration of the FCC/hydrotreating and hydrocracking fuel production were not provided. Without these metrics, it is hard to evaluate whether this project has successfully impacted the state of biofuel production. The comment "linked to FCIC database" is unclear. The interface should be a singular consistent user interface, not a conglomeration of different programs that are merged together. It is not clear whether the development of the instrument is ongoing or is considered complete. The fidelity of the carbon monitoring device is critical on equipment that is pumping millions of gallons per day. The presentation noted that it could measure down to a percentage, but this does not provide sufficient information to determine its benefit.

- This is a great project that is directly addressing knowledge gaps limiting the commercial processing of bio-oils. It has excellent industry participation, clearly identified challenges and a research approach to address them, and plans for a published database to disseminate information post-project.
- This is a solid project overall. It has a good management and risk mitigation plan; excellent outreach to catalyst vendors and refiners; and an effective plan to target the right feedstocks for the right processes and to acquire data, both primary (conversion to products) and secondary (catalyst life, operational issues, etc.). Progress so far has been good, and success versus the stated objectives seems likely. The one major concern is that by targeting low-level blending, the project may be a tactical success but a strategic dead end. We do not need 5%–10% bio content in a couple of process units; we need refineries that are processing >75% renewable feedstocks. If this is clearly a step along that path, fine, but it was not clear from the material presented that was so. The BETO vision for existing petroleum refineries should be that they will process mostly renewable feedstocks or they will go out of business.
- This is an excellent project that is achieving good results. I am amazed at the complexity of the project and how the objectives are being met despite this complexity. The team may want to review its objectives to ensure that they are not overstretched and can continue to function at a high level. It is well managed with excellent industry involvement. As with other projects, I really like that they are looking at coprocessing, and coprocessing in numerous unit operations. This reviewer also likes that they are tracking and documenting the feed quality and consistency, a deficiency of other projects. This is a great project and a great team.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their positive comments about this coprocessing project, including their support of the knowledge gaps the project is addressing, the database development, and industry participation through the project's IAB. We agree that increased refinery insight and operations experience are needed, and we are expanding refiner participation in the next 3 years of this project. We did not mention in the review that we are currently performing FCC coprocessing tests for two major refiners using NREL's Davison Circulating Riser system with their specific feedstocks and catalysts to define process parameters. We are also working with a refinery, which is producing renewable diesel by coprocessing biofeed, to evaluate coprocessing wastewater sludge HTL biocrudes in their hydrotreating unit. Additionally, biogenic carbon tracking is an ask of our IAB: to understand where biogenic carbon is reporting both during coprocessing and in the final product. Note that California is requiring ^{14}C analysis of biogenic C-containing fuels for RINs.

  Finally, TEA was performed using an Aspen refinery model and project-generated coprocessing data. The Johnson Matthey catalysts used in the FCC coprocessing work are HZSM-5 catalysts modified to enhance bio-oil conversion while retaining their original ability to convert vacuum gas oil. Catalyst characteristics must be maintained for FCC operation, and the modifications adhere to this requirement; thus, refiners should not have issues using these catalysts in their FCC systems. The SOA hydrotreating and hydrocracking catalysts provided by an industry partner were used for our coprocessing study. Project plans in years 2–3 will address catalyst lifetime and potential deactivation from fugitive contaminants, as will regeneration requirements for both FCC and hydrotreating/hydrocracking coprocessing. The bio-oil and biocrude database can be linked to the FCIC feedstock database because both use LabKey as the platform; this approach leverages the information in both databases for researchers and refiners.

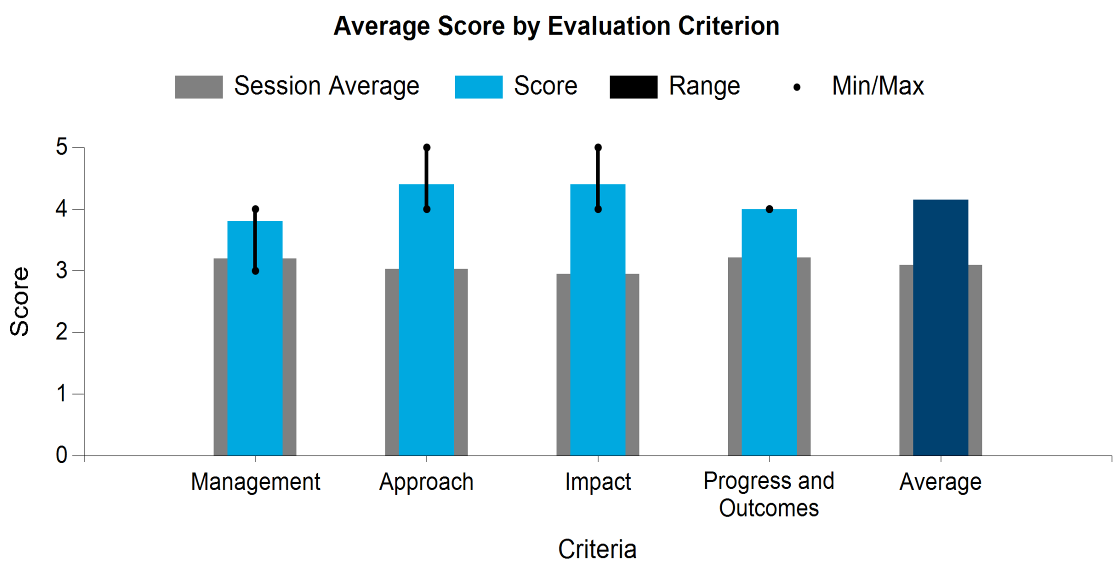
The biogenic C measurement systems under development are slated for ease of use and ruggedness in a refining environment. We agree that the more bio content in fuels, the better; however, refiners have told us that for FCC coprocessing, 10 wt % bio-oil blend is the current upper limit for coprocessing in FCC units. Greater than 10 wt % upsets downstream processes. Also, consider that biomass resources may limit how much bio-oil and biocrude are available for coprocessing.

We thank the last reviewer for their positive comments—they are very much appreciated. We believe tracking feed quality and consistency is a critical process parameter that must be understood if coprocessing is to be successfully adopted by refiners.

INTEGRATION OF IH² WITH THE COOL REFORMER FOR THE CONVERSION OF CELLULOSIC BIOMASS TO DROP-IN FUELS

Gas Technology Institute

WBS:	3.5.1.101
Presenter(s):	Terry Marker
Project Start Date:	10/01/2019
Planned Project End Date:	06/30/2022
Total DOE Funding:	$1,596,065



COMMENTS

- This is an excellent project with a sound technical approach and the potential to make a significant impact. It is clear that the presenter is experienced with developing and scaling up new technology, and the integrated hydropyrolysis and hydroconversion (IH^2) technology is known to be a promising, well-tested strategy. The reviewer would have preferred slides that were more detailed and, in a word, meatier. The management plan did not address the risks and mitigation strategy. The approach is sufficient but not detailed. No data or plans were provided, and the key technical challenges were very high level and were not really challenges but successes. It can be said that the review came at an awkward time, i.e., shakedown, which is a time of little to no data, known procedures, and much day-to-day problem solving, but I found the lack of detail disappointing. The impact of the project could be very significant due to the simplification of the flow sheet. The process improvements incorporated into the design and their associated impacts should significantly improve the economics and potential commercialization of this technology. The project looks on track to meet its goals, but it is difficult to assess due to the timing of the review.

- There is potential for significant impact of a reforming catalyst to handle carbon monoxide (CO) without CO_2 removal. The process has nearly 500 hours of time on stream (TOS) so far. The overall status of the catalyst in terms of its development plan was not presented. The validation plan for the catalyst would be helpful. Rapid cycling valves is a small but important improvement in reducing the overall size of a future facility. The project team has identified a consistent feedstock PSD as a key attribute in its development and has identified a new technology that they believe can provide them quality feedstock for this project. There are significant CapEx savings from utilizing the new reformer catalyst to cut down on several unit ops. It would have been beneficial to see TEA with and without the new reformer. The project team outlined clear goals to advance their technology to be more commercially viable; however, the project does not provide clear guidance (TEA/LCA) on where they are and what they consider commercially viable. This leaves the reviewer aware of a goal but unaware of what it looks like or whether the project knows what it needs to get there.

- This is a good project with a good management team and good industry engagement. "Avoid the bad stuff, and go straight to making the good stuff" is an admirable approach. It was unclear from the presentation whether there is commercial application for the catalyst beyond this process or whether the improvements in the lock hopper can/will be shared with industry as a whole. The integration of the reformer into the process to utilize the biomass-generated C1–C3 gases (versus natural gas) is an excellent advance, and it would be good to see this applied to other H_2-demanding projects.

- This was already a promising technology, and this project introduces multiple potential improvements, particularly the H_2 self-sufficiency required for a top-notch LCA result. The management plan is superficial, and it should be more detailed. Progress is very good for the middle of budget period two. Catalyst stability and integrated system performance/stability over longer run times will be the key to success.

- This is a very good and interesting extension of the IH^2 development by adding a new reformer combining steam and "dry" reforming. There is great collaboration with Shell and KBR. Hydrogen generation and balance is always under question until it is demonstrated at the commercial scale and for reasonable times.

TRIFTS CATALYTIC CONVERSION OF BIOGAS TO DROP-IN RENEWABLE DIESEL FUEL

T2C-Energy, LLC

PROJECT DESCRIPTION

WBS:	3.5.1.201
Presenter(s):	Devin Walker
Project Start Date:	10/01/2019
Planned Project End Date:	10/01/2022
Total DOE Funding:	$2,909,698

T2C-Energy has developed and patented a novel catalytic technology we have trademarked as TRIFTS for the direct conversion of biogas to drop-in transport fuels. A key aspect of the technology is the utilization of both the CO_2 and CH_4 portions of biogas and incorporating them into the hydrocarbon backbone of the final product (renewable drop-in diesel). We have previously collaborated with DOE to build a mobile pilot facility for the purpose of testing the technology on-site at multiple landfills and anaerobic digesters. The unit was designed to convert a 9–24-scf/min slipstream of raw biogas into renewable transport fuel. Successful demonstrations and testing at engineering scales are a proven pathway to commercialization and provide confidence to all stakeholders for scale-up. This project focuses on rigorously testing our TRIFTS technology at the engineering scale to convert a diverse range of biogas feedstocks derived from MSW, wastewater, animal waste, food waste, and crop residues into high-quality, renewable, drop-in diesel fuel. These feedstocks present variations in biogas feed compositions and varying levels of impurities that offer unique challenges. We therefore seek to prove the robustness of the TRIFTS process over this broad biogas range and efficiently convert them into middle distillate hydrocarbons in a profitable manner and at scales that were traditionally not economically feasible. The biogas variations, catalytic parameters, process dynamics, system performance, heat and mass recycle streams, process LCA, maintenance cycles, and fuel product quality will all be monitored and studied over sufficiently long periods to optimize the efficiency, productivity, and economics of the TRIFTS process and to determine the scaling factors and equipment specifications for commercial application. As of February 2021, the pilot unit has been demonstrated at a county municipal landfill and a private dairy farm anaerobic digestion with more than 5,000 hours of total run time processing raw biogas. The fuels produced were tested under ASTM D975 standards and met specifications for No. 2 ultra-low-sulfur diesel. The current modeled MFSP is $2.44/GGE for a 55-barrel/day production plant processing 1,000 scf/min of biogas. Economic opportunity; job creation; the production of drop-in renewable fuel, fertilizer, and fresh water; and the creation of circular economies within the United States at the rural and metropolitan levels are direct impacts of this project.

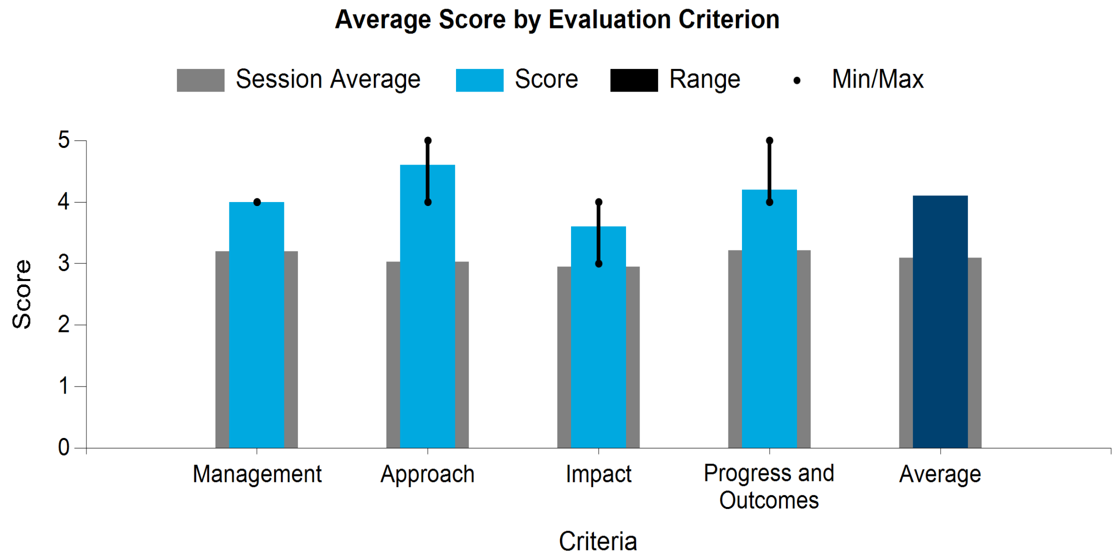


Photo courtesy of T2C-Energy, LLC

COMMENTS

- This is a very interesting project and technology. Some bits are a bit optimistic, but the technology and business model have great potential—specifically the mobile pilot plant within a truck and the universal waste. CapEx is verified by an engineering, procurement, and construction (EPC) firm. two catalysts in the project in-house seems risky, but it is great if it works. This is interesting low-carbon fuel standard (LCFS)/carbon intensity math; achieving additional lower carbon intensity with upgrading is questionable. There is no hydrotreating; only a single product from Fischer-Tropsch as a blendstock of $2.41/GGE per 1,000-scf/min scale.

- The project appears to be well managed and has a good approach to successful completion. The team is aware of risks and is actively managing them. Obtaining the assistance of an EPC contractor to verify the costs is an excellent approach. The project has developed a unique reforming catalyst that can convert both CO_2 and CO. This allows them to remove several units of operation from the process. The operational and CapEx costs impacted by not removing the CO_2 have to have been offset by the gain in yield, but that was not made clear in the presentation; however, a much simpler process with fewer unit operations is likely to be the more economic approach. The scale of the future commercial facilities is relatively small, making offtake a challenge for this technology. Additionally, this project will need to compete with RNG projects at many of its potential sites and is regionally limited by the fuel it is producing (cold filter plugging point [CFPP], flash). So although this technology likely has several homes, siting these locations will be challenging. The project has developed a focused technology that helps to provide a stranded feedstock problem. Scale-up metrics were not provided. The project will need to produce significantly high yield compared to kilowatt-hour production potential to be profitable. It is unclear how long the catalyst is supposed to last from a *pro forma* perspective—6 months is not a long time for a catalyst. All contaminants must be water soluble to be removed in this system because there do not appear to be any other scrubbing or filtering methodologies in place. The metrics listed appear to be impactful and measurable targets. The project provided a clear and well-organized project plan and appears to be making great progress toward their overall project. The mobile pilot plant will provide a great approach in evaluating the different potential feedstocks. The project presentation did not demonstrate that the kinetics of their process have been fully understood with the various potential sites.

- The management plan was good, but it could have been improved with more detail. Also, the risks and mitigation strategies got intermingled in their slide. All were listed as risks, but many appeared to be mitigations. The approach is excellent—using the trailer to develop the technology is a good use of resources. Also, the team appears to want to minimize unit operations and thus complexity. After numerous presentations with multiple products and unit operations where it appears that finding interesting things is more important than executing the project plan, this was a welcome respite. The choice to develop an imperfect (i.e., does not have the full range of diesel) fuel to limit project complexity could just be the factor that enables this project to be successful. The impact could be very significant, especially if some type of cooperation of small facilities was developed and the produced fuel was used in niche applications (e.g., farm machinery) or summertime blends. The ability to be small-scale and located at the farm and then pooling the dense liquid fuel could be very advantageous. I did not give the impact a perfect score because the team needs to determine where and how their fuel will be an acceptable substitute.

- This is a solid project with the potential to produce diesel fuel from biogas. The economics of Fischer-Tropsch are reasonably likely to work because they avoid both wax formation and the need for hydroisomerization. The price they pay is a blendstock that will be limited due to straight chains from meeting winter diesel specifications. The fuel is close enough that it still can be blended in high percentages, but it cannot be used neat in colder climates. The ability to use CH_4/CO_2 mixtures is key to the economics. This is simple and elegant. The management plan is good. The approach is especially detailed; all the relevant criteria are being addressed. This is among the very best in this round of Peer Review presentations.

- This is a very interesting project that appears to make a drop-in fuel suitable for local use (Florida) only due to neat fuel properties. There is a concept here that begs whether—like the ethanol craze in the 1970s—this technology is suited to farms for the self-production of biofuels for on-farm usage. Considering the energy density of both biogas and diesel, apparently approximately 20% of the biogas energy content winds up in the final liquid fuel product (based on the “final target” of 24 scf/min consumption and 11 wt % overall liquid yield), it looks like this technology would find it hard to compete with renewable natural gas from a purely energy storage standpoint.

PI RESPONSE TO REVIEWER COMMENTS

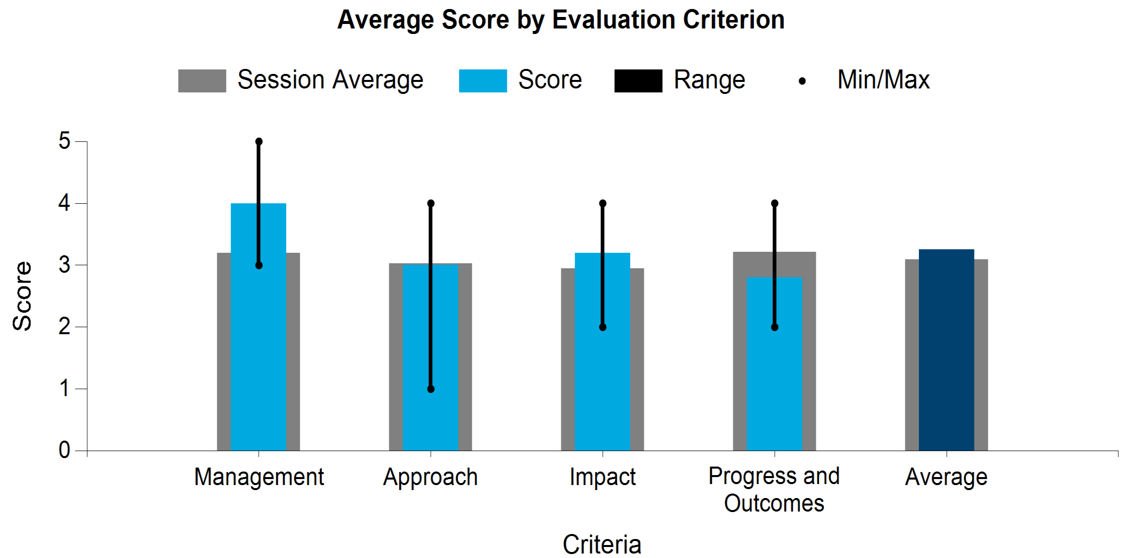
- We thank the reviewers for their efforts and comments in the review of this work. A reviewer concern was related to TRIFTS fuel being limited in its use due to the cold temperature properties of the fuel produced. The winterization (use of additives) of diesel is commonplace within the industry. The TRIFTS fuel produced has a cloud point of −1°C and a CFPP of −4°C (the CFPP of typical No. 2 commercial diesel is approximately −10°C). The addition of low-temperature additives to TRIFTS fuel would bring the CFPP to −14°C, making it acceptable for winter use within the majority of the United States. The TRIFTS fuel (100% neat) meets all ASTM D975 fuel specifications for ultra-low-sulfur diesel fuel, except for conductivity and viscosity. The conductivity is low to target relating to the static charge accumulation during the transmission of fuel and can be adjusted to the specification target with small quantities (<0 ppm) of antistatic additive. The viscosity is slightly low to target (1.8 versus 1.9 cSt) and can also be adjusted with small quantities (<15 ppm) of a viscosity improver additive. Both additives are widely used and readily available within the commercial diesel industry, adding flexibility to the use and distribution of the fuel. The addition of these additives (<1 vol % amounts) allows for the widespread use of the fuel throughout the year as a drop-in fuel replacement to petroleum-derived No. 2 ultra-low-sulfur diesel. The overall product yield of 11 wt % included feed stream masses of not only biogas but also water and air, leading to a deflated yield value. The final fuel product contains approximately 41% of the original biogas energy content, with another 40% of the original biogas energy content being recycled as fuel gas to heat the reformer and to attain lower carbon intensity scores; thus, 81% of the original biogas energy content is recovered by the process.

Preliminary LCA models give a carbon intensity score of −36 gCO_2 equivalent/MJ for a TRIFTS fuel landfill project compared to a score of +30 gCO_2 equivalent/MJ for a typical landfill RNG project. Energy-dense liquid fuels are more widely used in transport and have a significantly higher dollar value in an unsubsidized petroleum market than natural gas on a dollar-per-MMBTU and dollar-per-kilogram basis. A significant financial benefit to the utilization of TRIFTS technology is that even though the fuel produced qualifies for environmental attribute revenue (e.g., RIN or LCFS credits), it is not reliant on them to be profitable and creates a more secure/long-term route to sustainable energy from waste when environmental attribute programs begin to reduce or remove incentives and petroleum spot prices become more influential over fuel revenues. This is a major benefit over current RNG applications that receive more than 90% of their revenue from environmental attributes. The TRIFTS process includes pretreatment of raw biogas streams with our proprietary cleanup process to remove sulfur, siloxane, and halogen contaminants to below detection limits. This pretreatment process was tested with our mobile pilot unit and proven to effectively remove contaminants from dairy, wastewater, and landfill biogas applications over industrially relevant time periods (>6 months). Typical inlet contaminant levels treated at the pilot level are H_2S = 5,000 ppmv, siloxanes = 15 ppmv, and halogens = 5 ppmv. T2C-Energy is currently scaling the TRIFTS process for a 1,200-scf/min biogas landfill demonstration project and increasing its current catalyst manufacturing capability from 4 kg/day to 25 kg/day. The production cost for the 1,200-scf/min biogas capacity demonstration project is estimated at $1.47/gal renewable diesel.

INTEGRATED REACTIVE CATALYTIC FAST PYROLYSIS SYSTEM FOR ADVANCED HYDROCARBON BIOFUELS

Research Triangle Institute

WBS:	3.5.1.204
Presenter(s):	Dave Dayton
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2023
Total DOE Funding:	$3,000,000



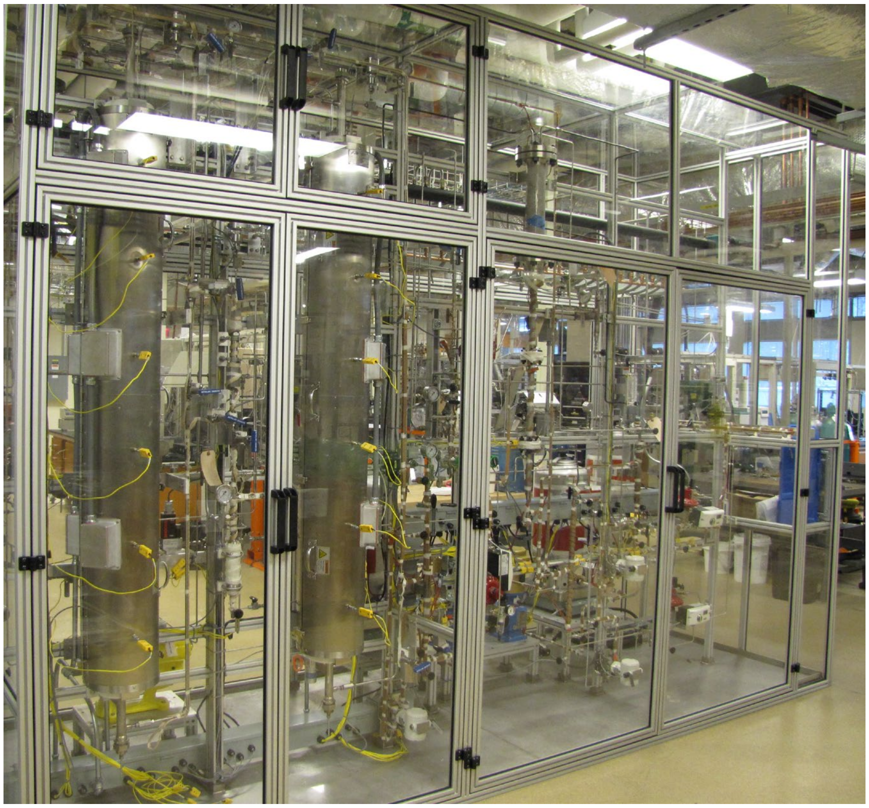


Photo courtesy of Research Triangle Institute

COMMENTS

- This is a very interesting take on reactive catalytic fast pyrolysis (RCFP) under moderate H_2 pressure to control the creation of oxygenated compounds, etc. It is always complex to get the right H_2 balance among generation, use, and circulating amount. Some of the initial results are a bit underwhelming, but it is in the early days yet. The team should concentrate on arriving to steady state and then improving performance. Catalyst lifetime is key. It is good to consider different upgrading options and arrangements.

- This is an excellent management plan. The Research Triangle Institute and the PI's experience in developing and executing technology experimental and development plans is evident in the comprehensive and detailed management plan. The project is making good progress, but it has not been able to hit steady state or process longer than 150 hours due to plugging and other issues. The project is still fairly new, so there is still time to meet the goals, but it would have been great if the proposed approach to meet those goals, given the difficulties, had been outlined. Although the management plan and approach are excellent, they should be revised to address the technical issues. Due to the technical issues, at this time, it is unclear if the impact will be significant or if the goals will be reached.

- The presentation was way too fast and difficult to follow. The nominal BFD on slide 2 is not useful. It does not begin to show all the key units of streams, and H_2 does not just spontaneously take three right turns and go back to the unit it came from. The processes cannot be addressed if they are not revealed. The task structure is laid out in a very detailed way, with appropriate milestones. The motivation was not made clear. Pyrolysis in general, regardless of method, tends to show an inverse relationship between C-yield and O-content. Why is RCFP superior, and is the push to higher C-yield simply moving into the range of hydropyrolysis, or is it breaking out of the inverse relationship somehow? If so, how? If not, why use RCFP where hydropyrolysis will deliver equivalent results? The catalyst is *much* too unstable (slide 13) to draw *any* conclusions about the products. Even at 144 hours TOS, the final data point, the product distribution is still changing. Also on that slide, the H_2/oil ratio is enormous! The value of 3,300 NL/L is equivalent to more than 18,000 scf/bbl. If the feed is approximately 20 wt % oxygen, that is more than 12 times the stoichiometric demand for H_2. This will complicate the reactor design, water recovery, and H_2 recompression and recycle. If this huge excess of H_2 is needed to prevent catalyst fouling, the process is highly unlikely to be viable.

- This project discussed some of the differences between the different types of pyrolysis oils. It would have been more impactful to tie the information to the final product distribution, CapEx and/or OpEx, and overall profitability. Testing of the system did not appear to reach a steady state. After 144 hours, the gas chromatography analysis was still adjusting. It is unclear if the project understands what the steady-state product looks like. It is not clear if the project continued to operate the reactor after 144 hours. The reviewer would have benefitted from understanding the state of the catalyst development and the additional risks/plans that the project has for the future.

  The project noted that they were attempting to test the catalyst for 500–1,000 hours to determine the lifetime, as is best practice, but it is not sufficient for a refinery application (8,000-hour testing). Depending on a number of factors, producing a batch of catalyst within only a 3-month period—if not requiring equipment or an outside manufacturer—would seem highly unlikely. This is an excellent representation of the efforts made in collecting and analyzing data. It appears that the data are being well managed on this project.

  Overall, the project is following a logical progression, which will help this project be successful. Similar efforts are ongoing elsewhere at DOE on the integration of refineries with bio-oil. The reviewer would hope that the project is talking with NREL on an ongoing basis and comparing best practices and process conditions, such as liquid hourly space velocity. Oxygen content shows a potential for a significant reduction in the final product oxygen content versus the other upgrading process. The control of the overall process appears to still be in development. I would like to know whether the impact of the different species listed is known or is still being studied. Based on the information provided, the project carbon efficiency goal is right at the top end of their expected potential for this process; however, no data point was shown at the target 50% conversion rate. It is not obvious why Research Triangle Institute believes this metric is possible with the technology.

  Refinery buy-in is absolutely critical for this path. It is critical to understand the level of information and type of piloting that is required to convince a refinery operation that the risk is sufficiently low for the potential payback. The project stated they were using a modification of a commercially available catalyst but did not discuss what modifications were being made or the overall validation and testing plan required for the new version. This is an excellent opportunity in the biofuel arena to involve the sunk capital of existing refineries in the biofuel space to help move these technologies forward and offer new avenues to biofuel production that do not currently exist. This cannot be the only pathway for biofuel production, but it could be a pathway.

- This is a very interesting project with a very good management plan; the WBS and milestones are clear, there is an industry partner/advisor, and the go/no-go criteria for budget period 3 are specific, measurable, attainable, and time-related. Having just recently started, it is hard to assess the progress to date, especially given the continually decreasing catalyst performance. Additional detail around the TEA and the $3/GGE claim would have been appreciated.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for taking the time to evaluate our project and for providing constructive suggestions for improvement as the project advances. The primary goal of this project to design, fabricate, install, and operate an engineering-scale (1–5-kg/hour biomass-fed) reactor system to scale up the promising RCFP process that was successfully demonstrated and developed in a 2-inch fluidized bed reactor in a previous BETO project. The addition of H_2 in the pyrolysis reactor enhances the hydrodeoxygenation of the biomass pyrolysis vapors and tends to inhibit char formation, thus increasing the yield of the liquid hydrocarbon intermediate compared to other biomass pyrolysis technology options. Specifically, the high-pressure biomass hydropyrolysis process can achieve high carbon efficiency and low biocrude oxygen content, but the RCFP process targets similar performance at low pressure to avoid the technical challenges associated with feeding biomass across a pressure boundary. This project supports further process development to increase biocrude yields in a continuous RCFP process design that will include tail gas recycling to conserve H_2 and return the C2–C6 hydrocarbon gases and light oxygenates back to the pyrolysis reactor. The condensation unit operations in the engineering-scale RCFP system will also be designed to improve the biocrude collection efficiency compared to the smaller laboratory reactor system.

There are two integrated catalytic processes in this advanced biofuel pathway. Both processes utilize commercially available catalysts provided by our partners at Haldor Topsoe. The RCFP process utilizes a hydrodeoxygenation catalyst in the primary pyrolysis reactor as the heat transfer medium in a fluidized bed and for deoxygenating the biomass pyrolysis vapors. Currently, this catalyst is available as an extrudate that was crushed and sieved to the appropriate PSD for RCFP process development in our previous project. Catalyst development and scale-up in this project will focus on converting that formulation into a spray-dried fluidizable catalyst. These catalysts will be screened for RCFP performance in the laboratory 2-inch fluidized bed reactor to meet or exceed the performance of the extruded catalyst. The best-performing material will be used in the engineering-scale reactor system to further optimize the RCFP process to maximize the biocrude yield and to produce hundreds of liters of biocrude for upgrading. A commercially available hydrotreating catalyst is used in our pilot-scale hydroprocessing unit for biocrude upgrading. Only limited quantities (13 L) of RCFP biocrude were produced in our previous project, so upgrading was limited. We used the same hydrotreating catalyst and process conditions that we have used in past biocrude upgrading experiments so we could compare results. The proof-of-principle experiment was very encouraging, and although we only had enough RCFP biocrude feedstock for 144 hours of operation, the pressure drop across the reactor did not increase, suggesting no reactor fouling. With the much larger quantities of RCFP biocrude in this project, we will be able to operate the hydrotreater for much longer periods to focus on the steady-state hydrotreating catalyst performance and reducing process severity (temperature, pressure H_2/oil ratio, and liquid hourly space velocity). The end-of-project goal is to produce 100 gallons of a renewable diesel blendstock from this integrated process and to verify that the blends meet the ASTM D975 specifications. The TEA will be updated based on the results obtained in this project to validate an n^{th} plant modeled MFSP of $3/GGE (2014$) for a pathway to hydrocarbon biofuel with a GHG emissions reduction of 50% or more compared to petroleum-derived fuel.

BIOCRUDE PRODUCTION AND UPGRADING TO RENEWABLE DIESEL

Research Triangle Institute

WBS:	3.5.1.301
Presenter(s):	Dave Dayton
Project Start Date:	10/01/2018
Planned Project End Date:	12/31/2022
Total DOE Funding:	$3,192,405

Average Score by Evaluation Criterion

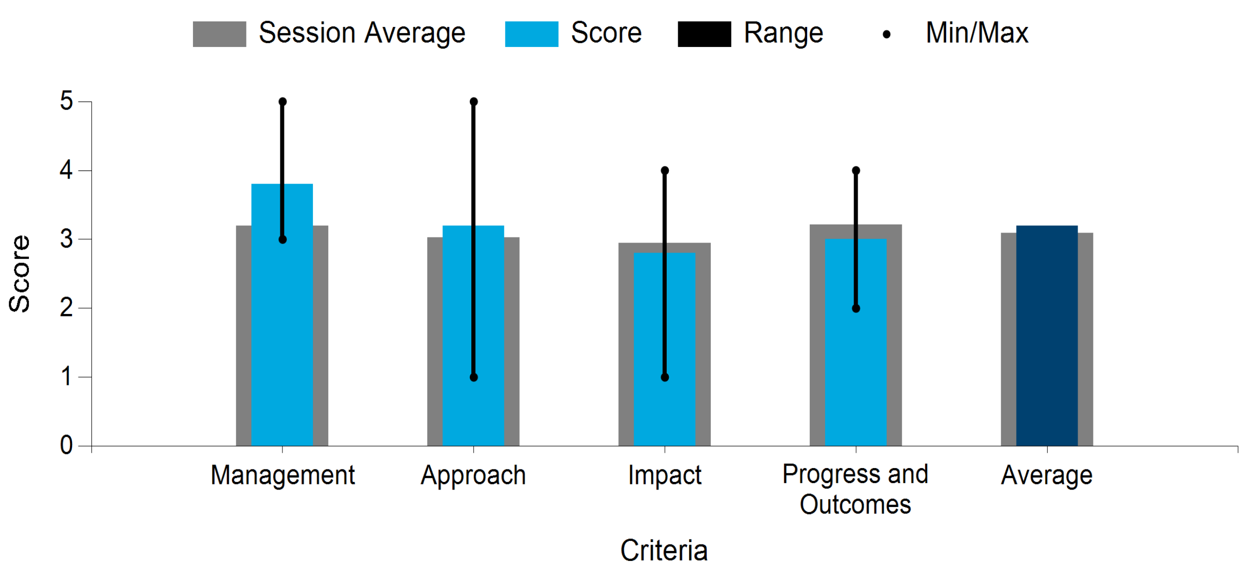


Photo courtesy of Research Triangle Institute

COMMENTS

- This is a newer project looking at catalytic pyrolysis and biocrude hydroprocessing. There are some interesting but commercially questionable process units and setup: the chiller (very expensive, high GHG, should be avoided if at all possible) and the solvents to recover extra carbon (very expensive to get at the total targeted carbon recovery; it is understood as a FOA requirement, but the economics of the process should and would eventually dictate the feasibility of the extra optional process variants). There are experimental issues for new processes that would hopefully be addressed soon.

- The go/no-go decision criteria seem to be far short of reasonable. A 30% oxygen product at 20 wt % yield is terrible—it has an approximate 25% yield of carbon in the product, and with significant oxygen yet to be removed. Much will leave as H_2O, but there will also be carbon losses. How can this be close enough to commercially viable even to be worth testing? This is confirmed on slide 10—the yield of solid is 55%–68%, with a further 9%–14% lost as gas. Only 20%–27% liquid yield is achieved. What is the point in doing further work with such yields? The table on slide 10 is also confusing. Which numbers are supposed to add up? Liquid, solid, gas = total, but how the other numbers relate is unclear. There is simply no point in the downstream processing of a liquid that does not represent a commercially viable yield. The catalyst's stability (slide 18) was not achieved in 144 hours, so there is no telling what the product is going to be. Why are data presented for a catalyst that clearly has not yet stabilized?

- The innovation in this project appears to be the use of a "crumbler" to prepare feedstock. Although there is some analysis of CFP performance with different sized "crumbles," it would have been very helpful to include this in the comparison feedstock prepared via the traditional/prior method. In addition, a statistical analysis of the results is missing; it is unclear how meaningful the different results are (e.g., hot filter organic carbon balance).

- The variability of the biomass based on the portion collected did not appear to be a part of the study. This seems to have missed a big part of the lessons learned from other campaigns and projects that were executed by the same people on this team. The study of PSD and other properties mentioned is good and should be part of a feedstock study, but it should not be the end point. The project is being well executed and well documented. A change in pyrolysis temperature was not planned but required at a different PSD when the initial temperature used on other experiments was insufficient to provide the expected or required results. The project noted that a higher temperature was needed for heat transfer and documented this change. Certain things in the future process—such as 10% solvent loss, regeneration, a chiller—do not appear to have been studied for the larger design and their impact on the process economics. The management really needs to step back, look at the overall process, and ensure that the TEA is not getting out of hand with respect to the process requirements in development. The reviewer seems to have missed where the project demonstrated the 40% increase in yield noted in the summary slide. The project is attempting to increase biocarbon yield regardless of quality followed by mild catalysis upgrading to improve quality. The plan to continue to increase the catalyst temperature clearly indicates that a regeneration is needed, but based on the data shown, it is required at a high frequency (depending on maximum temperature). Regeneration data on the catalyst were not presented. The attempt to reduce H_2 usage through a separate, smaller hydrocracking step makes technical sense because the H_2 at a refinery will be more valuable than the CapEx required for the different unit. Hopefully a TEA was performed to test this assumption. The project is doing a good job of determining the first-principles root cause of CFP performance through the study of PSD variations. This is a good approach. The project plan was well laid out and logical, with sufficient information presented to demonstrate good planning and metrics related to a successful project. It was not clear if a cold flow experiment was performed to determine the fluidization of the catalyst or how else the model was determined.

- This is a well-organized and well-managed project with a sound approach to a difficult set of constraints of improving costs, improving carbon efficiency and decreasing GHG emissions. It is unclear if the overall goals of this project make sense—i.e., should BETO be pursuing this? Combining the three ambitious goals into a single process/project results in a flow sheet with dilute aqueous streams that could be very expensive to upgrade/recover products. The flow sheet does not look commercially achievable due to its complexity. The program may be over-constraining this project. Due to the technical issues (e.g., plugging), it is unclear if the overall goals of the project will be met. This reviewer would have liked to have seen an updated plan for addressing the technical issues that were found.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for taking the time to evaluate our project and for providing constructive suggestions for improvement as the project advances. During the past 10–15 years, R&D efforts on biomass CFP, primarily at the laboratory scale, have demonstrated biocrude carbon yields between 12% and 32%, with oxygen content ranging from 4%–31%. Typically, CFP biocrudes from zeolites with oxygen contents less than 20 wt % have carbon yields less than 20%. Upgrading CFP biocrudes by hydrotreating to finished biofuels further decreases the carbon efficiency. Additionally, hydrotreating whole CFP biocrude in a single step suffers catalyst deactivation with TOS and usually lasts less than 140 hours due to reactor plugging. The main objective of this project is to improve the CFP biocrude yield and the upgrading process at the pilot scale.

  There are several goals to be achieved during this project. First, evaluate the impact of feedstock preparation on biocrude yields in the CFP process and revisit the CFP process conditions to maximize biocrude yield. Second, improve upgrading efficiency by fractionating biocrude using selected separations techniques and developing strategies to independently hydroprocess each fraction to maximize biofuel production. Fractionating the biocrude puts less emphasis on hydrodeoxygenation during CFP while putting a greater focus on increasing biocrude yield. 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-ton/day unit and (2) biocrude upgrading in a hydroprocessing reactor system.

The impact of feedstock and feedstock preparation on CFP performance has been a focus in the project until this point and is an ongoing effort in budget period two. We have evaluated the biocrude yields and quality produced from a softwood feedstock (Douglas fir) prepared to three different particle sizes (1 mm, 2 mm, and 4 mm). We will repeat this activity with a hardwood feedstock (alder) that has already been prepared and delivered to the Research Triangle Institute. These feedstock studies are being supplemented by CFD modeling of the mixing zone and riser section of the pyrolysis rector in the 1-ton/day pilot plant. The results of the modeling efforts will provide a better understanding of how process conditions can be adjusted to maximize mixing and conversion for the different particle size feedstocks to increase biocrude yields.

In the third budget period, blends of forest residuals and woody biomass will be the primary feedstock for biofuel production. The raw material and feedstock preparation costs will be balanced with biocrude yields and quality in a TEA of the integrated process that will be completed by the end of the project.

The second emphasis of this project is to develop new strategies for upgrading the biocrude intermediate into renewable diesel blendstocks. A primary driver of this effort is to segregate biocrude components that cause fouling in the hydrotreating reactor and expand the duration of upgrading experiments. The impact of process conditions on the steady-state hydrotreating catalyst activity can then be determined. Additionally, each fraction can be independently hydroprocessed to manage process severity and H_2 demand while maximizing biofuel production. Biocrude fractionation performed to date has produced a solvent extracted fraction and a raffinate (solvent-insoluble fraction). The raffinate was extracted with water to produce water-soluble and water-insoluble fractions. Upgrading the solvent soluble fraction was very successful—after 144 hours TOS, no increase in pressure drop across the reactor was measured. The hydrotreating catalyst activity was also partially recovered by increasing the average hydrotreating temperature during this experiment. Fourteen gallons of solvent-extracted biocrude has already been produced to build on this preliminary study. Upgrading studies with the water-soluble and water-insoluble fraction were not as successful; however, we are investigating hydrocracking as an alternative to hydrotreating and opportunities for bioproduct recovery from the water-soluble raffinate fraction.

A lot of biocrude upgrading is planned for the remainder of the project. The existing process model of the integrated catalytic biomass pyrolysis biocrude upgrading process includes an option for separations for bioproduct recovery. This model will be updated with a modified configuration for biocrude upgrading that represents the new strategy based on the experimental results collected during this project. This model will form the basis of an updated TEA for the integrated process to document the impact of feedstock preparation on biocrude yield and quality as separations are used to achieve commercially relevant upgrading to biofuel. The end-of-project goal is to produce 100 gallons of renewable diesel from this pilot-scale integrated biofuel pathway to inform a TEA for an n^{th} plant pathway to hydrocarbon biofuel with a target modeled MFSP of \$3/GGE and a 50% reduction in GHG emissions compared to petroleum diesel.

AGRICULTURAL AND WOODY BIOMASS TO DIESEL FUEL WITH BIO-OIL INTERMEDIATE

West Biofuels, LLC

PROJECT DESCRIPTION

WBS:	3.5.1.304
Presenter(s):	Matthew Summers
Project Start Date:	10/01/2018
Planned Project End Date:	06/30/2023
Total DOE Funding:	$4,200,000

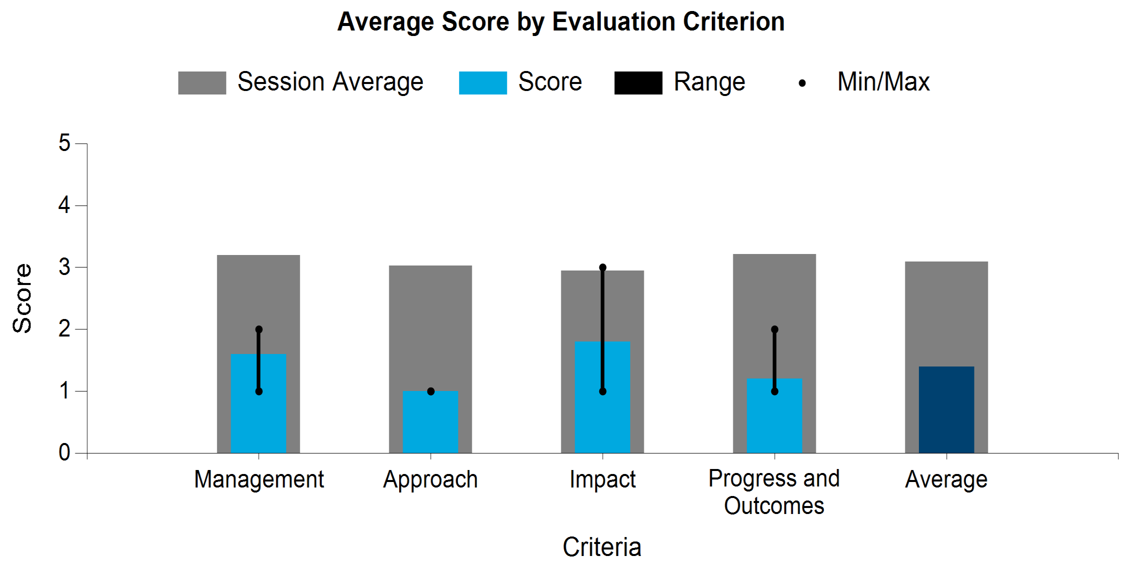
This project will demonstrate the production of a diesel fuel blendstock produced from biomass by gasification, Fischer-Tropsch synthesis, and coprocessing of the Fischer-Tropsch wax fraction in a conventional refinery unit operation, FCC. The use of a Fischer-Tropsch wax as a feedstock and/or blendstock in a standard petroleum refinery, either by replacing or supplementing fossil-derived materials with biomass-derived materials, is a very attractive option. This production pathway would economically advantage the biofuels industry by leveraging the multi-trillion-dollar refining and product distribution infrastructure already in place for fossil-derived fuels. Specific goals of the project include:

- Goal 1: Demonstrate the production of diesel fuel blendstock from biomass feedstock.
- Goal 2: Facilitate the introduction of renewable carbon into the fuels infrastructure.
- Goal 3: Reduce the carbon footprint of a refinery and the fuels it produces.

The project team will use a gasification and synthesis process to convert biomass feedstock into Fischer-Tropsch products. The project team will operate the West Biofuels 1-MW_{th} fluidized bed as the gasification reactor (~5 MT/day of biomass input), with bed material circulating between the reactor and the regenerator. The product gas undergoes bulk conditioning to remove particulate, tars, and other potential contaminants and is then compressed and stored in a buffer tank for synthesis. In the synthesis processing unit, syngas is filtered through some additional filter beds to guard for additional contaminants, followed by a fixed-bed Fischer-Tropsch catalyst reactor using a Co-based catalyst and low-temperature synthesis conditions. The Fischer-Tropsch products are then separated into a Fischer-Tropsch gas fraction (15%–20%), a Fischer-Tropsch diesel fraction (25%–35%), and a Fischer-Tropsch wax fraction (50%–60%). For comparison, project partner BEST Research will use the same syngas production process, but syngas is upgraded in a slurry-bed Fischer-Tropsch reactor so that the performance of the two approaches can be compared to determine the best option for further commercialization.

To validate the usability of the Fischer-Tropsch waxes for making additional diesel fuel, NREL will coprocess them with petroleum-derived vacuum gas oil in an existing FCC pilot plant to produce a product high in diesel fuel precursor fractions. In addition, subsequent upgrading by hydroprocessing will be investigated to determine the benefits of additional processing to improve diesel yield. This work is being carried out in an existing pilot-scale Davison Circulating Riser reaction system.

The objective is to introduce the biogenic feedstock to the FCC to preferentially produce products in the diesel boiling range. In particular, the use of a high-molecular-weight Fischer-Tropsch product as the biogenic feedstock—accompanied by a reduction in reaction severity—will allow shifting of the product slate away from gasoline and toward middle distillates, such as diesel fuel. Although some Fischer-Tropsch diesel is produced directly from the Fischer-Tropsch synthesis, a large portion of the material are waxes in the C20–C50+ range. Accordingly, mild catalytic cracking of this material will provide an excellent sulfur-free paraffinic product in the diesel range (C12–C20). Because of the highly paraffinic nature of Fischer-Tropsch waxes, the products from mild cracking will likely have a high cetane number.



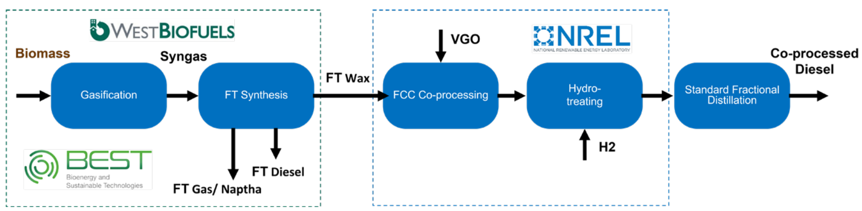


Photo courtesy of West Biofuels, LLC

COMMENTS

- This is a bit of a train wreck. The presentation started focusing on gasification, and it is now trying to pivot into CFP. Initial gasification results were horrible. I'm questioning the appropriateness to bring in so many international suppliers for a DOE-funded project. I have many questions on the right expertise and approach for this project. My advice is to reconsider and not go forward with the "requested changes."

- The project did not achieve any sort of success on its original target of CFP bio-oil, so it went after Fischer-Tropsch, a technology with literally thousands of man-years of effort since the 1930s and with virtually no success to show for it, and no success at all with biomass as a feedstock. The prime contractor was presumably selected based on expertise on CFP and upgrading; are they similarly an expert in gasification and Fischer-Tropsch? FCC upgrading is applied to some of the least valuable streams in a refinery. Sending Fischer-Tropsch wax to an FCC is wasteful. Slide 9 shows 50%–60% of the product will be Fischer-Tropsch wax, and it is essentially being downgraded to the value of vacuum gas oil by sending it to an FCC. It is unclear why this project was continued after the proposed approach for which it was funded failed. Gasification/Fischer-Tropsch are well known and historically well funded. There is no indication that there is any new or remarkable Fischer-Tropsch technology at work here, and sending half the product to an FCC only makes matter worse.

- The project does not appear to be developing or modifying the gasification design in any meaningful way, which would lead the reviewer to believe that they understand the challenges in the gasification of biomass. The project states that the gasification equipment is being done in Europe at a commercial scale but with a different wood feedstock. It is unclear why this project is not attempting to utilize feedstock as close to the European feedstock as possible (PSD, type, moisture content, etc.). The increase in cost going from pyrolysis to Fischer-Tropsch was not noted. It is not clear if the cost of overcoming the issues would be more than the CapEx increase going to Fischer-Tropsch. A TEA comparison to pyrolysis would have been helpful. It is not clear how long the project tried to increase yields on the pyrolysis system. The yields demonstrated were certainly much lower than other pyrolysis systems. It is not clear why they did not pivot instead to another CFP process, such as NREL's, which has shown better yields instead of a gasification project. It is difficult to believe that a pyrolysis technology company could switch over to gasification so readily. Although similar in nature, there is still a significant amount of unit operation knowledge tied into a specific mode of operation. It is unclear if the project has taken advantage of the many lessons learned by others in this area who have published their results through DOE based on the American Recovery and Reinvestment Act of 2009 and other efforts on similarly designed processes. The reviewer would not expect Fischer-Tropsch wax to present as many or as significant challenges in processing as pyrolysis oil due to the lack of minerals, water, and lower oxygen content. It seems the project ran into many of the issues that are known to be problematic in CFP. The basis for the claim that Fischer-Tropsch diesel yields are seven times the amount of pyrolysis was not laid out. The disadvantages of higher-temperature gasification over pyrolysis was not noted in the presentation, such as higher temperature (energy, MOC) and CO_2 production. The mitigation to modify or change the catalyst comes with its own risks, which the project does not seem to acknowledge. The overall testing plan for the Fischer-Tropsch wax coprocessing could have been better laid out with performance baseline metrics and planned run activity. The upfront gasification and Fischer-Tropsch processes do not appear novel. The project is well staffed in the subject matter areas. The economic viability of the project was not laid out. It is not clear whether the project has active team members in the refining industry who are interested in moving this technology forward.

- This project has some major issues, and it appears that successful completion is highly questionable. The failure of even the laboratory-scale process under the original approach should have been heavily investigated and an analysis submitted as part of this presentation. To change the approach instead, and then change back after a second failure indicates a poor management strategy and a complete lack of a risk/mitigation strategy. (On the plus side, yield problems presented from their original approach clearly show the risks associated with the scale-up of technology.)
- This project is looking to pivot from pyrolysis to gasification. The rationale for switching to gasification as well as the initial decision to do pyrolysis demonstrates a very low level of skill and discernment in management. The initial idea to use a gasifier as a pyrolyzer was ill-advised; it did not appear that this idea was even trialed with a smaller unit. Gasifiers and pyrolyzers, although similar, are not the same, and this shows a lack of foresight and management to assume they are. It actually is a bit arrogant. The rationale to pivot to gasification was said to be because Fulcrum is doing gasification. Again, this seems random and ill-thought-out. Finally, moving from the bench to the pilot scale when the yields were ≤10% also shows a lack of management and approach. Due to the difficulties of using the gasifier as a pyrolyzer, there was no progress toward goals. If the project were successful, they may have some impact because renewable, coprocessed diesel would be desirable.

PI RESPONSE TO REVIEWER COMMENTS

- We respectfully disagree with this comment. Clearly, in the short presentation, we were not able to convey to the reviewer the project and the nature of the "pivot" that is being considered. There were no "initial gasifier results." West Biofuels has performed no gasification work within this project yet. We have, however, demonstrated years of successful gasification R&D on our 1-MW thermal fast internal circulating fluidized bed (FICFB) system, and we are proposing to pivot the project to gasification operations using our existing and well-demonstrated FICFB system. We have not proposed the addition of an international supplier for the project. The addition of our international colleagues, BEST Research, has been proposed to broaden the scope of the project while providing unparalleled expertise in Fischer-Tropsch synthesis. They will advise on our Fischer-Tropsch development work at West Biofuels while also performing complementary studies, funded primarily with matching funds, with their slurry bed Fischer-Tropsch technology. In summary, West Biofuels has a long and successful history with biomass gasification, has a wealth of proven expertise in the PI (Matt Summers) and the rest of the team, and has built and operated a 1-MW thermal dual fluidized bed gasifier system with other catalytic synthesis systems. Publications exist on these projects. The attempts to scale up the fluidized bed reactor for CFP were not successful; hence, the request is to pivot back to gasification as the primary conversion process with Fischer-Tropsch upgrading of the syngas to make the biogenic feedstock. The prime contractor team has considerable experience with biomass gasification and with Fischer-Tropsch synthesis, thus reducing the risk and justifying the change in approach.

West Biofuels has a long and very successful history of biomass gasification and catalytic synthesis of product gas with a highly qualified PI that proves they are well up to the associated challenges. Concerns over feedstock selection are moot because feedstock has been run for many hours in our FICFB system. Although it is true that gasification/Fischer-Tropsch is not novel, there are very few references in the open literature on the use of a Fischer-Tropsch wax for FCC coprocessing and no commercial applications that we are aware of or projects that integrate all steps to produce diesel fuel. The technical and economic viability of the proposed approach are both superior to the initial approach (with bio-oil as the biogenic feedstock). After initially embracing the concept of bio-oil coprocessing, industry interest has waned to the point that there are no commercial trials being planned (with several planned trials now cancelled). On the other side, biogenic Fischer-Tropsch wax will soon be produced commercially by Fulcrum BioEnergy's Sierra Biofuels, with Marathon Petroleum as the offtake partner. This wax will be co-processed to make transportation fuels with renewable content, as is being planned for this project. Other refineries have expressed interest in the products and will be engaged by the team as the project generates results. A major unanswered question in this scheme for refiners and regulators is: How does the biogenic carbon partition in the products? Does the biocarbon go to the liquid products or to coke on catalyst? If the former, which fractions of the coprocessing products are rich in biogenic carbon, and which are not? The answers to these questions are critical to the issue of assigning carbon credits for RINs and the LCFS for coprocessing. We will answer this question with the data from this project—these data will be extremely useful to the EPA, California Air Resources Board, and other regulatory agencies that are concerned about providing incentives to produce low-carbon fuels. Also, it is well understood that biogenic carbon from bio-oil will be lost to carbon oxide gases and to coke—this will not be the case with Fischer-Tropsch wax as the biogenic feedstock, thus providing a strong economic incentive in terms of avoided CO_2 emissions and the resulting low-carbon fuel credits. Finally, the team has generated preliminary TEA, but there was insufficient time to review this in a brief presentation for the Peer Review. TEA development is a specific task number in the project, so this information will be further advanced as part of the research.

West Biofuels may not have clearly conveyed that the prior work on pyrolysis was performed outside of DOE funding and was not part of this project. We did state that we were still in budget period one prior to the engineering review and prior to doing any DOE technical work. Also, CFP catalyst performance of 10% yield of premium CFP oil during the lab trials can be a viable process if other products are generated, so we disagree with the comments on the value of upscaling with the catalyst we selected. Fluidized beds are commonly used for pyrolysis, and the team performed full computational particle fluid dynamics (CPFD) modeling of the reactor prior to conversion, so we do not believe the prior project on pyrolysis was ill-advised in any way. We fully documented the prior effort, and we believe it is a useful contribution to the literature on issues for the scale-up of CFP. We remind the reviewer that documenting issues and failures is an equally valuable part of advancing science and not an arrogant endeavor. Other comments in this paragraph have already been addressed in our previous responses.

There appears to be some level of misunderstanding according to several of the reviewers' comments. We are proposing the project pivot to significantly more proven technologies in which the project team has vast demonstrated experience. As described, the laboratory-scale trials were rather successful, and advanced modeling suggested successful CFP operation of our system. The team documented the CFP attempts, and these will be published in a report through the funding agency to contribute to the science in this area. The pivot is the first change in approach to be proposed for this project; the change would return the system to the well-documented gasification mode and represents a significant decrease in project risk from the CFP process.

We believe the previous comments and our team's extensive work in gasification and catalysis demonstrates our expertise in the proposed process. We disagree that Fischer-Tropsch technology has no success in the field of biofuels. Enerkem is successful using MSW (which is 50% biomass), and their technology is being expanded worldwide. Two Fischer-Tropsch projects are now in the final stages of construction, including Fulcrum BioEnergy's Sierra Biofuels and RRB. Fulcrum will be producing a full-range Fischer-Tropsch wax as its primary product. RRB will be producing a heavy Fischer-Tropsch material as well, which in theory should be suitable for FCC coprocessing. Our own team members have demonstrated Fischer-Tropsch technology with the gasifier being utilized for thousands of hours TOS. So, it could be said that Fischer-Tropsch is at the forefront of biofuels, not a failed technology with no demonstrated success with biomass. As to the comment on coprocessing Fischer-Tropsch wax in an FCC, we believe this is a viable pathway to diesel fuel, and there is substantial available FCC capacity at refineries across the United States. There are other potential uses for Fischer-Tropsch wax, as the reviewer points out, but the goal of this project is to maximize biogenic content of diesel fuel. So, the effort could be seen as upgrading vacuum gas oil to diesel fuel with a significant content of biogenic carbon rather than a downgrading Fischer-Tropsch wax, depending on one's perspective. In addition to substantial industry capacity, coprocessing in an FCC does not require additional fossil-generated, H_2-like hydroprocessing, so it could also be more carbon-efficient and viable at some refineries for increasing the renewable content of fuels. We believe that if the reviewer looked at the specific process steps being applied—from FICFB gasification to a simplified gas upgrading process, to testing a novel catalytic reactor type, and the coprocessing biogenic products in an FCC—this project represents several technology improvements over the status quo, making it a valuable technical contribution.

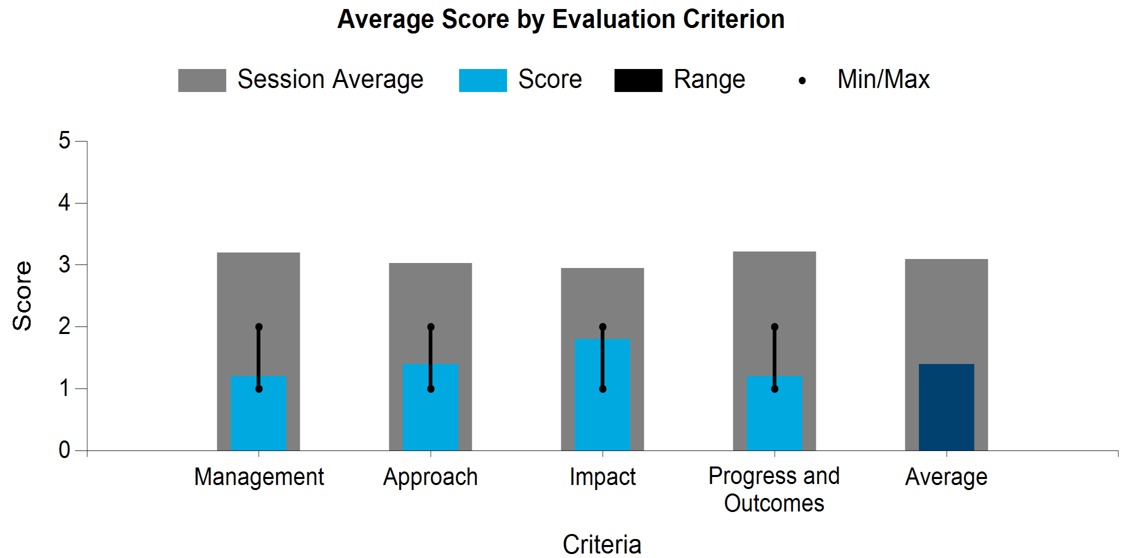
NOVEL METHOD FOR BIOMASS CONVERSION TO RENEWABLE JET FUEL BLEND

Technology Holding LLC

PROJECT DESCRIPTION

WBS:	3.5.1.401
Presenter(s):	Mukund Karanjikar
Project Start Date:	10/01/2018
Planned Project End Date:	11/30/2021
Total DOE Funding:	$3,125,000

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 such that private funding can be obtained after the initial governmental-funded period. Upon successful commercialization, the proposed innovation will enable the production of high-energy-density drop-in renewable jet fuel.



COMMENTS

- This is a very generic presentation. It claims there has been good development, there are but too many questions and too little is shown. Fermentation to isoprene: IP? (They seem to know, but the answer is not that credible.) Catalysis to what? $2.5 million, 2 years, and what? There is nothing much to show for this. Could get all isoprene to jet. Technology providers? TEA? Both blocks were validated: SLC fermentation, catalytic at Princeton (single-pass) 1,000-L fermentation capacity, 35 gallons in house for catalysis. It is unclear how the total production will be achieved.

- The information presented is very limited to produce a review. The information provided could have been said for any generic project. The project has no plan to get bio-derived sugars for fermentation. The project will require a much larger staff to be successful. There is no clear plan to make this fuel, no previous work described, no actual reason to believe this project can be successful based on the information provided. The progress slide showed some good progress but provided no actual information on any task. The risks presented do not have any association with the specific project. It is not clear whether the project has identified the technical risks of the project and is working toward resolving them.

The project appears to have limited personnel to develop and integrate a process. The project does not appear to be utilizing any outside resources for engineering or project management support. The project is also developing pretreatment, fermentation, and catalysis technologies. The fuel characteristics presented are promising. Additional fuel testing data are needed. The progress was all identified as complete but with no real information on any particular task.

- The management plan is all but nonexistent—a rudimentary organization chart, some buzzwords about risk management and project management. The project started 2.5 years ago, is only approximately 20% costed, and the progress is not commensurate with that. There is no BFD, no indication of how biojet was produced, whether it was produced from bio-isoprene or some other source. There is no indication of any economic analysis. What must be the sugar price? How high must be the yield of each step? Either the progress is very little or the slide deck does a poor job explaining it. It is not clear where larger-scale fuel production will be carried out or who will develop the basic engineering plan.
- The project presentation was lacking. No project plan, risks, or mitigation strategies were provided except for stock images. It does not appear that the project has a plan to meet its goal of 100 gallons of fuel by September of this year. Although the project claimed meeting several earlier milestones, no documentation or data were provided. The approach was a bulleted list of generic "optimize" statements. The impact of this project, if successful, could be significant due to replacing aromatics, and it is good that the team has industry interest as well as the Air Force Research Laboratory and the U.S. Navy; however, no documentation of this interest or specific partnerships were provided. The interest is a pretty vague description. This project did not meet the minimum requirements of the review and was highly disappointing given the stage of the project.
- This project makes several highly questionable claims with no supporting evidence, including "high level of industry interest" ("two oil and gas companies") and "potentially reduced engine maintenance." To date, the project appears to have produced 0.5% of the end-of-project milestone and could not provide a plan to produce the rest of the finished fuel in the remaining 8 months. The management plan is very weak and includes neither a risk assessment/mitigation strategy nor clear industry engagement (advisory). There is very little information presented on the fermentation process, including standard rate/titer/yield information. The approach includes "develop TEA models," which should have been completed prior to the award—it is very hard to envision this technology supplying fuel at competitive prices or even meeting the BETO dollar-per-GGE goal.

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

Washington State University

PROJECT DESCRIPTION

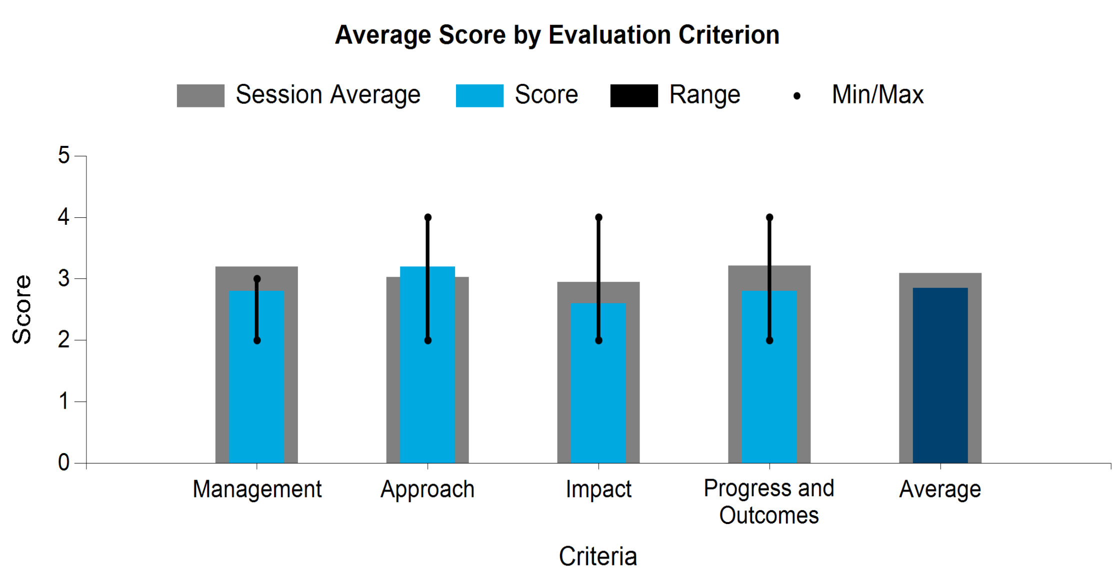
The purpose of the project: Production of hydroprocessed esters and fatty acids (HEFA) is the best current option for jet fuel production. Hydrodeoxygenation of bio-oils derived from pyrolysis and HTL of lignocellulosic materials produces jet fuel rich in aromatics, also known as hydrotreated depolymerized cellulosic jet (HDCJ).

WBS:	3.5.1.402
Presenter(s):	Manuel Garcia-Perez
Project Start Date:	10/01/2018
Planned Project End Date:	05/01/2022
Total DOE Funding:	$3,472,904

Relevance: Although HEFA is the most promising technology for jet fuel production, the construction of new units is limited by the availability of triglycerides. Coprocessing triglycerides with the phenolic-rich fraction of pyrolysis oils and yellow greases could help to increase feedstock availability.

Challenges: Our goal is to evaluate the technical and economic feasibility of using HEFA facilities for the coprocessing of pyrolysis oils or HTL oils with yellow greases. We will design and evaluate a supply chain for the hybrid HEFA-HDCJ concept for the conditions of Washington state. The fuel and combustion properties of resulting jet fuel cuts will be studied. Currently, our main challenge is the identification of a potential toller for the production of 100 gallons of jet fuel. To mitigate this risk, we are working to identify between two and four tollers to ensure one will be successful.

Accomplishments: We completed the collection of all the oils, and we are working in their characterization, emulsion stability, and batch hydrotreatment tasks. We will soon start with the bench continuous studies.



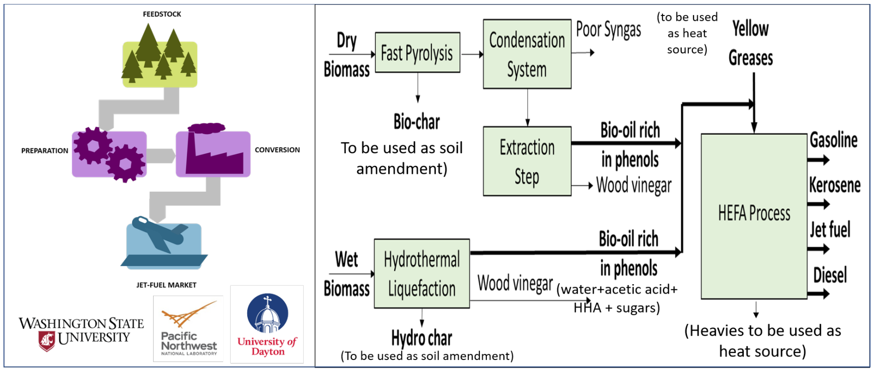


Photo courtesy of Washington State University

COMMENTS

- This presentation included bits and pieces from tolled and imported products and an unclear path to the scale and risks. The availability of pyrolysis oil is big question (BTG in Netherlands, Ensyn unresponsive). TEA/LCA tools being developed, but there are no results until there are lab data. Why not use the tools to decide where the experiments need to be? Toller? Working with PNNL to identify different oxygen content from different oils, then catalyst selection, might be nonoptimal and complicated.

- The reviewer had a hard time following this project approach and management plan. The project appears to rely on others to produce the pyrolysis oil because no work is being done specifically on this project for producing the oil. The 0.1% oxygen specification is much tighter than other targets of other projects attempting to produce equivalent pyrolysis oil-based fuel, and a 30% blend rate may be challenging to meet based on the progress of others. HEFA production is inherently limited by its available volume. The introduction of this technology will help expand this market by the 30% target blend rate. This does not dramatically improve the overall fuel market, but it is nevertheless improvement. Blending pyrolysis oil with fats only seems to mirror the issues of blending issues seen on other projects (FCC units). All the same problems with pyrolysis oil remain. The stability of the pyrolysis oil, its ability to be blended, and its varying makeup are not resolved. The project may need to track the carbons between the two different feedstocks as well for RIN maximization. It is unclear if that is being done. This project experienced turnover of staff in a few different ways due to COVID. It is not clear whether new staff has been identified to take over for those who are no longer part of the project or had their return delayed. The project appears to have had significant delays in obtaining their pyrolysis oil. Significant effort remains on this project to optimize the fuels. Wood vinegar is being supplied by the charcoal industry. It is unclear if this market is growing or if any production plant could saturate this market. Dependence on the sale of wood vinegar is unclear, as is the cost of disposal. The project did not discuss the characteristics of the biomass feedstock used in production to understand its potential variability and its impact on the process. The supply of pyrolysis oil does not appear to have been determined and sourced prior to the start of the project, which was a mistake. The project is relying on its partners to develop a pyrolysis oil, leaving them dependent on the work of others who are not themselves invested in this process. The truly "optimum" pyrolysis oil for this process may not be developed by the suppliers. The suppliers should be partners on this project to gain their investment in the success of the process. The maximum emulsion stability time has not been determined; it is important to know for developing the process design. It is unclear if the pyrolysis oil is to be blended at the supply pump or upstream in mix tanks. A 3-hour storage time in a tank would be relatively difficult in a first-of-a-kind plant to manage.

- The project appears to be well managed and on track from a technical perspective, but there are issues with the project management from a task organization perspective. The sourcing of the feedstocks and the development of primary standards of the feedstocks appear to be haphazard or nonexistent. The overall impact of this work is likely limited (as noted in the presentation) by the availability of triglycerides, and it is unclear if the impact is also limited due to the source of pyrolysis oils. There seems to be no recording of the feedstock source for these oils, and the HTL was made from a different feedstock. When the results are compared, will we be able to tell if it is due to the original feedstock or the type of processing—e.g., pyrolysis versus HTL? These oversights affect the approach as well. On the positive side, the project is making good progress toward its goals.

- This is a very promising concept. HEFA-based renewable diesel is and will remain feedstock- limited-based, and that feedstock is especially sensitive to food versus fuel concerned. An alternate feedstock source based on low-carbon biomass would alleviate those concerns. The management plan and tasks are well laid out. The risk mitigation plan is okay, but it might be a bit more detailed/imaginative. The impact could be very high, as described. Also, the final processing step represents an excellent option for utilizing renewable H_2, either from biogas/RNG steam reforming or from water electrolysis using renewable electricity. The approach is appropriate, and progress is good to date.
- This is an interesting project that shows potential for supplementing fuels production in existing commercial facilities. It was unclear from the presentation how much pyrolysis oil would saturate the market; with a relatively fixed supply of oil and grease, what level of biomass conversion would be enabled via this pathway? Silica gel does not sound very selective for oxygenated compounds, unless it is mostly water—it was unclear from the presentation if this is a proposed commercial-scale unit operation or only a temporary lab-scale stand-in.

PI RESPONSE TO REVIEWER COMMENTS

- First, the PIs thank the reviewers for their time and efforts reviewing our project. The United States currently has four commercial renewable diesel plants with the capacity for 356 million gallons, one renewable jet fuel plant with a capacity of 42 million gallons, and there is one plant under expansion and two more under construction that will add other 68 million gallons. In total, the United States should be producing in the next 5 years close to 466 million gallons of fuels derived from triglycerides. Our project aims to process vegetable oil and yellow greases in blends containing 20–30 vol % of the phenolic fractions of pyrolysis oil. If we consider that the fuel yield from triglycerides is typically 80 wt %, our study would open the possibility of coprocessing up to 175 million gallons of pyrolytic lignin (close to 760,000 tons). If we consider that the yield of the pyrolytic lignin is close to 15 wt % of the original biomass, this technology could allow processing the lignin fraction resulting from the pyrolysis of 5 million tons of lignocellulosic materials. The analytical method for the removal of oxygenated compounds in jet fuel is based on solid-phase extraction with a polar adsorbent. Our goal will be to adsorb any oxygen left in the jet fuel fraction in a column contained in a polar adsorbent such as silica gel. Although we hope to reduce the content of oxygenated compounds to a minimum in the hydrodeoxygenation step, we believe that perhaps an adsorption step with a polar adsorbent may be needed to achieve parts-per-million levels of oxygen content in the resulting jet fuel cut.

  The PIs thank the reviewer for the comments. As indicated in our presentation, most of the oils to be used in the project, from both BTG (Netherlands) and Baker Commodities, Inc. (United States), are already at Washington State University, ready to be used. BTG in the Netherlands pyrolyzed 1.6 tons of softwood in their Empyro-rotating cone reactor (5 tons/hour) to produce 1 ton of pyrolysis oil (230 gallons of pyrolysis oil). The oil was separated into water-soluble and water-insoluble fractions using a bio-oil/water ratio of 2:1. As a result, we obtained 55 gallons of the lignin-rich fractions available, which are now stored at Washington State University. We have also collected 42 gallons of the lignin-rich fraction from Pyrovac, Canada. Our team also collected 330 gallons of yellow greases from Baker Commodities. Our current yield of jet fuel is close to 25%. This means we will likely need to process 400 gallons of a blend of pyrolytic lignin (20%) and yellow greases. We will purchase more pyrolysis oil from BTG (likely 55 gallons of lignin-rich fraction), but this decision will be made as soon as we complete the continuous hydrotreatment tests. BTG is committed to providing all the oil needed for this project. Yes, we have results with our TEA and LCA, but the final results will depend on our product yield. The major challenge of our project is to maximize the yield of the jet fuel fraction and in this way facilitate the production of 100 gallons of jet fuel. Product yield depends on reaction conditions and catalyst used. We agree that different bio-oils will have different oxygen contents and that this will affect the optimal processing conditions. For now, we are optimizing our hydrotreatment conditions for the BTG oil in blends with the yellow oil collected from Baker Commodities. Separate experimental studies will be conducted to identify the optimal reaction conditions for the other oils. We were initially planning to produce the 100 gallons of jet fuel at PNNL, but the lab decided not to continue the operation of their largest demonstration unit. PNNL will conduct the bench-scale continuous tests that will be used to produce the large-scale production in the toller. The Washington State University and PNNL path forward to produce 100 gallons of jet-range fuels is through contacting a third-party contract manufacturer (toller). We posted a request for information (574700-RFI Hydro-Processing and Distillation Opportunity) between June and December 2020. So far, we have identified three potential tollers.

The PIs thank the reviewer for the comments. Yes, the pyrolysis oil used in this project for the production of the 100 gallons is supplied by BTG. The 0.1 wt % oxygen specification is not for the pyrolysis oil; this is the specification for the final jet fuel. We agree that there are challenges to reach the 30% blend rate. We are conducting our studies using 20% pyrolytic lignin in the blend with yellow greases. We agree that the HEFA production is inherently limited by its available volume and that this fact limits the quantity of pyrolytic lignin that could be processed by our process. Our estimates suggest that with this technology, we will be able to process the lignin-rich fraction resulting from the fast pyrolysis of 5 million tons of lignocellulosic materials. We agree that the problems encountered in this project are of the same nature as those seen on other cohydrotreatment projects. We improved the stability of the oil with the addition of a small quantity of butanol, and we are working on the stability of the blend with yellow greases with the formulation of microemulsions. Although we agree that tracking the carbon between the two feedstocks will help with RIN maximization, we are now focusing on the analysis of the oil. Pyrolysis oil is likely to contribute to the formation of aromatics. Yellow greases will be responsible for the formation of aliphatic compounds. It should be relatively easy to quantify the fraction from pyrolysis oil and the fraction from yellow greases. The issue with our postdoc (Dr. Yinglei Han) was mostly due to the difficulties to smooth his transition from his immigration status as a Ph.D. student to his new status as postdoc. We did not need to find a new researcher; we just had to wait for the visa paperwork to be completed. The project did not have any delay associated with the production and shipment of the oil. We have 55 gallons of the BTG lignin-rich fraction in our lab. Working with BTG has been a great pleasure. They are available to provide as much oil as needed. We have completed our batch hydrotreatment studies with the BTG oil and yellow greases, and the experimental conditions identified will be tested in continuous conditions at PNNL. Wood vinegar is studied as a source of income for our process. The use as pesticide may have a limited market, and we are studying other alternatives, such as wet oxidation of that fraction to produce acetic acid. The BTG oil used was obtained from softwood. We agree that the variability of the feedstock and processing technologies could have an influence on the process, which is why we decided to conduct batch hydrotreatment studies with other pyrolysis and HTL oils. The reviewer stated, “The supply of pyrolysis oil does not appear to have been determined and sourced prior to the start of the project, which was a mistake.” The sourcing of the BTG was not an issue for the project. We have 55 gallons of the BTG pyrolytic lignin-rich fraction ready to be used in our continuous hydrotreatment studies. We agree with the reviewer that there may be opportunities to tune the pyrolysis process to obtain higher yields of the pyrolytic lignin fraction or to improve the quality of this fraction. In fact, we considered this question and added batch hydrotreatment studies of different oils; however, the challenges of producing 100 gallons of jet fuel as required by the FOA imposed restrictions as to how many oils we could study in batch conditions. We agree with the reviewers, and we will invite the suppliers to be partners of this project. The maximum emulsion stability time achieved so far is 3 hours, and we are working to further increase the stability time. If a single pulp is used, our goal is to feed the emulsion to the pump.

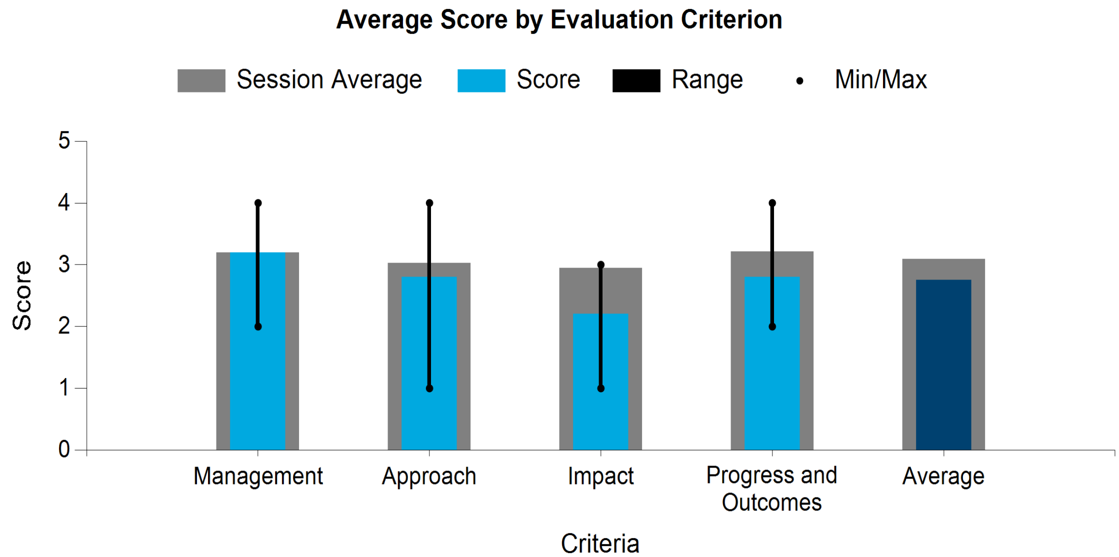
The PIs thank the reviewer for the kind comments.

The PIs thank the reviewer for the comments. Our pyrolysis oil was produced from softwood by BTG (Netherlands). The oil used is a typical fast pyrolysis oil. We thoroughly characterized the oil. Yes, the impact of our technology is limited by the availability of triglycerides. Yes, we have all the information of the feedstocks used. In fact, BTG sent us samples of the softwood used in the production of our oil for us to analyze it. All the oils studied were thoroughly characterized. The goal is to compare the hydrodeoxygenation performance of all the oils and explain the results based on the chemical composition of the actual oils. Our chemical characterization will allow us to document the differences between the pyrolysis and the HTL oils.

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

Applied Research Associates

WBS:	3.5.1.404
Presenter(s):	Ed Coppola
Project Start Date:	10/01/2018
Planned Project End Date:	07/30/2022
Total DOE Funding:	$2,950,000



COMMENTS

- This is interesting. The actual cost and availability of the right brown grease is not clear. Brown grease has limited availability, with lots of contaminants and fatty acids (which is no good for biodiesel). It is hard to get drums for development work; what is the expectation at scale? Waste as feedstock: There are no quality specifications (detergents, etc.), and what is the impact from variability? Survey, test, then create specifications. "Ask not to neutralize, etc." Feedstock logistics: large plant size? Brown grease cost evolution (waste then becomes a pricey commodity, etc.). Kudos on the ASTM approval.

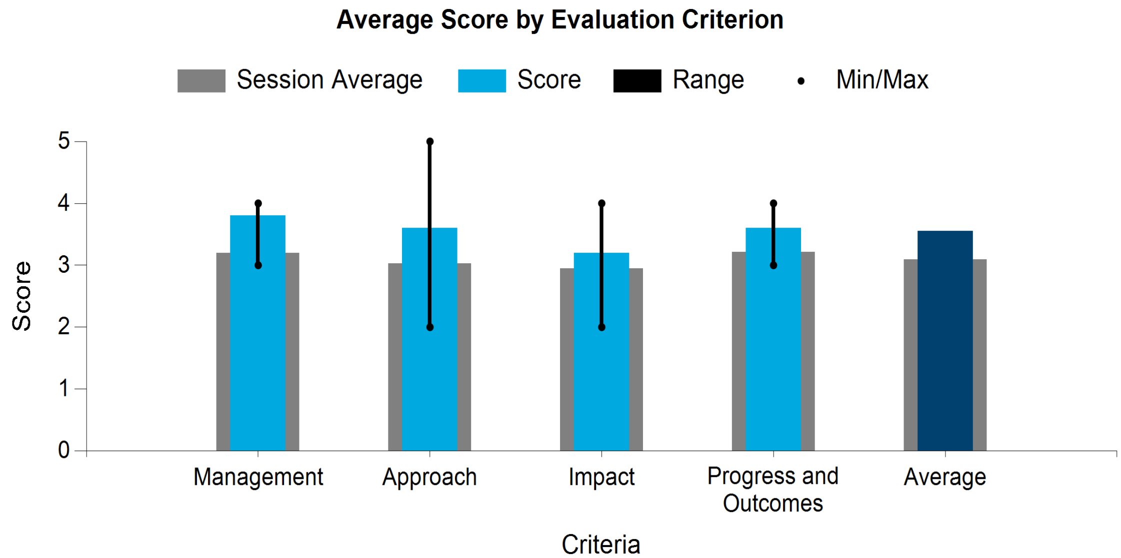
- The 1.7 million tons is spread across a number of different locations. The total project plan to deal with the small volumes at each site was not noted. It is not clear how many annual tons are available at the specifications required; however, the project team is working with aggregators of brown grease to make changes to their processes to meet the specification required. To date, aggregators have been amenable to making these changes. There are clearly delineated tasks with experts in their respective positions. It would be interesting to know more about the reluctance of brown grease suppliers to supply the quantities needed on this project. It is unclear how many brown grease suppliers were surveyed or the results from that survey. The presentation did not describe how long the pretreatment analysis was run or how the team was confident that they fully understood the variability of the feedstock and its impact on the process. Two different contamination effects have been discovered so far. Variations in the different suppliers and their impacts on the two different catalytic processes were not discussed. This seems to be a large risk not considered by the project. Overall economics (TEA) were not presented. It is not clear what feedstock specifications are required to provide an economic process. The process is in development for brown grease and is currently being licensed for less challenging but similar feedstocks. This is a good method to expand the current market of an existing product and to tackle another waste challenge in the industry without needing to develop a completely new design. The project has required more than 2 years for testing, which is not very significant in the overall goal of the project. It is not clear if additional catalyst testing, validation, or production scale-up for future facilities has been done during this time as well.

- The project is making excellent progress toward their goals, and achieving the ASTM D 7566 Annex 6 specifications is a notable achievement. What is unclear, however, is the ability to obtain enough brown grease to make a difference, the impact of increasing demand on tipping fee and the required feedstock specifications, and the ability to meet these at a realistic quantity. For these reasons, the approach and especially the impact were downgraded. The project should provide a high-level assessment of the ability and method to procure enough brown grease at sufficient quality to supply a reasonably sized facility as well as the industry at large. It is unclear that this can be commercialized.
- There is virtually no information provided about either of the primary process steps, making them impossible to evaluate with any accuracy. There is not much in the way of results for a project that started 2.5 years ago, only one product stream that narrowly meets ASTM specifications. Nitrogen looks to be a problem; it is not reduced much by the process. Other contaminants were reduced, but nothing is said about any waste stream cleanup (no BFD to show all process units and all streams). Brown grease is ultimately a low-impact feedstock. It is certainly worth diverting from landfills and converting if the economics work, but it is too low in volume to make much of a dent in a market the size of jet fuel. Aggregating supply will be challenging. In large urban areas, ideally, yes, but lots of material will be too sparsely distributed to make collection practical.
- This project has the potential to turn a waste stream into a feedstock for biofuels production; as with any process that utilizes a waste stream, it is important to ensure that the TEA allows for a positive cost for the feedstock, though, outside of logistics/transportation. The biggest issue with the concept proposed in this project would be feedstock sourcing—without a feed aggregator, the logistics of collecting grease from hundreds of small sources could prove impractical; with an aggregator, the cost of the feed goes up. The presentation would have been greatly improved with the addition of a BFD or process flow diagram to highlight key streams. It was unclear from the presentation what, if any, waste streams such a facility would generate. Given the highly variable nature of brown grease as a feedstock, it is expected that there will be undesirable molecules present; it would be helpful to understand the ultimate disposition of these contaminants.

COOL GTL FOR THE PRODUCTION OF JET FUEL FROM BIOGAS

Gas Technology Institute

WBS:	3.5.1.405
Presenter(s):	Terry Marker
Project Start Date:	10/01/2018
Planned Project End Date:	01/30/2022
Total DOE Funding:	$3,758,632



COMMENTS

- This is a good project. It looks like they are on target and have a sensible approach. It is early in the scale-up, so it is difficult to assess progress. The management plan does not outline project risks and mitigation strategies and is too high level to be of much use. The approach is high level and does not provide much detail, but it is sufficient. The key technical challenges are informative, but it would have been helpful to have more detail on the methods to reach these goals, especially on the slides. It is difficult for reviewers to catch everything during a 20-minute presentation, so slides should be informative. The impacts section was especially deficient.

- This is a new, interesting project. There is not much in terms of results to date. This is a very interesting electrically heated reformer. How does it scale? Energy efficiency should be considered, especially in terms of primary energy. There are some integration questions, such as biogas and syngas cleanup requirements and the ability to hit the C:H ratio from steam additions. Some interesting possibilities in scale matching IH^2 and reformer sections could be investigated.

- There is obvious relevance to biogas high in CO_2. The management plan is superficial; it needs more detail. It relies on the Fischer-Tropsch technology that is commercially unproven, even with cheap natural gas feed, and cool reformer syngas will be more expensive than that. Slide 13 shows, in effect, that Fischer-Tropsch will only get a fraction of the net feed; it is not clear how the IH^2 process has the capacity to make "extra" syngas. Are not all the reducing equivalents converted to fuel, CO_2, and water already? Then on slide 21, it looks like it is back to the drawing board on Fischer-Tropsch, not a microchannel design but rather a pair that have been looked at extensively before. The best use for incrementally reducing equivalents with IH^2 would probably be to use them as an external H_2 source, as in earlier designs. In the absence of biomass, straight biogas or possibly methanol, but no Fischer-Tropsch.

- The process has nearly 500 hours of TOS so far, and based on Gas Technology Institute's track record of extensive catalyst research, we would expect that this catalyst is thoroughly vetted prior to commercialization. The state of the catalyst (whether small batch or from a toll manufacturer) would be helpful to understand at this stage. An electrically heated reformer is a novel concept to reduce overall CapEx for the facility. The economics of the trade-off between steam or other heat versus electricity at a larger scale would have been beneficial. Several use cases presented provide new opportunities to expand the biofuel market. It is not clear whether the catalyst has been tested for susceptibility to poisons or its ability to be regenerated in these applications. The project is dependent on the development of three separate new innovations (reformer design and two catalysts). This increases the overall risk of the project, but the improvements appear necessary to provide the process economic viability. The wax cracking catalyst appears to possibly be a version of a commercially available catalyst and therefore lower risk. It would be of benefit to understand whether the reactor design has any particular or unique features compared to other reactor designs or if it is simply being designed for the process conditions required of this particular system. The commercial partnerships on this project are impressive. It would be great to know whether these partners are in active development of larger-scale facilities.
- This is a good project with considerable potential. The analysis of the jet fuel within the project appears to be limited to "pass specifications," but more detail on what would be needed to meet standards and pass certification trials should be considered. The "small footprint" modular approach is interesting, but the lack of economical small-scale reactors will limit this application. More detail with regards to the TEA should be provided; too many projects are claiming to reach dollar-per-GGE targets without explaining at least *how* they are impacting the current TEA models.

ULTRA-LOW-SULFUR WINTERIZED DIESEL

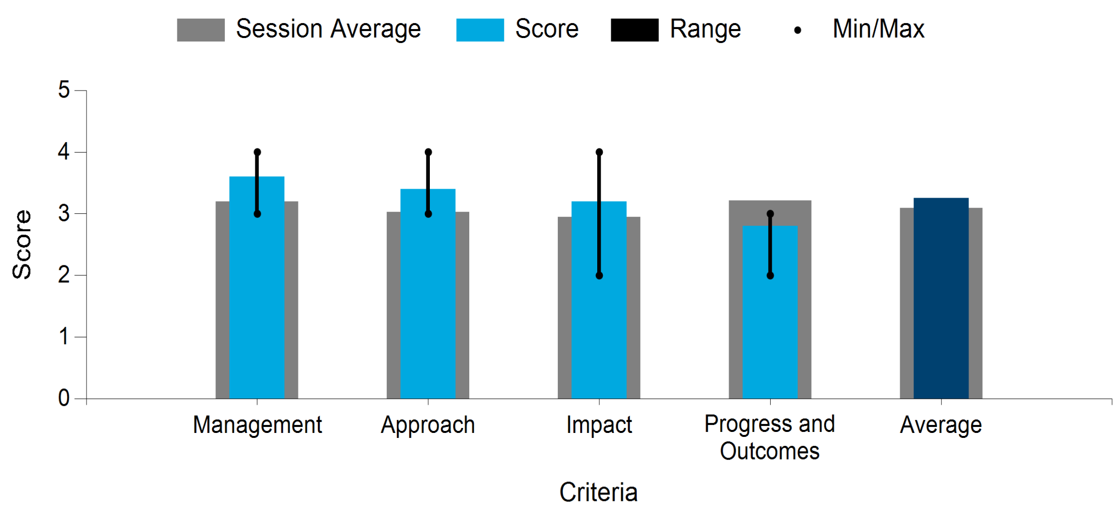
LanzaTech, Inc.

PROJECT DESCRIPTION

WBS:	3.5.1.406
Presenter(s):	Laurel Harmon
Project Start Date:	10/01/2019
Planned Project End Date:	03/31/2023
Total DOE Funding:	$3,130,327

In this project, LanzaTech is leading a team with PNNL and Zeton developing and validating a robust, flexible alcohol-to-diesel (ATD) technology that sources biomass-derived ethanol. The process will produce drop-in, renewable, paraffinic diesel offering low sulfur content and superior low-temperature performance. Research will adopt the alcohol-to-jet (ATJ) process to maximize synthetic paraffinic diesel (control of carbon number and level of branching) needed for select applications, including arctic conditions. The catalyst optimization will be done using commercially relevant catalyst preparation methods. At the conclusion of the project, we will produce 500 gallons of diesel fuel in an ATD production unit. We will provide a basic engineering package for the next-scale implementation. The ATD technology offers biorefineries making ATJ optionality to respond to changing market conditions.

Average Score by Evaluation Criterion



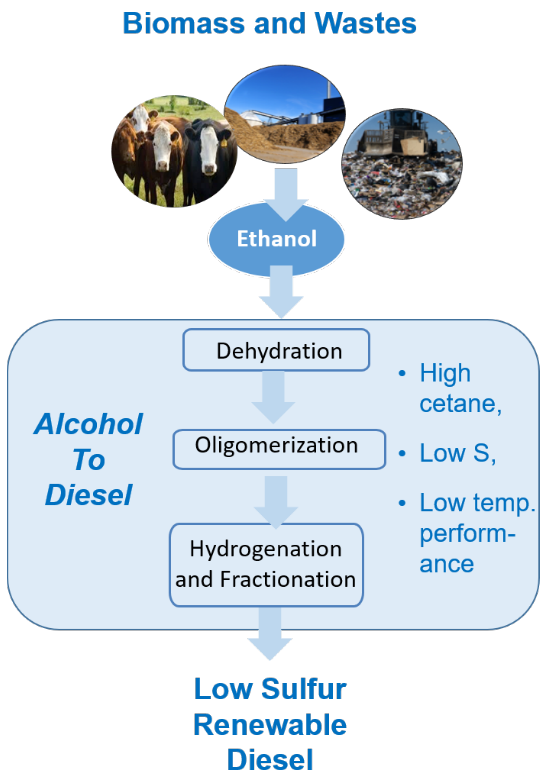


Photo courtesy of LanzaTech, Inc.

COMMENTS

- This is a variant of the LanzaTech/PNNL ATJ technology to maximize the diesel yield beyond what can be done currently. There are continued questions on the economics of going from ethanol to ethylene to liquid hydrocarbon fuels. Diesel brings even more questions than jet fuel when considering the current market availability and margin. The risk matrix should be revised in a more realistic way.

- This is a good approach and results for a very early project. The management plan has most of the necessary components and identifies many of the potential risks with mitigation strategies; however, the project appears to have all "low" risks, which does not seem reasonable. Even proven technologies could have moderate risks. This project is very early in execution, but it looks to be off to a good start. The reviewer would like to see a more thorough and realistic risk assessment. Due to the very early stage of this project, as well as the delays due to the pandemic, the overall progress and outcomes can only be scored average.

- The project appears to have a good management plan and approach for meeting its stated objective. The production of ethylene from ethanol should be devoted to displacing fossil-based ethylene first. Second, oligomerization essentially follows the pathway by which alpha-olefins, especially 1-hexene and 1-octene, are produced, and because of the costs of that process, those materials sell at a substantial premium to the ethylene feedstock. Without cheap fossil ethane from natural gas, ethylene *and* alpha-olefin prices will increase, and this route will be economically inferior to simply selling ethylene and/or alpha-olefins. There is also the issue of ethanol supply. Ethanol will continue to be a widely used gasoline blendstock for many years, and cellulosic ethanol will never be economic at a great scale; therefore, ethanol supply (at reasonable prices) is unlikely.

- The reviewer is confident that this is being well managed; however, all risks were noted to be low level, which is unlikely in a first-of-a-kind facility. Although the project did not present the risks as low level, the team has a recent history of scaling up technologies. The reviewer recommends that the risks be reevaluated for their overall level. The project appears to be well managed and has presented a logical workflow, a reasonable schedule (going forward), and awareness of the market in terms of the advantages/disadvantages of their technology. The process requires a large amount of H_2 but has still determined that the economics for the process works. The project has presented an exciting pathway to produce diesel and is developing the technology along a method similar to their existing projects. The overall economic advantage of this process was not discussed in detail; however, a pathway to producing large volumes of diesel without utilizing refinery operations or requiring refinery-level validation testing is exciting for the near-term renewable diesel market. The project is based on a lot of technology that is or has already been proven at scale and is based on the development of a limited number of items (one catalyst, unit operations). A study on the economics of ethylene to other products instead of fuel would have been of benefit. Although the project is already further in the development of its jet technology, this advancement will aid the company by allowing it to take advantage of swings in market prices and produce the best fuel for the market conditions, reducing the overall risk profile of LanzaTech. The project through the first year has been minimal (project verification and scope definition). The project did not report what difficulties they ran into during budget period one, which extended the period. The status of the catalyst development was unclear. Data were not presented on any catalyst performance test.

- This is a good project that has the potential to leverage existing commercial-scale ethanol production, which of late has been hitting the "blend wall" and is, by necessity, looking for other opportunities for growth. The presentation could have benefited from additional discussion of the fuel standard and of blending requirements for the fuel generated.

PI RESPONSE TO REVIEWER COMMENTS

- The reviewer concerns can be binned into three areas: (1) project performance, (2) business case/economics, and (3) risk.

  Project performance: Reviewers noted concerns on the project performance. These include a request to provide more detail on fuels standards, delays during budget period one, the catalyst development status, and the rate of progress during the pandemic. The renewable diesel produced from ethanol comprises hydrocarbons. The fuel meets and exceeds ASTM D975 standards (slides 8 and 9). The fuel offers value, with a high cetane, +50, and low CFPP (−25°C). The budget period one delays were contractual. In March 2021, the project moved from conditional to a full award. Prior to DOE removing restrictions on the conditional award, DOE's independent engineers working with our partner, PNNL, completed the verification, allowing the project to enter budget period two. In terms of catalyst development, during the verification, PNNL demonstrated, with the independent engineer, achieving 75% diesel selectivity, which is equivalent to the selectivity of hydroprocessed esters and fatty acids.

  Business case/economics: Reviewers noted concerns related to the business case and the economics of bio-ethylene to fuels, specifically to diesel fuel. This project is a renewable diesel project in which we offer new chemistry from an abundant resource. The central challenge of renewable diesel today is having an abundant resource. Waste oils and fats such as used cooking oil are limited. Sustainability concerns continue to be raised about both used cooking oil (traceability) and virgin vegetable oils. Looking at the project as a bio-ethylene project seeking new ethylene markets misses the impetus for the ATD pathway as a solution for the challenges of sourcing renewable diesel sustainably. The current margins of petroleum diesel versus jet fuel production have little meaning as we consider long-term needs. To a biorefinery operator, the flexibility of making either jet or diesel in high selectivity offers optionality. The pathway includes starting with low-cost waste carbon gases and solids, converting CO-rich gases/syngas to an intermediate, and that intermediate to fuels. Other pathways to sustainable ethanol are equally viable. The use of ethanol as an intermediate provides attractive process economics for ATD because the conditions are mild, and no special metallurgy is required. We are considering volume and Btu incentives, ethanol, and diesel balance. The request to study the economics of ethylene to products is outside the scope of this DOE project. Chemical markets are important, and we are examining those outside of this project, including GHG savings relative to conventional sources. But the focus of DOE for this project is GHG savings in transportation; the products of ethylene, including polyethylene and polyethylene terephthalate, do not contribute to GHG emissions in this sector. Ethanol will be used for many years, but gasoline demand is going down, so ethanol producers are looking for new markets.

Risk: Reviewers asked that the risks by revised with an eye toward a first-of-a-kind facility. A reviewer noted that even mature technologies have moderate risk. This is a research project, and the risks stated are consistent with the TRL. LanzaTech has a sister project with DOE on a demonstration facility for SAF. Risks related to a first-of-a-kind facility are covered in the sister project. The risks in this project center on the catalyst performance: selectivity (control of carbon length and branching), rate, and life. With an independent engineer, PNNL demonstrated 75% selectivity (carbon length) and cetane exceeding 50 (control over branching). From earlier work, PNNL has demonstrated catalyst life and rate, and we believe the risk is manageable, and we agree with the reviewer that the risks need to be considered realistically.

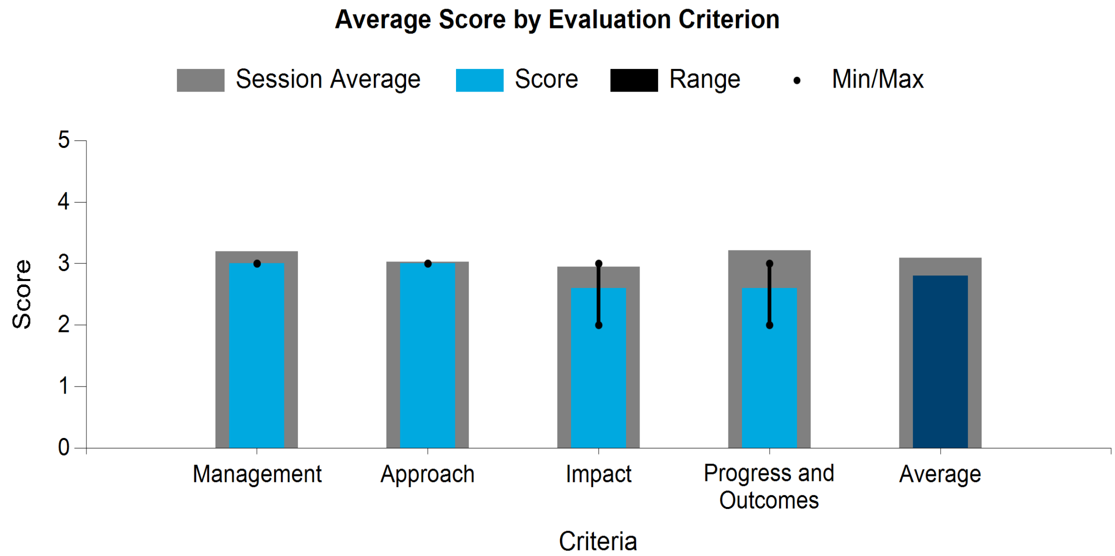
HIGHER-ENERGY-CONTENT JET BLENDING COMPONENTS DERIVED FROM ETHANOL

Purdue University

PROJECT DESCRIPTION

WBS:	3.5.1.408
Presenter(s):	Gozdem Kilaz
Project Start Date:	10/01/2019
Planned Project End Date:	02/29/2024
Total DOE Funding:	$2,217,768

BETO efforts in generating SAF have helped establish the production of synthetic isoparaffinic jet fuels with favorable properties, such as high energy density, excellent thermal stability, and favorable cold flow performance. When blended with isoparaffins, cycloalkanes carry the potential of further fuel performance improvement with at least a 4% net increase in energy content. PNNL and LanzaTech have already demonstrated a sustainable, nonpetroleum route to isoalkanes; however, economically attractive cycloalkane production from waste and biomass is challenged by large H_2 requirements, preferential selectivity to aromatic compounds, and low yields to jet-fuel-range components. Many gaps in understanding cycloalkane properties and performance in complex jet fuel mixtures remain. Purdue University has teamed with LanzaTech and PNNL to fill these knowledge gaps by analyzing fuel samples generated using a novel cyclization chemistry, providing a feedback loop to inform that chemistry based on properties that are proxies for performance and operability, followed by an examination of economic, ecological, and societal pressures associated with the deployment of the technology in the United States. The close tie and integration of Purdue's fuel property analysis, with PNNL's process development, can lead to an economically attractive process. The overarching strategy of the Purdue-LanzaTech-PNNL team's work proposed here targets the understanding of current and new cycloalkanes for use as a jet fuel. Through catalyst development, this work will provide a route to control the cycloalkane/n-alkane/iso-alkane content of a next-generation fuel with minimal or no aromatic content. Combining n-alkane and iso-alkane streams (high specific energy, MJ/kg) with cycloalkanes (higher energy density, MJ/L) is expected to enable at least a 4% net increase in combined (specific [MJ/kg] and volumetric [MJ/L]) energy content without impacting "drop-in" fuel requirements, such as seal swelling. This project will result in a selective low-cost route to high-performance renewable blendstock fuels. The team will develop a novel process and catalyst system for building cyclic alkanes in the jet fuel range with minimal H_2 consumption, processing requirements, and carbon intensity. This cycloalkane-rich fuel can be blended with n-alkanes and iso-alkanes (based on performance testing data from Purdue) from the previously developed LanzaTech/PNNL ATJ process to provide a fuel with ideal performance attributes. The fuel analysis and testing by Purdue will enable a robust understanding of the properties and behavior of the cycloalkanes produced to inform process development. Additionally, seal-swelling analysis will quantify the ability of fuel blends with zero or minimal aromatics content to satisfy the seal swell requirement of O rings. Last, Purdue's system-level analysis will lead to the development of a roadmap for deployment in key regions that considers system pressures such as H_2, water, energy efficiency, and ease of infrastructure access.



COMMENTS

- Ethylene-to-ethanol (E2E) and cyclization are well-known technologies; it is unclear what the innovation in this project is. The project management plan is lacking industry representation, at least in an advisory role. There is a good risk analysis and mitigation plan.
- This project has a good partnership approach with good delineation of tasks. Both LanzaTech and Purdue should have an excellent base of known risks in catalyst development in this field. It would be of benefit to understand what new risks have been considered specifically for this fuel and catalyst type. The target of 60% cycloalkanes is unclear in where it was derived. The remaining 40% of the products were not provided or how that works in the overall economics of the process. The project has not started yet. By creating a higher-energy-density fuel, airplanes can either travel longer distances or the same distances on less fuel. This could be an immense draw to pay a premium for a green fuel more than for the sake of it being "green." The approach is targeted to address unknowns in the fuel properties and application in jet fuel specifically for cycloalkanes. This follows the research of others that has shown the advantages of cycloalkanes over aromatics in jet fuels; however, it looks like this project is advancing two well-known processes: E2E and the cyclization of olefins. The project says they are doing work in this area, but they could not say specifically. It is not clear how many blends or catalyst types are expected to be analyzed during this process or the number of hours under test. The total duration of all these tests in relation to the overall plan is unclear. It is not clear if the process addresses the challenge of large quantities of H_2 required for hydrogenation steps or where that H_2 will be produced. The project did an excellent job of detailing the current SOT and the planned path forward.
- Is there any communication with the Bio-JET project, which is looking at direct biological routes to similar molecules? That project essentially proposes: sugar → high-energy-density jet fuel via fermentation. This project needs a fermentation to ethanol, dehydration to ethylene, oligomerization/cyclization, and then hydrogenation. There is also every likelihood that direct biological synthesis will produce a water-insoluble product, meaning that instead of distilling ethanol and then distilling the hydrocarbons at the end, the direct biological route will require only one simple decantation step after fermentation. The flow sheet here looks too complex. The cyclization of linear/branched alkanes is not new. Some of the products proposed appear to be novel, but strained-ring compounds are notoriously difficult to produce and possibly unstable. The management plan and risk abatement are adequate. The significant need for hydrogenation of aromatics will be a further significant cost. It will

also require H_2, which will require recovery, purification, and possible incremental supply. There are also implementation challenges. If "high-energy jet" is not available everywhere, then planning for cargo capacity and range will be complicated for airlines.

- The project has not yet started, so the progress was rated as average. The approach is feasible and sound. The management plan needs work because the overall tasks and working strategies are left to the imagination. The impact of this project is not clear and could be better explained. It is interesting that the energy density could be improved, but there is no assessment whether the proposed approach is necessary or likely to yield good results. It is unclear whether this project is needed at this time—i.e., is the potential benefit worth the additional development effort when those funds could be used in other, less studied areas?

- This is a very new project just starting to look at new, improved molecules in the jet range. There are many questions, such as yield, energy efficiency, and the conservation of carbon distribution when going through a conversion step. Academic enthusiasm should be tempered by commercial awareness and experience.

PI RESPONSE TO REVIEWER COMMENTS

- Regarding the comment, "This follows the research of others that has shown the advantages of cycloalkanes over aromatics in jet fuels; however, it looks like this project is advancing two well-known processes: E2E and the cyclization of olefins," and "Ethylene-to-ethanol and cyclization are well-known technologies; it is unclear what the innovation in this project is": Indeed, others have reported how cycloalkanes would have advantages over aromatics and other constituents in a jet fuel; however, our goals here are to further develop the scientific basis and also to quantify how cycloalkane-rich components could produce favorable jet blendstocks. Further, we will develop the tunable processing for producing different mixtures of cycloalkanes and paraffins—with selectively to the jet range—that can be optimized for the best combination of energy density and other characteristics. This is a distinctly different objective and approach from any known reports in the literature. Certainly, there exist known catalysts and conditions that facilitate cyclization from olefins, and these will be leveraged here; however, commercial systems have been optimized with different goals and using different feedstocks. For example, incumbent catalytic reforming processes convert low-octane linear alkanes into branched alkanes and cyclic naphthenes that are then partially dehydrogenated to produce high-octane, aromatic-rich hydrocarbons. This includes the UOP Platforming and UOP-BP Cyclar processes aimed at producing aromatics but not cycloalkanes. Cyclization processes typically use homogenous catalysts and are employed at smaller scales. Here, we leverage the ATJ process that selectively produces iso-paraffins that was developed by PNNL and is being commercialized by LanzaTech. Our aim is to tailor the catalyst and conditions for the formation of cycloalkanes versus iso-olefins. To accomplish this goal, we are using newly developed multifunctional catalyst(s) and the same number of processing steps as the current ATJ process. Different from the aforementioned aromatization processes, we aim to tune the olefinic distribution to cycloalkanes in the jet range (C8–C16) and with minimal aromatics. This is in stark contrast from the processes described above that typically produce aromatics in the C6–C8 range. Further, most of these traditionally used processes report up to 40% yield to aromatics. Our objective is to obtain at least 60% selectivity to cycloalkanes in the jet range. We are not aware of commercial-scale processes dedicated to the production of cycloparaffins from ethylene through cyclization or any other process (e.g., alkylation). Commercial uses for ethylene are currently aimed at the production of polyethylene, ethylene oxide, chloride, and styrene.

  Regarding the comment, "The significant need for hydrogenation of aromatics will be a further significant cost. It will also require H_2, which will require recovery, purification, and possible incremental supply": Our intent is to avoid the formation of aromatics either as a product or as an intermediate. By preferentially producing cycloalkanes over aromatics with H_2-neutral ring closure, we will limit the need for external H_2 for hydrotreatment. If unsuccessful, one of our risk mitigation approaches is to hydrogenate produced aromatics as a path to selectively form cycloalkane; however, because of the additional processing costs incurred using this alternative approach, we will only consider it if other approaches cannot achieve the 60% cycloalkane selectivity target.

Regarding the comment, “The project management plan is lacking industry representation, at least in an advisory role”: LanzaTech is participating in this effort to ensure that both the catalytic processing and jet fuel analysis efforts are successful. LanzaTech’s aim is to ultimately commercialize the technology developed here. The project management includes regular meetings with participation from all three project partners (as shown on slide 5). We also note that LanzaTech is already commercializing the benchmark ATJ process that was codeveloped with PNNL; therefore, a track record for commercial offtake already exists in the project.

Regarding the comment, “Is there any communication with the Bio-JET project, which is looking at direct biological routes to similar molecules. That project essentially proposes: sugar → high-energy-density jet fuel via fermentation. This project needs a fermentation to ethanol, dehydration to ethylene, oligomerization/cyclization, and then hydrogenation. There is also every likelihood that direct biological synthesis will produce a water-insoluble product, meaning that instead of distilling ethanol and then distilling the hydrocarbons at the end, the direct biological route will require only one simple decantation step after fermentation. The flow sheet here looks too complex”: Certainly, there are many biomass-to-jet routes being investigated, using alcohols, oils, gases, and sugars as feedstocks. Multiple processes exist, all at various TRLs. The ATJ process being commercialized by LanzaTech has many benefits. First, it uses ethanol feedstock that is already produced and distributed at the commercial scale. Second, it uses thermochemical processing that enables high throughput. Further, although multiple unit operations are required, it is selective toward producing an isoparaffinic hydrocarbon with >90% carbon efficiency to the jet range. Carbon efficiency is one of the most critical cost metrics when considering the use of biomass or recycled-carbon feedstock. Together, this process has many benefits and is currently being commercially deployed for SAF.

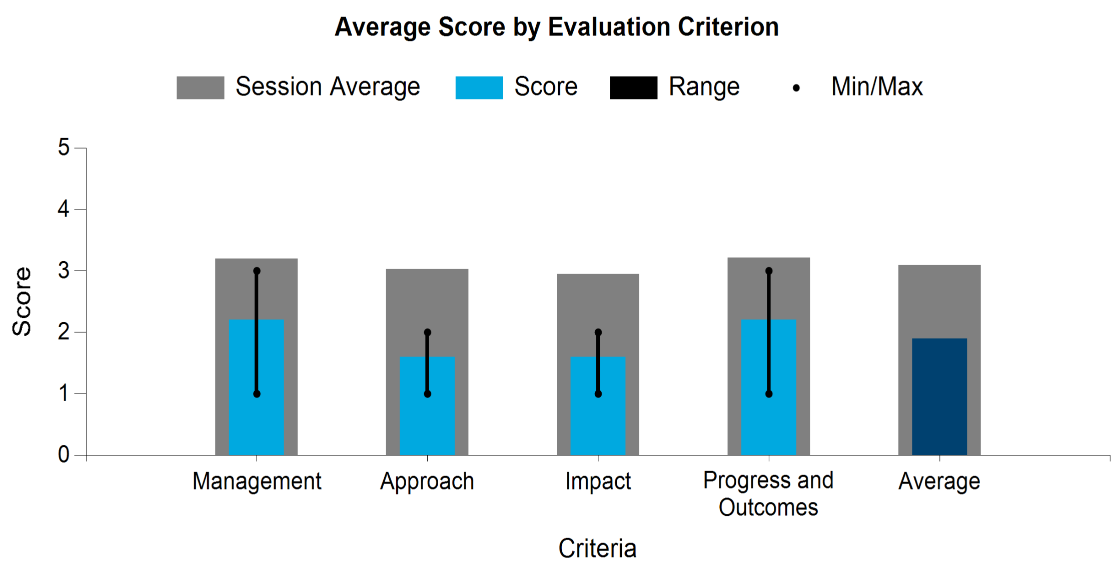
MULTI-STREAM INTEGRATED BIOREFINERY ENABLED BY WASTE PROCESSING

Texas A&M AgriLife Research

PROJECT DESCRIPTION

WBS:	3.5.1.501
Presenter(s):	Joshua Yuan
Project Start Date:	05/01/2018
Planned Project End Date:	11/30/2021
Total DOE Funding:	$2,795,276

The project will integrate recent advances developed by a multidisciplinary academic and industry coalition to address one of the most challenging issues in lignocellulosic biofuel: the utilization of biorefinery waste in producing valuable products. The success of a modern biorefinery heavily depends on the creation of diverse and valuable product streams using all fractions of input material. None of the lignocellulosic biorefinery is operating at the commercial scale, partially due to the failure of capturing value from all components of the cell wall. Essentially, all current lignocellulosic bioconversion platforms lead to a lignin-containing waste stream that needs further processing into valuable products. Although a certain amount of lignin (approximately 30%–40%) is needed for the thermal requirements of biofuel production, a modern cellulosic processing plant will have approximately 60% excess lignin that is mainly burned. The utilization of lignin-containing biorefinery streams as feedstock for renewable products offers a significant opportunity to improve operational efficiency, reduce cost, reduce carbon emissions, and enhance the sustainability of lignocellulosic biofuels. We will uniquely address the challenge by developing technologies for a multi-stream integrated biorefinery, where the lignin-containing biorefinery waste will be utilized for producing high-value products.



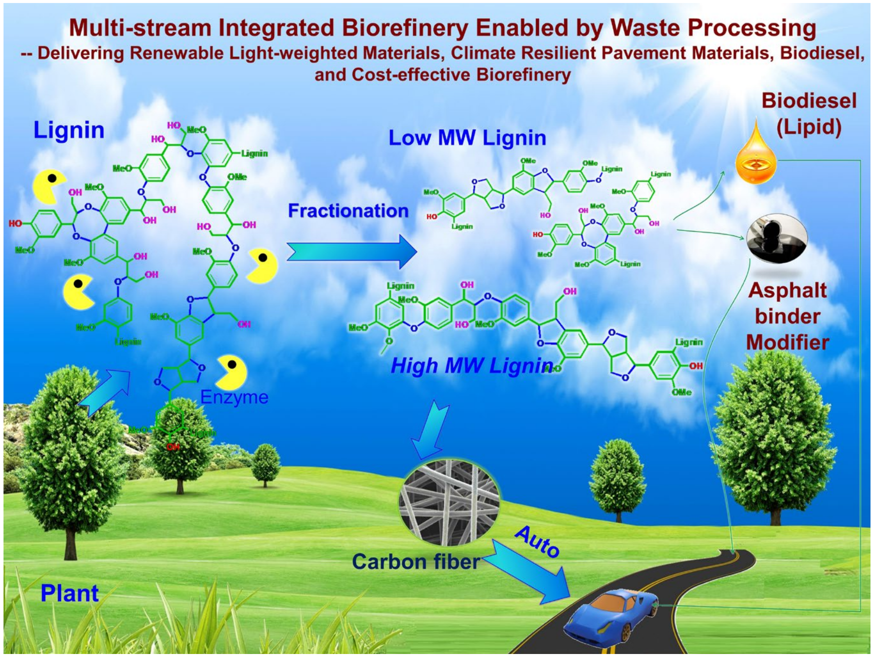


Photo courtesy of Texas A&M AgriLife Research

COMMENTS

- This is interesting but complex and has many risks. The products are carbon fiber, an asphalt binder modifier, and a lipid. The expected prices look very overoptimistic. How are the new operations costs estimated? Size? CapEx? This is too much, it is too unclear, and it is too complicated.

- Although the level of engagement is not defined, the project has a large group of industry and academic partners. The presentation and project approach were incredibly difficult to follow. It appears that the project is doing research and discusses metrics, but I could not follow how they plan to arrive at a process that meets their economic requirements. This reviewer appreciates the metrics; however, they appear to be highly aggressive targets. The required targets for profitability were also not presented; therefore, the targets may be both too aggressive to be realistic as well as insufficient to demonstrate commercial viability. The project did not demonstrate whether the prices for their products are based on realistic, high-volume offtake agreements. The product quality dependence on the upfront hydrolysis process is unclear. The utilization and success of the upfront process was not demonstrated. The quality metrics for the large-scale electrospinning process is not clear. Although they are not listed as a partner, FCIC within BETO is doing work on lignin valorization, which may be of benefit to this project. The project is aware of and is working toward understanding the relationship between the feedstock properties and their final product quality. This is a sound objective, and the project presented a number of methods in which they are attempting to understand this relationship. Unfortunately, this reviewer could not follow this complex plan in the short time period allowed. The project stated that they had obtained a lignin fractionation technology that this reviewer has not heard of. This project relies on the development of other processes and projects that are, unfortunately, going slowly. It will be difficult for new technologies to add another new technology to their platform to get financing. I would have appreciated hearing about existing facilities where this technology could be proven.

- The biggest issue with this project is that it takes a standard pretreatment (dilute acid) and enzymatic hydrolysis and claims that with the addition of NaOH to the lignin, it is worth anywhere from $1,000 to $20,000/ton. It is clear that the management team does not involve industry engagement or an IAB.

There is no discussion about the commercial cost of the unit operations and the impact on the TEA; the claim to reduce minimum ethanol selling price (MESP) by $0.5/GGE (?) is not suitably substantiated.

- This project has too many products, is too complex, and the economic assumptions are too rosy. To its credit, the project listened to the reviewers of the previous Peer Review and downselected products from three to two based on potential revenue. The project appears to be making good progress toward its goals, but the presentation contained so many slides, it was difficult for this reviewer to follow everything, absorb all the information, and focus only on the salient points rather than a lot of extraneous information. The overall impact of the project is severely limited due to its complexity. It has a very high technical risk profile due to its complexity, so it is unlikely to be commercialized.

- There are too many products for a lignocellulosic biomass plant. The unit operation count is simply too high, and the byproducts are not market-balanced. The small-product markets will be saturated long before a meaningful volume of fuel can be produced. The management team is on par with the process itself—there are much too many people and organizations for a project of this scope. We do not even reach the quad chart until slide 34, which is indicative of the unreasonable volume of this being addressed. The complexity needs to be dramatically scaled back or the project should be terminated.

PI RESPONSE TO REVIEWER COMMENTS

- General: One reviewer mentioned that the slide set he looked at is different from the presentation. We have double-checked to make sure that the correct version is in the system. In addition, for some reason, the sound for the presentation is not ideal and probably caused difficulty in following the presentation.

  The reviewer's concern over the NaOH cost is a very fair one; however, our TEA has already considered the NaOH cost and still shows the decrease in MESP. We have prepared a detailed TEA; however, because no questions were raised about the detailed TEA, we were not able to present these details. Several factors need to be considered. First, the process does not necessarily involve NaOH for the carbon fiber stream. Second, the commercial facility in the paper and pulping industry has been well established with NaOH recycling technologies. Third, we are working on adjusting the temperature and trying different chemicals to reduce the alkaline cost. Fourth, in the wastewater treatment after acid pretreatment, a neutralization step will also need alkaline inputs. The step can consolidate the alkali lignin dissolution with the acid stream to form a lignin stream, which reduces the neutralization cost. The net additional cost for NaOH will not exceed $5,000, and will mostly be within the $1,000 range. Considering the significant cost recovery by asphalt binder modifier (>$2,000/ton lignin, >$10,000/ton biomass), the net cost scenario remains to reduce the MESP. We do heavily involve the industry advisors, including ICM, POET, and CarbonFIT. We did not have regular board meetings because industry partners each have a distinct interest in working with us, and a board would be counterproductive. For the commercial cost of the unit operation, we included the detailed Aspen model in the slide attachments but never got a chance to discuss it. The MESP reduction is based on the sensitivity analysis of the carbon fiber price's impact on the MESP. It is based on the market price of carbon fiber.

  Regarding the product, we will focus on carbon fiber and an asphalt binder modifier only to reduce the complexity. We have carried out a sensitivity analysis of the carbon fiber price and its impacts on ethanol price. We are actually very conservative in price evaluation. The current carbon fiber market price is between $30/kg and $35/kg. The MESP is below zero with this price. We found that the MESP can achieve $2.67 with a carbon fiber price between $17 and $21. This price is significantly less than the current market price. In addition, for the asphalt binder modifier, we have increased 2 PG (performance grade) with a 5% addition of the fractionated lignin. The asphalt binder price increases by $100/ton for every PG, and the 2-PG increase at 5% lignin translates into 200/0.05 = $4,000/ton of fractionated lignin. We are counting the lignin-based asphalt binder modifier as only half this price, at $2,000; therefore, all prices are conservative and substantiated. For carbon fiber, the new operation size is a regular biorefinery at 2,205 tons/day. The CapEx and other costs were all integrated with the Aspen model.

Regarding the relevance of research and technical metrics to economics, the project is focusing on making quality products to enable value addition to the biorefinery. Technical metrics are essential for economics. With carbon fiber, previous lignin carbon has an elastic modulus around 30 GPa and a tensile strength around 400 MPa. This mechanical performance is not commercially relevant. DOE automobile-grade carbon fiber expects to exceed the elastic modulus of 100 GPa and the tensile strength of 1 GPa. The economics evaluation only makes sense after we reached such technical performance. In the same way, the price for lignin as an asphalt binder modifier will depend significantly on the PG increase. We agree with the reviewer that the targets are aggressive; indeed, they are. However, we have increased the elastic modulus threefold and the tensile strength for 2.5-fold during the past 2 years using the science-driven approach. This is not only important for the project but also represents a significant contribution to the carbon fiber, lignin valorization, and biorefinery fields. The question regarding the price at high volume is a very fair one. The carbon fiber market is increasing rapidly, and asphalt binder modifier also has a fairly large market. We have carried out market plasticity analysis showing that a few midsize biorefineries will not impact the carbon fiber market. The other side of the volume question is the multiple product streams. The ultimate solution to avoid market saturation and product devaluation is to develop multiple product streams. This is why the project actually focuses on multiple products. Currently, we are not using electrospinning at scale. The slide shows a customized (ready-to-scale-up) wet spinning facility. Wet spinning is the most common spinning technology being used in the industry now. We appreciate that the reviewer mentioned the FCIC and BETO efforts. We have an ongoing collaboration with FCIC-funded researchers. We are happy to expand the collaborations. We agree with the reviewer that a lot of progress needs to be accomplished within a short period of time; indeed, we made significant progress within a short period of time. We agree with the reviewer very much on using the existing facility to demonstrate the technology. We are working with NREL to scale up the biorefinery processing to demonstrate the applicability to the current biorefinery. The technology leading to carbon fiber is a universal (proprietary) treatment technology for lignin to allow high-quality carbon fiber. It is a novel invention in the project. We are happy to share it with the public when the patent is filed.

We agree with the reviewer that the complexity needs to be scaled back. We will scale down from the three product streams to two product streams at the technology scale-up to a half dry ton/day. We do not agree with the reviewer in terms of "too many products." If we examine a petroleum refinery or a wet milling first-generation biorefinery, each has multiple products to add value to the refinery and supply chain, allowing the low fuel price. The single- or limited-product biorefinery concept is partially accounted for in the current failure in the low-carbon biorefinery industry. No low-carbon biorefinery is currently operating even at the commercial level. This is partially due to the limited value that fuel can bring to the biorefinery. More importantly, the reviewer has concerns about the market size. Few products can share the same market size as fuel yet maintain high prices. This is why multiple product streams are essential for this project.

The number of products has been previously addressed. The multiple products are to avoid market saturation. Indeed, as the reviewer noted, we responded to the previous Peer Review and will scale down to two product streams in the scale-up. The economic assumptions were substantiated by the complete Aspen model, current market price, market plasticity analysis, and performance-based product price analysis. We very much agree with the reviewer on the high risk of the project. The project is high risk and high impact, with the potential to deliver at least two product streams to significantly decrease the fuel price for the biorefinery. The significant progress—including the more than threefold increase of the elastic modulus, the 2.5-times increase in the tensile strength, and the approximate two-times increase in the PG temperature—has demonstrated the team's capacity of de-risking.

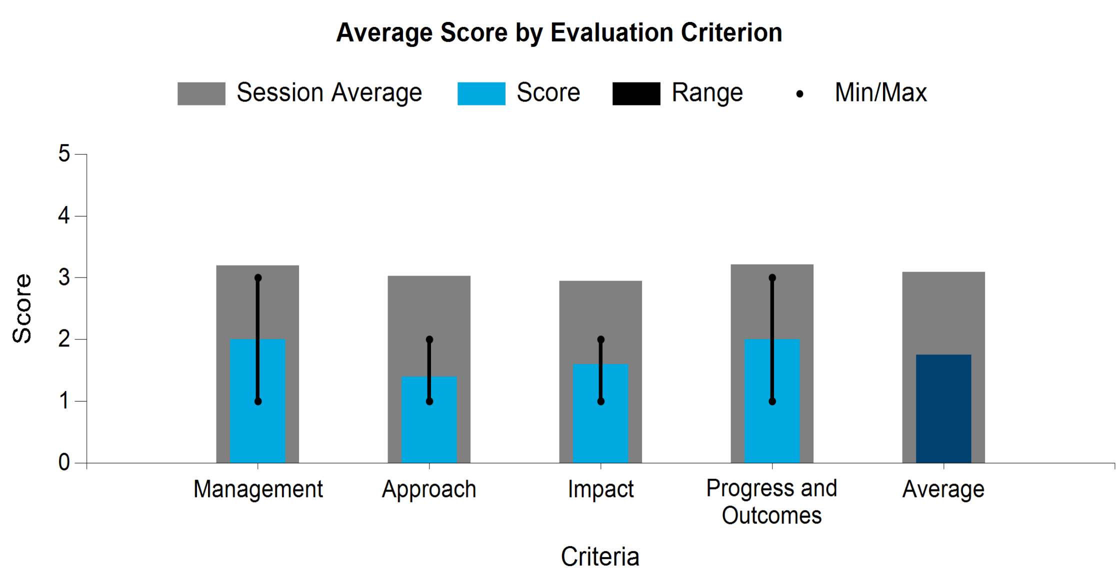
PILOT-SCALE BIOCHEMICAL AND HYDROTHERMAL INTEGRATED BIOREFINERY FOR COST-EFFECTIVE PRODUCTION OF FUELS AND VALUE-ADDED PRODUCTS

South Dakota School of Mines and Technology

PROJECT DESCRIPTION

WBS:	3.5.1.502
Presenter(s):	Rajesh Shende
Project Start Date:	02/15/2018
Planned Project End Date:	01/14/2022
Total DOE Funding:	$2,317,995

The major objective of this project is to demonstrate the cost-effective production of high-value products (biocarbon, carbon nanofiber felt/sponge, phenol, and lactic acid) from the waste streams (unhydrolyzed solids [UHS] and aqueous waste) originated from the biochemical processing of corn stover at a pilot-scale level with a throughput of 1 ton/day. An additional goal is to understand the revenue stream generated from these four high-value-added products and perform TEA/LCA to achieve BETO's 2022 cost target of $3/GGE with >50% reduction in GHG emissions. An integrated technology approach was developed to convert UHS into biocarbon and carbon nanofibers via HTL followed by graphitization and electrospinning, respectively. Aqueous waste generated from HTL processing was attempted to enrich for lactic acid by the wet oxidation technique. The project is focused on developing two products: product 1, biocarbon, and product 4, lactic acid. The key activities included were (1) preprocessing of corn stover at a pilot scale; (2) pretreatment and enzymatic hydrolysis to obtain UHS from corn stover; (3) optimization of HTL processing of UHS and characterization of biochar, heavy bio-oil, and aqueous waste; (4) wet oxidation of aqueous waste to enrich lactic acid; (5) graphitization of biochar to obtain battery-grade biocarbon, and (6) pilot-scale trials and TEA/LCA.



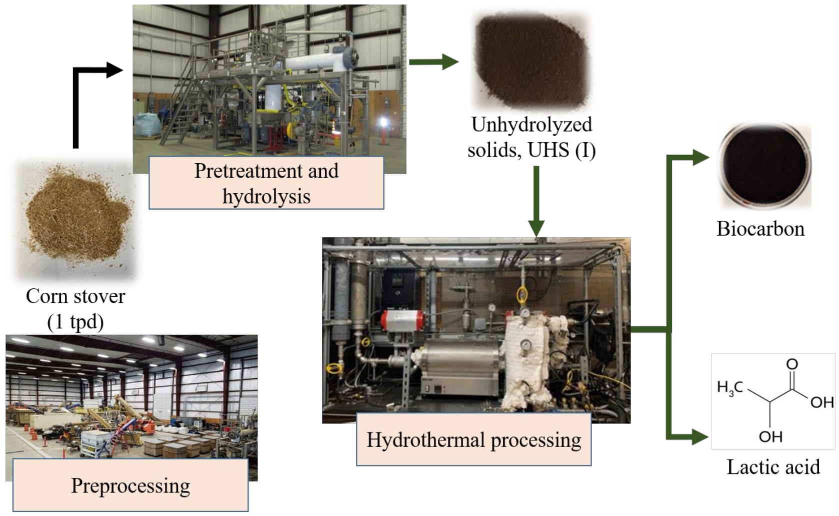


Photo courtesy of South Dakota School of Mines and Technology

COMMENTS

- There are unanswered previous questions, and this is complex. There are so many products, there are confusing BFDs, it is too optimistic, and the theoretical yields should be from the simulation. Is this waste or a specialized solid product? Four products downselected to two? There are plenty of undefined aspects and an unclear path to any commercialization.

- The project is looking to optimize conditions in their pilot plant by using DOE software and other simulations (risk registry). This is backward. Software and simulations help plan the operations of a pilot plant. From that point forward, if the simulation is not correct, its algorithm will necessarily be adjusted based on actual data. The risk of degradation or other changes to the properties of materials between facilities does not appear to be considered in this project. The structural degradation of fibers, sugars, and other properties can be considerable in short time periods if not properly neutralized; however, neutralization brings its own set of process-related challenges that must be considered. The process appears to be very complex and interdependent for the production of several relatively low-value products. The market size of the products is overstated. The project is studying simply too many individual issues and products in this project to ever make any headway. It needs to pick fewer products, reduce the scope, reduce the complexity and CapEx of its design, and move forward. The project plan is not really presented in a logical manner. Although it is appreciated that pilot trails are being done as well as integrated testing, how it is being managed and the validation plan were not clear. The project was able to demonstrate that they can meet the metrics that are specified and approved by DOE. The process yields from each unit operation were discussed, but the feed stream requirements for that unit operation were not. It is not clear if the project understands the impact of changing variables to each unit operation or has a validation plan to determine that impact. The project has multiple products to consider and is dependent on each to be of a good quality to be sold on the market. This is not ideal. If the quality of one product is insufficient to meet market conditions, the overall profitability of the facility is in question. Each product being offered by this facility has high barriers to entry, with unknown specifications and purity requirements.

- There are too many products and much too many unit operations for this process to succeed. This was addressed in the 2019 Peer Review, but the exact same comment applies 2 years later. The set of four sub-flow sheets on slide 28 is perhaps twice as complex as the most unrealistically complex low-carbon biomass flow sheet I have ever seen, all to produce a suite of products with markets much too small to support meaningful fuel production. The project needs to be completely redirected or terminated. It is, at present, a waste of money.

- This project appears to be focused on graduate school projects instead of advancing the technology. The overall approach is unrealistic, with too many products and too much complexity for a commercial facility. Evaluating numerous coproducts is better done at a much earlier development level, not SDI. In addition, at the last Peer Review, the project was advised to limit the number of products, and they failed to do so. Further, the Peer Review Panel asked why this was not done, and the PI replied that the side products are generated by “default,” they wanted to see the impact on the TEA, and they wanted to investigate “any low-value” streams. At the pilot scale, they would “mostly narrow down to the solid products.” This appears to be an exploration activity instead of an SDI project focused on scale-up. Although the project has made some progress on its goals, it is unlikely that this project will have an impact due to its complex flow sheet and the inability of the team to modify its approach and to recognize the overall goals of SDI projects.
- This project is badly in need of industry advisors. The goals are not realistic, the products are not realistic, and it is much too aggressive in TEA assumptions. The concept is to enable biofuels via high-value products from waste; this project uses a nonstandard pretreatment process to maximize “waste” streams, and then it focuses on multiple operations to make myriad products. It is hard to believe that with the proposed number of unit operations anything close to $3/GGE for the fuel product would ever be reached, and no TEA or financial data were presented to support this claim.

PI RESPONSE TO REVIEWER COMMENTS

- Regarding the comments, “There are unanswered previous questions, and this is complex. There are so many products, confusing BFDs, it is too optimistic, and the theoretical yields should be from the simulation.” The focus of the proposed work is to utilize the waste streams generated from the biochemical technology platform and convert it into high-value products. It is expected that the revenue stream generated from these high-value products will reduce the fuel cost to meet the objective of $3/GGE. Originally, we proposed to derive four products—product 1, biocarbon; product 2, carbon nanofibers; product 3, phenol; and product 4, lactic acid—from the UHS recovered from the biochemical platform. Among these, products 1 and 2 are solid products, whereas products 3 and 4 are liquid side products. Product 1, biocarbon, which is also used for battery carbon electrodes, has outperformed in terms of specific capacitance (>300 F/g) and cyclic stability over 10,000 charging/discharging cycles. This type of carbon is currently being sold in the market at approximately $20,000/ton. Product 4, lactic acid derived from lignocellulosic biomass, is an industrially useful product because almost all current feed streams used for polylactic acid manufacturing are derived from the edible source that competes with the food chain supply. Looking at the complexity of the unit operations and BFDs, we can select two products (product 1, biocarbon, and product 4, lactic acid), per the panel recommendations; however, we further seek approval from our technology manager. Currently, my team is working with the commercial partners and developing a five-step commercialization path. An invention disclosure is being filed with the South Dakota School of Mines and Technology office about the HTL-derived hydrochar and its subsequent chemical/thermal processing to obtain high-quality carbon. We are also continuously monitoring the market for the products of interest. Our value chain involved the participation of different people from technology developers, experts from the raw material chain, investors, startup companies, and end users. At this point, companies such as NEI Corporation and Nanopareil LLC are evaluating our products. Clear roles and responsibilities are assigned to the team members. A person at Lonza Group AG has been contacted for further process/product development aspects on a commercial scale. The Office of Economic Development at the South Dakota School of Mines and Technology has also been contacted to share technology concepts at their Entrepreneur in Residence program. In addition, technical risks have been identified, and the management of these risks will be facilitated by pilot-scale trials. This project had laboratory-scale optimization studies with respect to the corn stover-derived UHS to convert it into four high-value products. The entire technology conversion pathway was optimized and demonstrated at the laboratory scale to the contract engineers. Transitioning the technology to the pilot scale was delayed due to the (1) overall pandemic situation, (2) unavailability of staff for the lab trials, (3) no on-time delivery of materials and supplies, (4) no fixed timeline provided for equipment repairs, delivery, etc.

Regarding the comments, "The project is looking to optimize conditions in their pilot plant by using DOE software and other simulations (risk registry). This is backward," We fully agree with the reviewer. We can downselect to two products, mainly product 1, biocarbon, and product 4, lactic acid, among the four products originally proposed. This aspect will be thoroughly discussed with our technology manager to execute a follow-up action plan if such changes are acceptable. The aim of the simulation was to understand the variability of HTL process conditions on the product yields. We performed HTL experiments at a bench scale to understand the mass and energy balances with respect to the quality and yield of different products by changing the HTL processing parameters, such as reaction temperature, initial nitrogen purge pressure, reaction time, and biomass-to-solvent ratio. The results obtained from these experiments were published in peer-reviewed journals and have been regularly communicated in our quarterly reports. Response surface methodology was used to generate contour 3D plots to understand the impact of HTL processing conditions on product yield as well selectivity. This simulation study provided us with some guidelines about the selection of specific processing parameters to maximize the product yield. Simulations also helped to develop understanding of the interdependence ability of the coproducts in terms of their productivity. Experimental and simulation results agreed within a 94% confidence limit. The PIs fully agree with the reviewer that the simulation based on the pilot-scale trials will need adjustment of specific algorithms with respect to the product yield. Once a few pilot-scale trials are done, we will address the simulation task again. We are fully aware of the potential risks involved with the degradation of feedstock or the products. Please note that there is no inclusion of storage of derived sugars after the biochemical processing of preprocessed corn stover. With prior consultations, the project was advised to focus only on the waste conversion into high-value products. As such, INL has sufficient storage resource to store preprocessed corn stover. We have been storing INL-supplied, preprocessed corn stover inside a room at ambient conditions in a typical laboratory setting. Using this preprocessed corn stover, multiple HTL batches were performed. As such, no major change in the product yield or quality was observed. We fully understand that the biochemically derived material will need appropriate storage conditions. We do value the comment made by the reviewer on the neutralization step and the complexity that might arise after the alkaline pretreatment. Regardless of acid or alkali, a neutralization step will be necessary for enzymatic hydrolysis. Both steps were considered to derive the UHS to be able to process it further to generate high-value products. All feed streams were fully characterized for different unit operations and were regularly documented in the quarterly reports and in peer-reviewed publications. For example, ultimate and proximate analysis, particle size, moisture, pH, lignin content, amount of sugars generated, etc., were thoroughly characterized and documented. Presenting all relevant characteristics during the Peer Review meeting was a serious omission on our part, but this has been addressed. The global graphite market is predicted to witness a 7.4% compound annual growth rate between 2020 and 2030 to reach $36,889.1 million in 2030 from $19,092.9 million in 2019 (https://www.prnewswire.com/news-releases/graphite-market-to-hit-36-889-1-mn-revenue-by-2030-ps-intelligence-301233102.html).

Regarding the comments, "This project appears to be focused on graduate school projects instead of advancing the technology. The overall approach is unrealistic, with too many products and too much complexity for a commercial facility," developing a cost-effective conversion pathway for waste to high-value products is very challenging because of the feedstock complexities that exist at the front end. Devising conversion pathways involved a risk assessment. Although we were establishing a conversion pathway, a significant amount of data/results were generated, which resulted in a number of peer-reviewed publications. Including all the data/results in the presentation might have made an impression of a graduate student project. The conversion pathways derived are novel and are not reported in the literature. We fully agree with the reviewer that the evaluation of coproducts is done at earlier development than at SDI. Because pilot-scale trials were delayed due to the pandemic situation, we investigated several possibilities at a laboratory scale to examine the feasibility for integration. Pertinent results made us make very important decisions that will be useful and impactful during the pilot-scale trials. For instance, the hydrochar derived from the HTL processing can be treated via various processing options; however, which one will be more impactful in achieving a certain level of graphitization at a later stage is critical and cost-effective. Typically, product 3, phenol, and product 4, lactic acid, are observed, along with other oxygenated hydrocarbons in a wastewater stream originating from the HTL regardless of the processing conditions employed. This is precisely the reason of the PI mentioning the default action. Without looking into a possibility of recovering these products, the wastewater stream can also be treated directly. The wastewater treatment cost will negatively impact the fuel cost. Our logical approach was to investigate if any of these products can be either enriched or recovered and sold as a coproduct. The obvious benefit will be the positive impact that these products can bring over the fuel cost as well as GHG reductions that can be validated with TEA/LCA.

Regarding the comments: “This project is badly in need of industry advisors. The goals are not realistic, the products are not realistic, and it is much too aggressive in TEA assumptions.” Currently, my team is working with commercial entities such as NEI Corporation, Nanopareil LLC, Polykala LLC, and Lonza Group AG. In addition, we have contacted the Office of Economic Development at the South Dakota School of Mines and Technology to share technology concepts at the Entrepreneur in Residence program. The Entrepreneur in Residence program has more than 25 highly successful entrepreneurs and businesspeople. This program offers entrepreneurship activities, business formation and networking, market trend analysis, team building, IP, etc. Many CEOs will be on the South Dakota School of Mines and Technology campus, and it is the PI’s intent to meet these chief executive officers and present the technology concept, products, and their quality, and to seek guidance on the commercialization strategy. Our industry advisors will help us set up the commercial goals, market assessment, investments, and profit estimation. Currently, they are seeking the pilot-scale data and TEA, which are currently lacking. These activities were delayed, but they are forthcoming. Our team has mass and energy balance data for optimized, laboratory-scale, integrated processing. Among all pilot-scale processing, only preprocessing is completed at a pilot scale. For TEA, we are aware of the costs associated with the mechanical separation, size reduction, and chemical pretreatment and drying costs of $1.00, $17.21, and $20–$40/ton, respectively. In addition, we are continuously monitoring market data (global market, compound annual growth rate, market price) for the products of interest. Damon Heartly at INL has been contacted to perform TEA. Once entire pilot-scale trials are done, the data/results will be provided to Heartly for TEA.

Regarding the comments, “There are too many products and much too many unit operations for this process to succeed. This was addressed in the 2019 Peer Review, but the exact same comment applies 2 years later.” Developing a conversion pathway for the complex feedstock, such as waste solids derived from the biochemical platform for its conversion into high-value products, is very challenging because there are no relevant studies reported in the literature. If these pathways are not fully understood and analyzed well, errors will accrue at each processing step. At a glance, BFDs appear too complex, with many unit operations involved, which will get simplified as we move to downselect to two products. In our original proposal, we proposed four products: product 1, biocarbon; product 2, carbon nanofibers; product 3, phenol; and product 4, lactic acid. Among these, products 1 and 2 are solid products, whereas products 3 and 4 are liquid side products. Product 1, biocarbon, which is battery-grade carbonaceous electrode material, was found to have superior characteristics (specific capacitance >300 F/g and stability over 10,000 charging/discharging cycles). This type of carbon is currently being sold in the market at $20,000/ton. The technology of electrospinning for product 2, carbon nanofibers/felt, is not yet demonstrated at a mass production scale corresponding to the throughput referred in this project. Typically, product 3, phenol, and product 4, lactic acid, are observed, along with other oxygenated hydrocarbons in a wastewater stream originating from the HTL regardless of the processing conditions used. Without recovering these products, the wastewater stream can be treated directly; however, the treatment cost will negatively impact the fuel cost. Our logical approach was to investigate if any of these products can be either enriched or recovered to generate revenues. If the separation or enrichment is cost-competitive, these products can reduce the fuel cost as well as GHG emissions. Product 4, lactic acid, derived from lignocellulosic biomass, is industrially relevant because almost all current feed streams used for polylactic acid manufacturing are derived from the edible source that competes with the food supply chain. At this moment, we do not have pilot-scale data/results for the entire waste conversion pathway, which delayed our decision about the possible omission of two products. Successful laboratory trials suggest the selection of two products—product 1, biocarbon, and product 4, lactic acid—which will reduce the number of unit operations and simplify the BFDs. We fully agree with your recommendations; however, regarding the change in the direction of the project, we would like to seek approval from our technology manager. We could not make a decision about eliminating certain products because the development of an entire conversion pathway took a significant amount of time, and, also, many activities (for almost 9–10 months) fell out of schedule due to the pandemic. Without a complete assessment, no logical baseline was available to our team to disregard any of these products. Regarding scope, the PIs will focus their attention on other aspects of the project after two products are eliminated from the originally proposed list of four.

PILOT-SCALE ALGAL OIL PRODUCTION

Global Algae Innovations, Inc.

PROJECT DESCRIPTION

WBS:	3.5.2.201
Presenter(s):	David Hazlebeck
Project Start Date:	01/15/2017
Planned Project End Date:	12/31/2021
Total DOE Funding:	$4,471,580

The goal of this project is to scale up an open-raceway algal biofuel process that is economically viable and sustainable. This project will result in a front-end-loaded design document with −5%/+15% cost estimate accuracy for a 160-acre, pilot-scale algae farm; a business plan, including TEA results; and a project management plan for the detailed design, construction, and start-up of the pilot facility. The project team includes the California Center for Algal Biotechnology at the University of California, San Diego, and TSD Management Associates. The project will scale up Global Algae Innovations' technology suite of novel technologies to improve every area in the algae cultivation and processing. The technology suite includes scalable open raceways with innovations that greatly increase productivity and reduce energy use; the Zobi harvest system that achieves 100% harvest efficiency with 1/100th the energy use of centrifuges; a suite of contamination control innovations that enable stable, large-scale open raceway cultivation; and direct air capture for CO_2 supply.

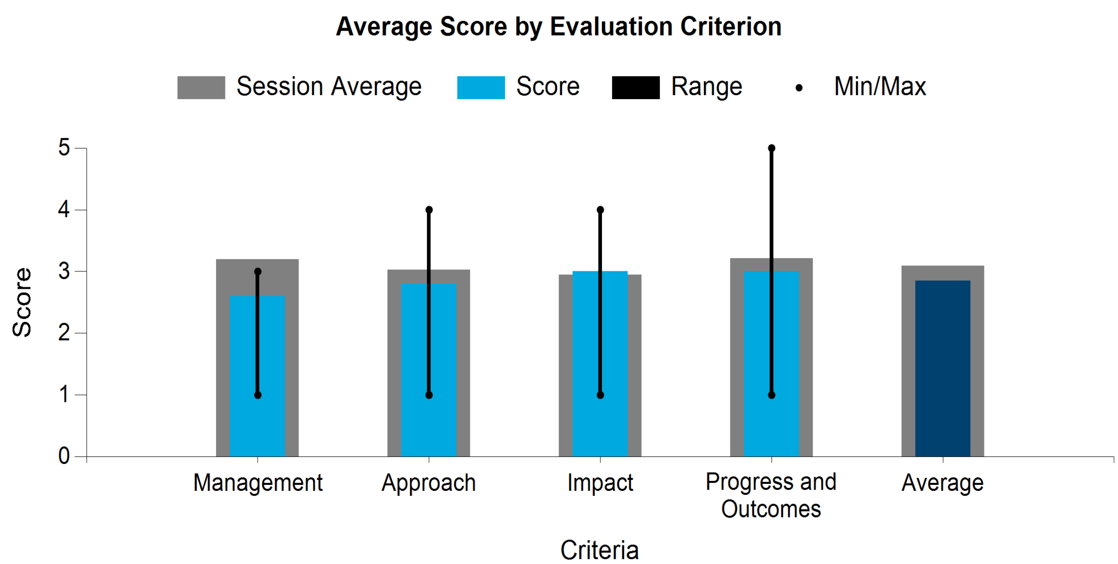


Photo courtesy of Global Algae Innovations, Inc.

COMMENTS

- The output of this project is supposed to be a package ready to go to, if not construction, at least EPC, with investor support. This is possibly good, and all is reasonable in the algae, but there are so many specifics, it makes it hard to judge CapEx. Included, a major component, is $500 million for a large facility, but also a high return on investment. The cost is a bit higher than NREL's. The largest cost is the raceway, which costs right in the middle of NREL's TEA models. The total cost is high enough to be credible, but it is also too high to attract commercial interest for a first facility, even if the return on investment is as high as claimed. What is the plan?

- The presentation is filled with unnecessary hyperbole and "data" that are at worst speculative and at best based on ideal lab results never duplicated even in real-world trials. The plot on the right-hand side of slide 4 is misleadingly labeled with "yield" on each axis. Yields are indeed plotted for the non-algae species, but lab results are plotted for algae, plus an undemonstrated "farm 160 design," as if it had been achieved. This hyperbole has long plagued the field of algae, and it does no good and perhaps much harm here. Both other plots on that slide are equally misleading and border on scientific dishonesty. The only question is which side of the border. On slide 5, the assault continues. Algae for *fuel* have achieved precisely none of the benefits listed, and even algae for higher-value products have barely scratched the surface. Slide 6 cites more speculation, with no real-world data involved. All presenters are expected to advocate to some degree for the work they are doing, but this is by far the most excessive in the full 5 days of the SDI Peer Review. The technology advisory committee is experienced but primarily in exactly the mode of algae cultivation correctly identified as being 10 times too expensive for fuel production. It is not clear that their experience best addresses the need for a true breakthrough. Slide 11 sums the contributions of 11 "major breakthroughs," but none are described. There are no actual data anywhere, only claims of economic impacts of "breakthroughs." Slide 18 assumes 22 t of CO_2 will be available affordably from direct air capture (slide 17). The only commercial direct air capture I am aware of sells CO_2 credits at 1,100 Euros/t, hardly fuel economics for algae. In harvesting, the unlikely "Zobi harvester" supposedly affordably separates 10 t of algae from 12,000 t of water (11.9 megaliters). It is simple enough just to repeat the 2019 Peer Review comment: "It is not clear that the project advances the SOA." The act of repeatedly *saying* that you are advancing the SOA is hardly enough.

- The presentation spent a lot of effort going over the advantages of algae, which took away from some detail that they appear to have at a project level but did not come through in the slides. The project lays out many of the items required to properly manage a project but did not provide many details on any piece. How CO_2 capture is being done is not clear, nor is the cost for it. It is unclear how this project plans to scale up each piece of equipment. It appears that significant research has been done in selecting equipment and species; however, it is not clear what information or actual operating algae projects have validated some of the technology here. The project had to reset due to COVID, but it continues to attempt to make progress toward construction. It is not clear why the design lagged behind the construction projects or whether their office had to be closed as well. The project appears to be working toward a fixed-bid contract to construct, but it is not clear if the design is complete or not. Scale-up and testing of so many new innovations is a challenge for any project. It is unclear if any or all the innovations noted have been tested at any scale. The advantages of the SOA in terms of making this project economic over other technologies was presented; however, a TEA for this project was not noted. It is unclear who is purchasing the dried algae for further processing or if that is a part of the future commercial plans. A 5,000-acre algae is a good opportunity to produce oil and protein for the biorefinery industry; however, algae projects have been beset by high CapEx costs and low productivity, and the project does not make clear that they have hit targets high enough for commercialization. The cost of $500 million with land costs appears to be lower than expected. It would be great if the costs projected are accurate and the money can be raised. The ability to demonstrate the number of new advances in the technology presented would be helpful (while also risky, as noted) to other algae industry players because some of the technologies appear to be off the shelf.

- The summary of technology selection (slide 17) was terrific. Elaborating on these achievements and their impact would have been much more informative and helpful in the review instead of including wide-ranging claims regarding the algae industry (e.g., preventing mass extinction). As a reviewer, for most of the presentation, I felt that I was reviewing a sales pitch for algae instead of a technical presentation on this specific project. The management plan was very basic, without a discussion of project risks and mitigation or how the team and tasks are organized. They do have a good technical advisory committee, which is great. The approach appeared to be just a list of activities without some explanation of how they will/were tackled. The impact has already been briefly discussed, but the impact of the specific project appeared to focus on achievements rather than how these will translate to impacts. Finally, it appears that goals are being met, especially with respect to improved technology and equipment selection. It is my sense that the project could have been graded much higher, but I was unable to do this given the lack of specificity on almost all the metrics.

- This is a very good project that suffered from a poor presentation—the focus needed to be on the technical advances made that can lead to the feasible commercialization of the project. It would have been nice to hear more about the commercialization of technologies, such as the harvester and the dryer, as well as additional detail around the TEA to help understand the project and the likelihood of implementation at the commercial scale.

PI RESPONSE TO REVIEWER COMMENTS

- We agree—more time on the technical advances and commercialization would have been beneficial and preferred from our perspective; however, it was important to spend a few minutes providing information on algae technology in general because the institutional knowledge on algal biofuels needs to be built up. The differences between algal biofuels and cellulosic fuels require different thinking in many areas. Cellulosic fuels have a 10-year head start in BETO funding and have received at least 10 times more R&D investment, so it is natural that most projects on scaling up technology have been cellulosic biofuels, and, of course, this is SDI's experience base. The fact that one of the reviewers believes that actual yield data from the large-scale production were lab data or hyperbole illustrates part of why building this institutional knowledge is important. The data points on the plots are actual yield data from two commercial facilities that have been growing algae for years and from our large-scale outdoor facility in Hawaii. The design point on the chart is conservative relative to what has actually been demonstrated and verified by one of DOE’s independent engineers for our large-scale outdoor algae cultivation. The response of disbelief is not unreasonable, given the incredibly high productivity and wide-ranging potential impacts of algae.

The high productivity and protein coproducts from algal biofuels lead to the need for a paradigm shift in thinking about many aspects of biofuel production. For example, algal biofuels do not compete with food. Instead, land or water used for algal biofuels actually generates much greater protein yield as a coproduct such that algal biofuels free up land and water that would otherwise be needed for this protein production. Many of the reviewer comments hit on the most important question: Has the technology progressed enough to enable commercial production? The technology selection slide listed many of the breakthroughs and innovations in this project. All these innovations have been demonstrated, and the majority were reviewed and verified by a DOE independent engineer. The cost projections are based on these innovations. Looking at some of the specific techno-economic questions: On harvesting, the Zobi harvester is being operated 24/7 in commercial algae farms, so the economics presented have very strong backup. On direct air capture, the technology has been demonstrated at the Kauai algae facility, and the actual cost for supplying CO_2 at this scale was $8/t. On the overall CapEx, it is driven primarily by cultivation and harvesting; the cultivation estimates are in line with estimates from two independent engineering firms, and the Zobi harvester estimate is based on systems of similar size supplied for commercial algae farms. There is a strong basis for the TEA presented and for the conclusion that a commercial facility will be economic and financeable; however, the risks are still high, especially with so many innovations incorporated into the design, which is why this project to design a facility for an intermediate-scale, 160-acre farm is so important.

HYPOWERS: HYDROTHERMAL PROCESSING OF WASTEWATER SOLIDS

Water Research Foundation

PROJECT DESCRIPTION

WBS:	3.5.2.202
Presenter(s):	Jeff Moeller
Project Start Date:	01/15/2017
Planned Project End Date:	03/31/2021
Total DOE Funding:	$24,457,299

The purpose of the HYPOWERS project is to design, build, and operate a hydrothermal processing (HTP) system to convert wastewater solids into renewable biofuel and methane at an operating wastewater treatment plant. The process has been developed by DOE primarily at PNNL and has been demonstrated at smaller scales, but a larger system running continuously in an industry environment is needed to support full commercialization.

The project has attracted intense interest from the wastewater industry because of the capabilities of the technology:

- By eliminating organic solids, HTP addresses solids management, which is 60% of total OpEx.
- Reduces life cycle cost by 50% compared to anaerobic digestion, which is the incumbent technology.
- Full implementation of HTP in the wastewater industry will save $2.2 billion and produce 41 million barrels of oil/year.

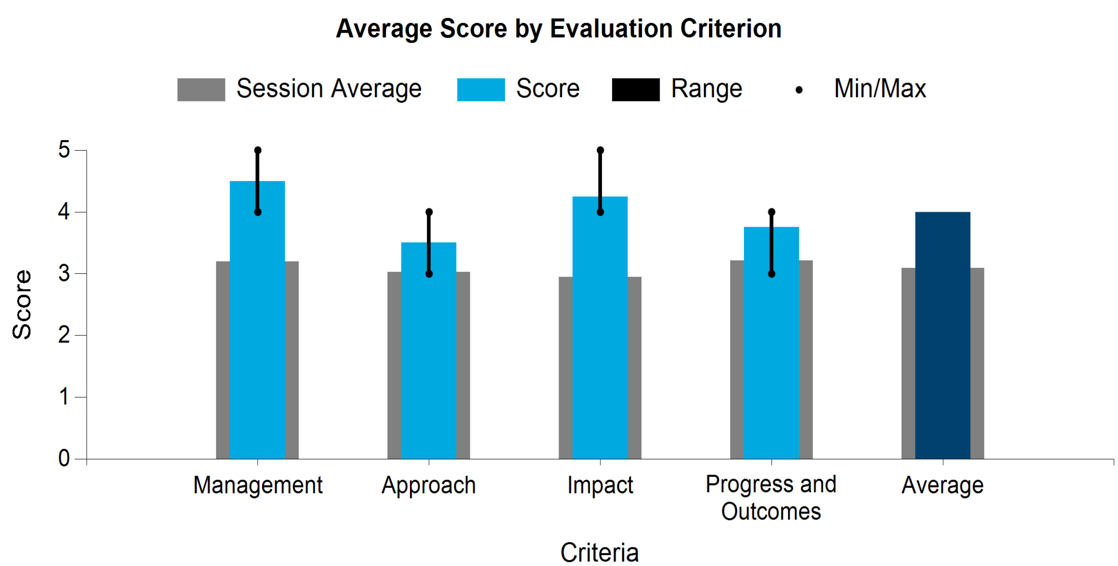


Photo courtesy of Water Research Foundation

COMMENTS

- This is a very interesting and good project, but the presentation could have used some more detail. The presentation provided critical insights into moving from Phase I to Phase II, particularly the difficulty of finding cost-share sources even with a successful initial phase. There are questions on the long-term ability to generate tipping fees from waste, but these are addressed through the reduction of dangerous targeted compounds in wastewater (PFAS). It is always good to question the upgrading strategy and options for the final products as well as the dependence on financial incentives (RINs, LCFS, etc.)

- There are clearly defined roles for the different project participants. There is good discussion on the risks of the project going into the scale-up of the existing system. The team is working with the right DOE team (PNNL) as well for the advancement of this technology. It is unclear why a fabrication partner that has experience in hydrothermal systems is important on this project. The project has taken the time to test the feedstocks for both wastewater treatment and HTP for the validation of the engineering assumptions prior to the build. It is unclear if this work can be translated into additional facilities or if this work will need to be repeated at the next facility. The project did not present any information that would lead the reviewer to believe that they understand the fundamental factors in their process. This project has the potential to have a large impact by getting rid of a waste as a feedstock, producing more fuels, and reducing local utility costs for communities around the nation. The project has put together a solid business plan with what appears to be all the necessary focuses. They are working with refiners to offtake this oil and have interest from several in hydrotreating it for a final fuel product. It was not clear what the project was doing to address the technical challenges it raised at the start of the presentation, such as catalyst life due to sulfur. The scale-up of 10 times on its surface seems reasonable, but the details of what is being scaled up and how were not discussed. The project reports that it has been scaled up eight times so far.

- The project appears to be stalled looking for funding. The management plan looks sound, and there is an excellent risk register in extra slides that should have been highlighted. The project team is highly qualified. The technical approach is sound and was progressing well until the funding gap. It would have been good to understand how the team is going about closing the gap. The chance for impact is significant due to the potential for PFAS resolution and the need for a wastewater treatment facility to reduce waste. It is unclear whether the economics will work when the waste is needed as a feedstock. Finally, the team has been meeting its goals.

- This is an excellent project that directly addresses a major problem in one industry while implementing a solution to commercial biofuels production. The ability of the process to destroy PFAS is huge and should be highlighted more. There is an excellent management plan, with industry engagement and an advisory committee. The approach guarantees a supply of feedstock for commercial implementation and has the potential to provide a significant amount of biofuel.

PI RESPONSE TO REVIEWER COMMENTS

- We thank all the reviewers for their time in the review and for their encouraging comments as well as constructive feedback. Following are our responses to several questions and items of note from the reviewers.

  We agree with the reviewers that the ability to destroy PFAS is extremely important, and we are working to be able to publish proof of destruction. Team discussions with the EPA are ongoing about including this technology in its list of PFAS destruction solutions for wastewater solids. The difficulty is that there are hundreds or even thousands of PFAS compounds, and concentrations are extremely low, making precision in testing essential—which takes time. The scientific credibility of the testing results will be essential.

  With regard to the reviewer's comments about the cost-share and tipping fees, these are good points, and they are interrelated. The difficulty in obtaining funds to go from Phase 1 to Phase 2 is real, and it even has a name: "The Valley of Death." As noted in the presentation, the team is indeed working diligently to secure the remaining cost share and contingency funding needed and has plans to bring on a new capitalization partner so that the project can proceed. The problem has arisen because we have not had a single large team member that can serve as a funding source for the remaining cost share, whereas external sources—such as private equity, "clean funds," and family offices—raise the same questions as the reviewer about tipping fees and government incentives. Our response is that tipping fees are real because solids management is proven to comprise up to 50%–60% of the total operating cost for most wastewater utilities, and the figure is almost certain to increase with PFAS and other chemicals, landfill closures, new regulations, etc.; however, competition among those seeking to use this resource could still diminish its value. In this case, though, we believe HTP technology is in a stronger position than any other currently available technology.

  With regard to financial incentives, the topic of government incentives is always difficult because such incentives can change. The counterargument is that the current environment is highly favorable to such incentives, and the probability of removal seems low for now. Whether these arguments will cause new funds to flow to projects such as HYPOWERS is the question for the project.

  Regarding the need for a fabrication partner with experience in hydrothermal systems, such experience is not absolutely necessary; nevertheless, we feel that it is a positive qualification. So far, three different firms have built recent systems, and all have been successful. Our goal is to get to a small number of standard sizes and designs so that standard modules can be built repeatedly and differently finished sizes can be achieved by mixing standard modules in a train. This would reduce the engineering costs and the overall schedule, and it would allow cost reductions from experienced suppliers building repeatable units.

  Regarding addressing the catalyst life, PNNL is currently developing sulfur-resistant gasification catalysts that will be scaled up and tested by using an existing mobile catalytic gasification system as part of the HYPOWERS demonstration. No pilot-scale gasification system will be designed and built as part of the HYPOWERS project. The HTL aqueous phase will be returned to the treatment plant after some cleanup using conventional methods. Thank you again to the reviewer for their comments and feedback.

SMALL-SCALE DECENTRALIZED FUEL PRODUCTION FACILITIES VIA ADVANCED HEAT EXCHANGER-ENABLED BIOREFINERIES

ThermoChem Recovery International, Inc.

PROJECT DESCRIPTION

WBS:	3.5.2.204
Presenter(s):	Ravi Chandran
Project Start Date:	01/15/2017
Planned Project End Date:	06/30/2022
Total DOE Funding:	$8,116,984

This project will leverage the existing commercial, technical, and operational capabilities of both TRI and Velocys to demonstrate this in a 4-ton/day IBR PDU at the TRI Advanced Development Center in Durham, North Carolina, which includes both TRI and Velocys systems. The modifications will include the addition of an advanced heater and changes to the gas cleanup system. The project will be validated by performing a continuous, long-duration, integrated trial to produce diesel and naphtha and estimating the benefits for a reference 150-dry-ton/day biomass-to-diesel commercial plant. The anticipated benefits at this scale are:

- 25% increase in usable syngas ($H_2 + CO$) per unit mass of dry feedstock
- >35% decrease in overall CapEx of the IBR
- >$2/GGE OpEx of IBR.

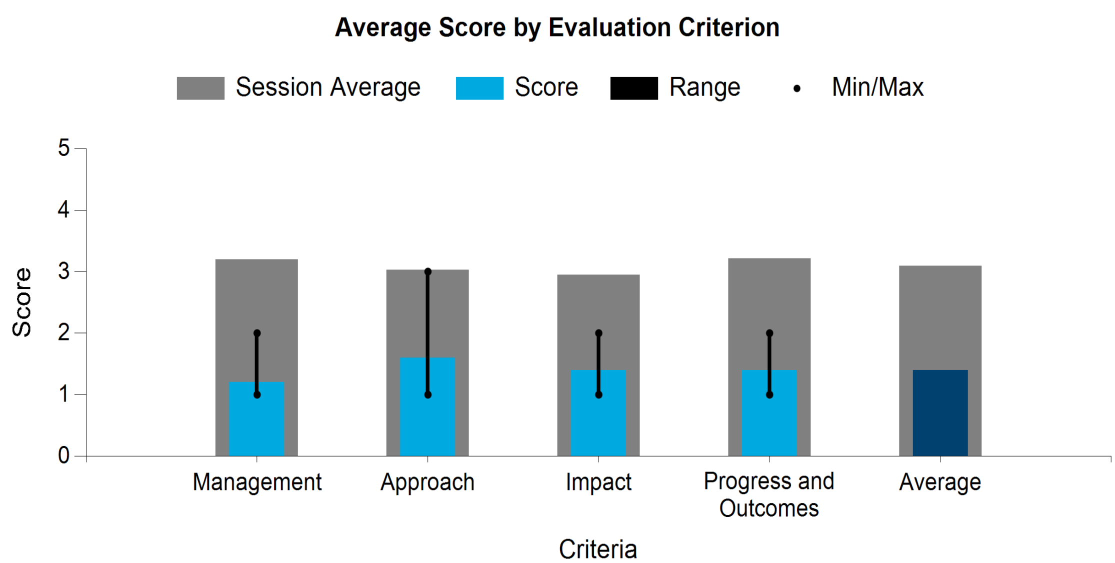


Photo courtesy of TRI

COMMENTS

- This is an extremely generic presentation, especially the management and approach section. There is some insight into the partnership, but I was underwhelmed by the review. The project team needs to take these peer reviews seriously and understand that they are part of the necessities for publicly financed projects.

- It is unclear what the project is validating these models against. Limited information was presented on what unit operations were being targeted for elimination or the impact of said elimination. The project expects the only process disadvantage to be the loss of char as a byproduct. The changes presented (reduction of compression, etc.) certainly do reduce CapEx, but the process will still need to compete economically with natural gas. A more complete comparison to a natural gas project on Fischer-Tropsch fuels would be helpful. There was no information on how the team plans to achieve <$2-GGE operation costs. The project did not provide a clear management plan that would support the effective completion of this project. There were no metrics or milestones provided other than high-level generic project needs (design, build, test). It is not clear what work has been done since 2019 that the reviewers should look at. Kinetics in the indirect (first-generation) and direct (second-generation) heated units are completely different, and it is not clear what studies TRI has done to determine the kinetics of this process. It was unclear if cold flow modeling was done to determine the CPFD simulation or how the fluidization was determined.

- There are no meaningful results to review. The project is only approximately 10% costed, but 4 years of a budget period of approximately 7 years have passed. What is going on? The BFD (extra slides) is very complex to succeed at the biorefinery scale. Also, it includes two inputs of natural gas and one of superheated steam from unspecified sources. With steam and natural gas being fed to the steam reformer, how much of the syngas reaching the Fischer-Tropsch reactor will be fossil-derived? It appears that only simulations have been run, but slide 15 appears to report experimental results? Are these actual trials? Is the syngas source TRI?

- This presentation was received late, and when it was received, it was a nothing-burger. It did not appear that the presenter took the time to develop a presentation that would address the requirements of the review. No data or results were presented—only generalities of achievements. Sitting through this presentation was a waste of time, and I feel that the reviewers' time was not respected. Additional slides included addressing risks, which all showed that they were addressed in 2019, so it is unclear what work was done and/or why it was done in 2020. Also in the additional slides was the comment that the project had been reviewed in 2019, and all comments were complimentary. These should be shown in any case.

- This project is lacking in several areas. The risk analysis is limited, and there is no meaningful mitigation plan. There is very little detail about what work is actually being completed, and the financial impact is poorly described, as is any detail of a TEA. The lack of information in the presentation makes it difficult to provide a meaningful review.

PI RESPONSE TO REVIEWER COMMENTS

- Phase 1 involved tasks related to process and data verification (budget period one) and component design (budget period two). Most of these tasks were completed prior to the 2019 BETO Peer Review meeting, and the details were presented in that meeting. Subsequently, we completed the finite element analysis of the advanced heater, and we prepared the budget for Phase 2 (budget period three and budget period four). Due to (1) the requirement for a contingency cash reserve of 25% of the Phase 2 budget and (2) TRI revenue impairment due to COVID-related delays, both projects have been on hold since 2020, with the consent of DOE. Because our understanding was that we were to provide an update since that 2019 meeting, we did not include a list of tasks and milestones and the details for work accomplished prior to that date. We did request permission from DOE and we prepared and submitted a more detailed version of the presentation, but it appears that version did not get distributed to the reviewers. From a macro perspective, the legislative requirement that a small startup company such as TRI place more than $2 million in escrow has disrupted progress. We are thankful to BETO for giving us more time to clear this big hurdle, but it has been difficult, especially with the COVID headwinds.

  The models were validated using data from small-scale tests. Two sets of experiments were performed: the first comparing syngas production (H_2 + CO yield) in the second-generation advanced heater mode with that from the first-generation heater mode, and the second to delineate the improved heat transfer performance of the advanced heater. CPFD's Barracuda software was used to validate the model and was subsequently used to project the performance of the PDU steam reformer. We have a long history of working with CPFD (approximately 14 years), performed cold flow fluid dynamic studies to tune the fluidization dynamic parameters, provided the kinetic parameters from our database, validated the Barracuda simulation results on several platforms (PDU-forest residuals, PDU-MSW, and commercial black liquor steam reformer), and projected the syngas output for the Project Sierra MSW reformer. Once the Sierra unit comes online, we shall compare the predictions with field data and tweak the model if necessary.

  We worked with Siemens PLM Group to develop and validate a pulse combustion and heat transfer model, and then we used this to project the performance of the PDU advanced heater design. To reduce the CapEx and OpEx and facilitate IBR viability at a small scale, the focus was on eliminating oxygen input, reducing compressor power input, and employing modular high-intensity components. TRI normally employs a two-stage gasification process, i.e., indirectly heated first-stage steam reformer and a char converter or carbon trim cell as the second stage. The configuration of our first-generation pulsed heater is such that oxygen co-feed is typically required at the commercial scale; the advanced heater or second-generation heater can provide all the heat required for the endothermic reactions. The carbon trim cell operates in the partial oxidation mode to gasify the refractory char and hence requires oxygen input. So, we eliminated the carbon trim cell to cut out the need for oxygen. We included warm gas cleanup and conditioning, including partial catalytic hydrocarbon reforming; we eliminated the high-temperature, slagging Pox unit (this again eliminates the oxygen input); and we included the CO_2 capture upstream of the syngas compressor to improve the syngas quality and reduce the compressor power input. The IBR includes the modular, high-intensity Velocys microchannel Fischer-Tropsch reactor. We are aware that steam-methane reforming units are quite expensive, and this impacts the cost of natural gas-derived transportation fuel; however, this—when combined with RINs and LCFS credits—may help small-scale IBRs close the gap. Because the gasifier is feedstock-agnostic, utilization of a feedstock with tipping fee may further improve the economic viability. A TEA is planned in Phase 2 to assess these options. Finally, some of the technologies developed here would also help improve the economic viability of large-scale IBRs.

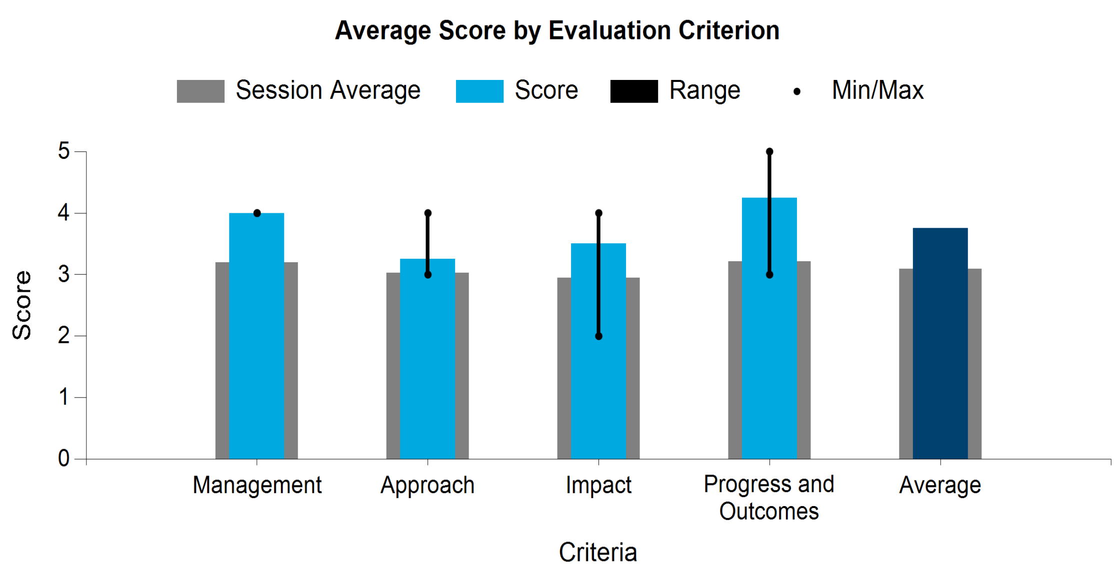
LOW-CARBON HYDROCARBON FUELS FROM INDUSTRIAL OFF-GAS

LanzaTech, Inc.

PROJECT DESCRIPTION

WBS:	3.5.2.403
Presenter(s):	Laurel Harmon
Project Start Date:	01/15/2017
Planned Project End Date:	12/31/2023
Total DOE Funding:	$9,017,103

The aviation industry is seeking economic and technically viable approaches to providing sustainable alternatives to petroleum-based jet fuel that reduce the carbon footprint of air travel. LanzaTech and its partners are implementing a 10-million-gal/year facility to demonstrate the production of low-carbon jet and diesel fuels from ethanol using a process termed ATJ. The ATJ technology originated at PNNL and was scaled by LanzaTech. The technology will be demonstrated using ethanol from steel mill off-gas and cellulosic ethanol, among other sources. The new facility, Freedom Pines Fuels, is a project entity that will be owned and operated at LanzaTech's Freedom Pines Biorefinery by LanzaJet, a company formed by LanzaTech for the commercialization of the ATJ technology. During Phase 1, LanzaTech completed the design and engineering required to achieve a −5/+15% cost estimate and two independent engineering reviews were completed. All technology and EPC partners have been selected. The environmental assessment required to obtain National Environmental Policy Act approval for the project and permit plan was developed to ensure that all required permits are obtained at each stage of the implementation. The project development has advanced: ethanol supply and offtake agreements have been secured, all equity has been secured, the project is in the late stages of a USDA loan guarantee, and LanzaTech is in negotiations with DOE for $14 million in additional funding for Phase 2. During Phase 2, the engineering of the process modules will be completed in parallel with preparation of the site and utilities. The modules will be fabricated and tested outside of the DOE-funded project scope. Modules will be shipped to Freedom Pines Fuels for on-site assembly, commissioning, and the start of fuel production.



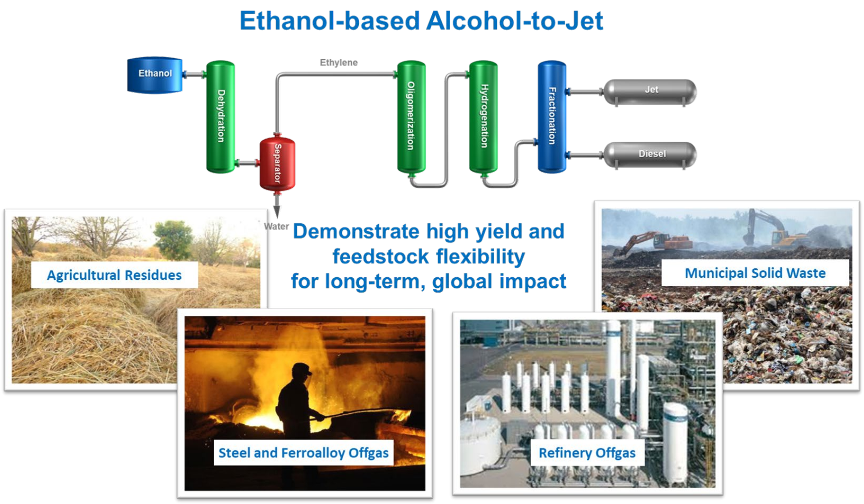


Photo courtesy of LanzaTech, Inc.

COMMENTS

- Past successes should not be considered justification for a weak risk assessment and mitigation strategy. "Technology validated at multiple prior scales" was the risk mitigation strategy for a prior risk; the risks presented here should have included those specific to the design, construction, startup, and operation of this facility, including risks of amending existing permits versus submitting for new permits. There is good industry engagement and excellent potential for industry impact; approximately 125 A380 flights/year is a good scale for demonstration.

- The need to test "multiple sources" of ethanol was unexplained. It is not clear if the project is concerned that certain small-percentage compounds in the ethanol could negatively impact the process. If so, this was not presented in the risk management plan. It is not clear whether the cellulosic fiber residuals are a necessary part of the project to be operational (i.e., whether equipment is sized to operate without that feedstock stream). It does not appear that the cellulosic fiber stream is a part of the DOE project because it was not highlighted in the presentation. It is not clear who would be supplying the ethanol from these residuals. If the process has not been designed to operate without this particular feed stream, the entire project could be impacted due to procurement issues. This has happened in the past on other DOE projects, with poor results. The procurement strategy for this stream should have been laid out. The risks presented were all significant risks: feedstock supply, offtake, technical, and financial. Although the project team has a history of successful scale-up, additional details on the technical risks of this project were not provided, nor were their assessed impacts. Other risks, such as financial, were noted to have been addressed at this stage. The overall project was presented in a logical manner with a good comparison to other technologies for awareness of the specific process advantages and disadvantages, commercialization strategy, and market awareness. The project reported that the commercially produced catalyst was tested at a small scale by another project participant. The results of that testing were not provided in this presentation. It would be of benefit to understand how their commercially produced catalyst compares (technically) with their previous lab-produced catalyst. The project has advanced as far as they have been able to without the National Environmental Policy Act rating having been completed. Their plans are to move to finalizing their design and begin construction (Phase 2) once complete. It is unclear if all ethanol from China will be used in this project or only the amount necessary to provide technical validation that the process functions on the desired future LanzaTech feedstock. The project has made good progress in the 3 years that it has been in development. A study on the economics of ethylene to other products instead of fuel would have been of benefit. Other than already owning the site, it is not clear what advantages there are for the selected location for this project.

- The presenter mentioned several times that there were no remaining technical risks and frequently minimized other risks. Scaling up by six orders of magnitude is a significant risk that appears to be underestimated. I think this approach is very risky, and it should be reconsidered. Although there are many good parts of this project, the glossing over of potential pitfalls of a project with a significant scale-up makes the team appear overconfident. This overconfidence is also evidenced by a scant management plan.

- The project appears to have a good management plan and approach for meeting its stated objective. The production of ethylene from ethanol should be devoted to displacing fossil fuel-based ethylene first. Second, oligomerization essentially follows the pathway by which alpha-olefins, especially 1-hexene and 1-octene, are produced; and because of the costs of that process, those material sell at a substantial premium to the ethylene feedstock. Without cheap fossil ethane from natural gas, ethylene *and* alpha-olefin prices will increase, and this route will be economically inferior to simply selling ethylene and/or alpha-olefins. There is also the issue of ethanol supply. Ethanol will continue to be a widely used gasoline blendstock for many years, and cellulosic ethanol will never be economical at a great scale; therefore, ethanol supply (at reasonable prices) is unlikely.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the reviewers' thoughtful attention and commentary on the project. The reviewers expressed concerns in the following areas: (1) site location, (2) business case, (3) ethanol sourcing, and (4) risk. In the following, we respond to the reviewers' concerns organized by area.

  Site location: A reviewer expressed concerns over the site location. The site had been developed and prepared by the previous owner. Significant infrastructure is already in place that will be leveraged for the project. Prior development meant that no land needed to be cleared and that the site had previously gone through multiple environmental assessments with a finding of no significant impact issued by the USDA and by DOE, thus reducing the National Environmental Policy Act approval burdens. In addition, toward the goals of the current administration, LanzaTech's Freedom Pines Biorefinery and LanzaJet's Freedom Pines Fuels provide high-paying jobs to residents of Soperton, Georgia, a rural community that is 52% African American with a median household income of $20,000 (U.S. Census Bureau).

  Business case: Reviewers expressed concerns about using ethylene, derived from ethanol, to produce SAF. A reviewer suggested a "study on the economics of ethylene to other products." Another reviewer suggested that bio-ethylene should be used only for current ethylene markets. This project is focused on SAF in which we offer new chemistry tied to abundant resources. The central challenge of SAF is having an abundant feedstock. Today, SAF is made from waste oils and fats, such as used cooking oil, and these are limited in supply. Sustainability concerns continue to be raised about both used cooking oil (traceability) and virgin vegetable oils. The use of ethanol as an intermediate also provides attractive process economics for ATJ for many reasons, including that the conditions are mild, no special metallurgy is required, and very high carbon yield and selectivity is possible. Viewing the project as a bio-ethylene project seeking new ethylene markets misses the impetus for the ATJ pathway as a solution for the challenges of sourcing SAF. Airlines need SAF today to achieve their carbon reduction goals. SAF is addressing a need for an industry in which electrification has limited opportunities. In the future, sourcing SAF will become even more important because the market for aviation fuels is projected to grow while demand for petroleum (gasoline and diesel) is projected to decrease due to electrification. The request to study the economics of ethylene to products is outside of the scope of this DOE project. We recognize that chemical markets are important, and we are actively engaged with partners in supply chains that can be accessed via ethanol dehydration to ethylene. That work is proceeding in parallel with this project, including understanding the GHG savings from such chemicals relative to conventional sources; however, the focus of DOE for this project is on GHG savings in transportation. Other products of ethylene, including polyethylene and polyethylene terephthalate, do not contribute to GHG emissions in this sector.

Ethanol sourcing: Reviewers expressed concerns about the sourcing of ethanol. The concerns range from the reason for testing “multiple sources”; the use of cellulosic fibers in ethanol production; who would be supplying the ethanol and the impact of procurement of the ethanol; and doubt that low-cost, sustainably sourced ethanol will be available. This project explores new chemistry to produce SAF based on ethanol as a platform molecule. The purpose of sourcing ethanol from multiple sources within the project is to demonstrate to sustainable ethanol producers and to offtakers that may not be chemically sophisticated that their ethanol works and that SAF production is independent of ethanol source. Corn kernel fiber ethanol is a source of D3 ethanol in the United States today, and it has been secured as one ethanol source. Ethanol producers are seeking new markets for their ethanol, and many have reached out to us. Ethanol supply agreements are in place for the first facility and in development for future commercial facilities. Although ethanol will continue to be used as a gasoline additive, ethanol producers are looking for new markets because gasoline demand hit a peak in 2007 and demand is now shrinking; as electrification of the light-duty fleet accelerates, ethanol demand will further decrease. The effects of a shrinking gasoline demand on the ethanol market were demonstrated in 2020. As gasoline demand fell because of COVID, ethanol demand plummeted with it.

Risk: Reviewers expressed concerns regarding risk. The concerns include that the risk assessment is weak, “past success should not be considered justification for a weak risk assessment”; requesting detail on how the commercially produced catalyst compares to the lab catalyst; the risk should cover design, construction, startup, and operation; and scaling by a million-fold is a significant risk. Along with risk, a reviewer asked for more details in the management plan. In response, we note that risks were outlined on slides 14 and 21. In Phase 1 CD-3, two independent engineering reports were completed. Both examined risk and recommended that the project proceed. Risks on design, construction, startup, and operation were assuaged in Phase 1. The design and construction of the SAF facility is being executed with a modular approach in which modular units are assembled and tested before delivery and then reassembled on-site. Testing the units before shipping and reassembly also reduces startup risk and startup time. Permitting risks are minimized by the site location. The site was fully permitted for this type of work prior to the project. A finding of no significant impact has been issued by USDA and by DOE, as mentioned. Finally, the “six orders of magnitude” objection came from a misinterpretation of slide 20, which showed DOE-funded work. Aside from the DOE-funded work, LanzaTech conducted a field demonstration equivalent to 50,000 gal/year. The scaled-up catalyst and the process were demonstrated during the field demonstration.

ADVANCED BIOFUELS AND BIOPRODUCTS WITH AMERICAN VALUE-ADDED PULPING

AVAPCO LLC

PROJECT DESCRIPTION

WBS:	3.5.2.405
Presenter(s):	Kim Nelson
Project Start Date:	04/01/2017
Planned Project End Date:	03/31/2022
Total DOE Funding:	$8,341,328

The project Advanced Biofuels and Bioproducts with American Value-Added Pulping (AVAP) involves upscaling the patented AVAP pretreatment technology, coupled with innovative sugar fermentation to mixed alcohols, which are then converted to full-replacement liquid hydrocarbon biofuels at the existing biorefinery site in Thomaston, Georgia. The targeted scale is 50 dry tons/day of woody biomass from neighboring sawmill residues and harvesting operations. The coproducts include AVAPCO's revolutionary BioPlus nanocellulose and bio-based 1,4-butanediol (bio-BDO) with project partner Genomatica.

In the AVAP fractionation, the process starts with wood chips fed into a continuous digester. The chips are impregnated with sulfur-dioxide-ethanol-water liquor and cooked. These conditions dissolve nearly all lignin and hemicellulose without creating unwanted side products. The chemicals are recovered via washing and stripping, then recycled to the digester, resulting in a hemicellulose sugar stream and a high-purity cellulose stream. Part of the clean cellulose is directed to produce nanocellulose. The rest of the cellulose is enzymatically saccharified at a low enzyme dose for hydrolysis to C6 sugars, which are one-fermented to bio-BDO by Genomatica. Genomatica's direct fermentation to bio-BDO is cost-advantaged over the petrochemical route.

The remaining cellulosic and hemicellulosic sugars are fermented to produce ethanol. The remaining lignin and fermentation residuals are burned for process energy. In the hydrocarbon plant, these alcohols are converted to full-replacement liquid hydrocarbons using a catalytic synthesis process that produces petroleum distillate equivalents with overall LCA reduction greater than 60%. Alcohols are dehydrated over catalyst to produce alkenes using technology from project partner Petron Scientech, Inc. Using technology from project partner Byogy, the resulting alkenes are then oligomerized to mixed olefins, which are further converted to a variety of distilled biofuels, such as jet fuel, diesel, and gasoline. Jet fuel from the pilot plant has undergone advanced U.S. Air Force testing for JP-5 and JP-8 grades with the unique ability to vary aromatic content. Byogy was a finalist as one of four companies of 90 under the Federal Aviation Administration's Continuous Lower Energy, Emissions, and Noise program, where rigorous engine testing was performed by Rolls Royce that demonstrated Byogy's fuel characteristics provide a premium full-replacement renewable aviation fuel. Byogy's technology is a direct chemically and thermally efficient route to convert ethanol to jet fuel.

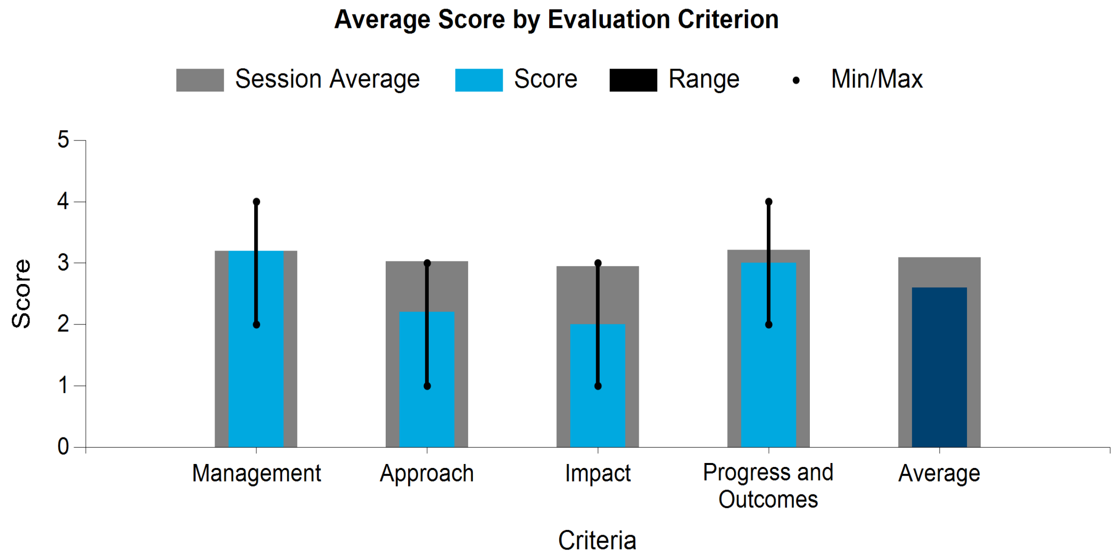


Photo courtesy of AVAPCO LLC

COMMENTS

- Biomass to ethanol and nanocellulose plus ATJ: The ATJ section (Petron for EtE and Byogy) looks to be an add-on and a bit of an afterthought in order to fit within the FOA. It is hard to see how they are commercially viable. The Byogy "process" is rather undefined and lacks detail and definition. There is too much undefined "proprietary" technology. Especially the ATJ side is basically nonexistent.

- Remarks are based on the slide deck only. Due to extremely low volume and background hum, the audio during the presentation was completely unintelligible to me. The BFD shows nanocellulose at roughly one-fifth the production of jet fuel. Based on a 2025 market report, demand for nanocellulose will be 10,000 t/year, which is approximately 50,000 times less than demand for jet fuel. This is the problem with specialty lignin products as well. Some of them may very well be valuable enough to enable the coproduction of fuels, but the markets are so small that the amounts of fuel produced are trivial. And developing many such coproducts will not help. The entire chemicals industry—including high-volume commodity chemicals such as ethylene, propylene, and BTX—is only 15% the size of the petroleum fuels industry. Specialty products like nanocellulose are much more than an order of magnitude smaller, combined. Ethanol-to-jet via dehydration and synthesis will add too much cost for any mogas/jet-fuel price differential to overcome, in any case.

- This project has the potential to produce a facility that makes a coproduct from cellulose that can completely "subsidize" the production of biofuels and help achieve commercial-scale production. It was unclear from the presentation at what scale the nanocellulose market will operate in the near and mid-future, which could significantly limit the amount of fuel that would be produced; although the goal of replacing the whole barrel cannot necessarily be met with only a single technology or a single fuel, those that are selected for funding at the demonstration scale (and larger) should demonstrate large-scale impact in the fuels market.

- This project is well run and is meeting its objectives on time and on target. It appears, however, that its main concern is developing nanocellulose, and this appears to have a higher focus than it should. Although coproducts are important and nanocellulose will be used in a method that should impact the energy use and hence the GHG emissions from the transportation sector, it is not clear that the team is as focused on the codevelopment of biofuels. The team admitted that their product slate will depend on the economics, which, of course, is critical in business, but it gave no assurance that biofuels would be any part of that. They did state that both nanocellulose and biojet are cost-effective, and it would have been good to understand this by providing values or an analysis of the trade-offs. Because too much of the focus is on nanocellulose, the approach and impacts are both downgraded.

- It is unclear if the nanocellulose specification to the wide variety of customers was dictated to the offtakers or if different specifications were dictated to AVAPCO. The purity requirements of the final products are critical to understand for an evaluation of potential impact and risks. It is not clear if this market is looking for a larger quantity of nanocellulose, or a cheaper one to expand the market. The management plan is clear and detailed, including the risk and engineering design plans. It is unclear what state the catalyst is in or if it has been produced at a larger scale by a toll manufacturer. The project claims thousands of hours, but what that actually means in regard to a single formulation is unclear. In total, there are a significant number of technology companies coming together at different levels of commercialization for this project, which is always risky. Specifications among companies, schedule, and budget concerns all become interdependent for the success of one project. The management appears to be considering this in their planning. It is not clear how the project intends to grow the market of nanocellulose beyond making it available for other companies to purchase and develop for their own processes. The demand for nanocellulose appears to be limited but with certain core requirements and processing requirements, which AVAPCO claims to have resolved. The IP on this resolution is key to maintaining their market advantage and not allowing other companies to saturate this small market with their own product. The IP position was not discussed in the presentation. AVAPCO is utilizing a commercially sourced and screened yeast for ethanol production. It was not clear whether these commercially sourced yeasts are new to the industry or require additional validation on their own, or if this project in any way aids their development. At the market prices noted by AVAPCO, the overall project would likely benefit economically by focusing their process on nanocellulose in the near term. Additionally, ethylene can often be more valuable than jet fuel, which was not discussed in the presentation. The demonstration project appears to be geared toward meeting the DOE FOA requirements than actual business plans. Lignin is being burned in the current process, which is a good way of not making this project more complicated than it already is. The demonstration site could, in the future, be used to test out different valorization techniques for the lignin if it is of good quality.

PI RESPONSE TO REVIEWER COMMENTS

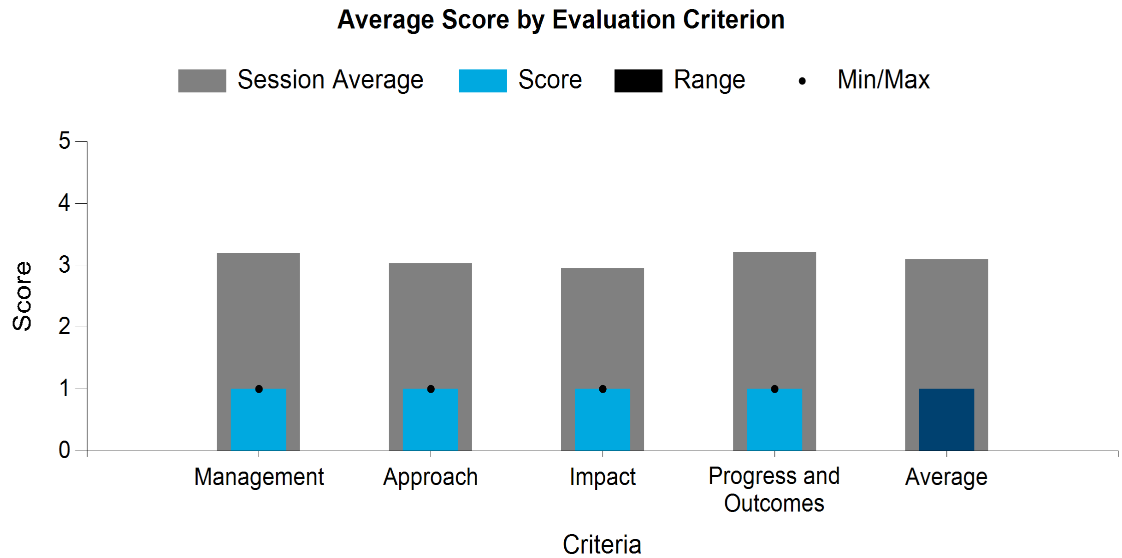
- There are currently seven technology pathways approved by ASTM for SAF use. The ATJ pathway from lignocellulosic sugars to cellulosic ethanol to jet fuel was approved in 2018 after a 16-month certification and testing process. Considerable scientific and business development resources have been dedicated to this pathway for more than a decade. AVAPCO does not provide nanocellulose to other companies for these companies to develop for their own processes. We partner directly with end-use companies through product development partnerships to codevelop nanocellulose-enabled solutions with verified value proposition based on both performance and sustainability enhancement. The joint development partnerships define the nanocellulose specifications for the best performance for each application (particle morphology, surface chemistry, dry or wet form, etc.). AVAPCO's AVAP process is the only nanocellulose process that produces either cellulose nanofibrils or nanocellulose crystals; hydrophobic or hydrophilic varieties; and slurry, dry concentrate, or masterbatch form. Different engineered forms are used for their unique properties in different applications. Our previous DOE Peer Review focused on the jet fuel production process. For this Peer Review, we focused on our recent, exciting developments in the nanocellulose dewatering and drying funded portion of the project, including our product launch and commercialization efforts for low-rolling-resistance tires. The cellulose intermediate from the AVAP process can be spilt across nanocellulose and jet fuel production according to market conditions. In the near term (5–10 years), AVAPCO's BioPlus nanocellulose market size estimate is 53,000 tons/year for products currently under development with partners in fields including high-strength and high-barrier plastic food packaging, paperboard, tires and rubber goods, and reinforced automotive plastics. The U.S. Forest Service estimates the total annual U.S. market potential for nanocellulose to be 6.5 million metric tons and 35 million metric tons globally. BETO strongly supports high-value coproduct technical and market development initiatives for de-risking and incentivizing biofuels production (https://www.energy.gov/eere/bioenergy/bioproduct-production).

RIALTO ADVANCED PYROLYSIS INTEGRATED BIOREFINERY

Rialto Bioenergy Facility LLC

This project did not present at the 2021 BETO Peer Review.

WBS:	3.5.2.601
Presenter(s):	Yaniv Scherson
Project Start Date:	01/15/2017
Planned Project End Date:	12/31/2021
Total DOE Funding:	$5,390,938



COMMENTS

- This project was not presented.
- This project declined to provide an update. This is unacceptable.
- This project failed to show or submit a presentation, and therefore it cannot be adequately reviewed.

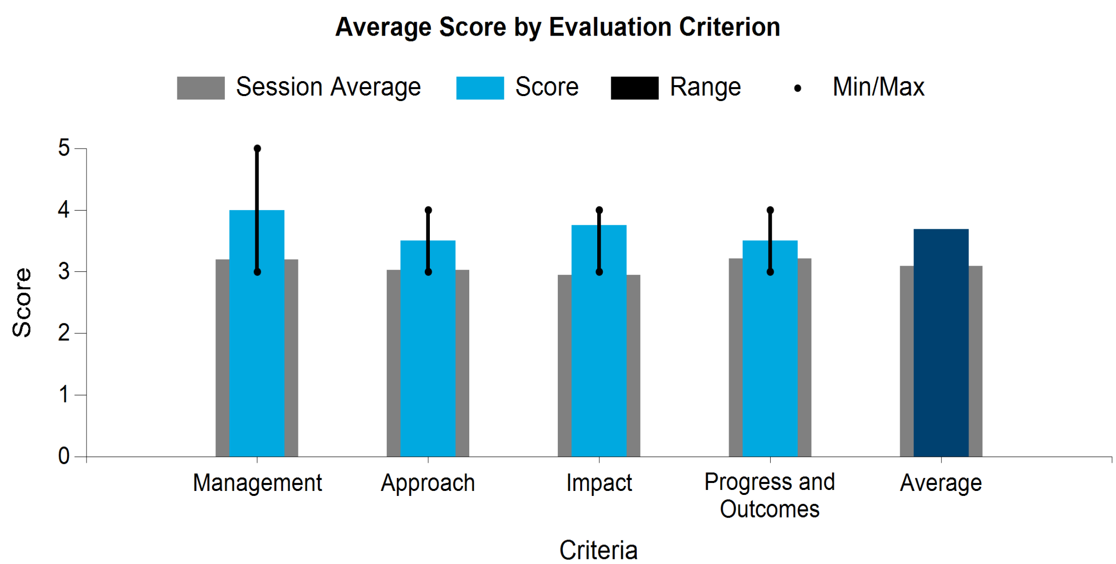
OPPORTUNITIES IN BIOJET: BASELINING AND EVALUATION

Sandia National Laboratories

PROJECT DESCRIPTION

WBS:	3.7.3.303
Presenter(s):	Anthe George
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2022
Total DOE Funding:	$1,249,747

Demand for liquid aviation fuels is currently 3.6 EJ and is projected to double in the next 30 years. In ground transportation, fuel use is expected to decline due to emerging technologies such as electrification or due to engine efficiency improvements; no such opportunities exist in aviation, with electrification limited to short ranges and limited efficiency improvements. There is thus a greater need, and a larger opportunity, to discover and deploy SAF. Barriers to deployment of SAFs include: (1) knowledge gaps in structure-function relationships, blending behavior, and decision optimization (i.e., identification of the chemical structures and blends that optimize performance); (2) high costs associated with producing/deploying new fuels with conversion routes that utilize lower-cost carbon sources; and (3) lack of understanding of the value conferred to industry by these SAFs. This project addresses aspects of each of these barriers as follows: (1) We developed and deployed predictive tools to identify promising SAFs and to optimize blends; (2) we produced promising SAFs from low-cost waste sources (in this instance, cycloalkanes and branched alkanes from alcohol intermediates and wet wastes); and (3) we conducted fleetwide analyses to understand the cost and emissions benefits to industry.



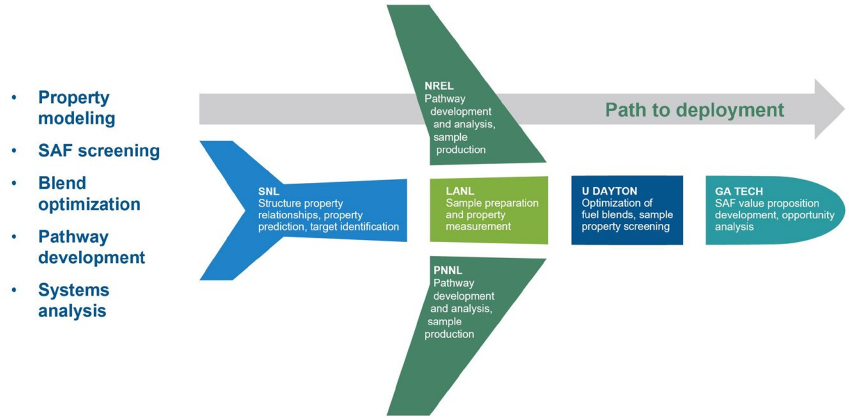


Photo courtesy of Sandia National Laboratories

COMMENTS

- This is an excellent project looking at different bio jet fuel options. The project looks at different aspects of the fuels and their production, including the targeted molecules and ASTM testing (excellent!). There is a limited (too limited, in my opinion) look at the processes and final products (one pathway through ethanol, one through fatty acids/ketones). The number and type of scenarios should be increased.

- The breadth of relationships is impressive, but it is not clear how much communication actually existed in terms of time/effort provided by partners. The tool to help determine the fuel properties of a blend prior to production or testing appears to be an excellent aid to industry. Although progress was noted in the presentation, the overall status of this tool was not made clear, nor how it will be implemented, nor its cost to industry. In general, tasks were so grand that the finish line was not made clear, and thus the overall status of this project is unclear. Metrics are needed to better evaluate and understand this project. This is an important project that could advance the adoptions of bio-derived fuels in aviation. This is a logical but complicated plan that is being well managed by the project manager. The project has achieved their milestones set out in the project plan to date.

- The objective of the project is good, but this reviewer found the presentation exceptionally difficult to follow. This may just be due to the ambitious nature of the project and its numerous successes, even though it is relatively new. The management section was good in that it listed the team and steering committee as well as some risks and mitigation strategies; however, it was impossible to understand what tasks were being done and what the overall plan was. A very high-level plan was outlined in the approach, but the milestones were so high level that they were not very useful. After reviewing the presentation several times, it is apparent that the team is making excellent progress toward developing screening tools for SAF blends and individual components, as well as identifying potential routes for waste to SAF. These tools should prove very useful to industry as well as SAF-focused projects within BETO. They have great industry involvement and are already widely disseminating their results. Achievement of the overall goals would have a significant impact, and this early-stage project looks likely to get there.

- This is an excellent project that is clearly consulting with industry and developing a useful tool for application upon project completion. More information on fuels selection would be helpful, especially with regard to source variability and the impact on output from the tool. There is an excellent management plan with very good communications with industry, risk analysis, and mitigation, and an implementation plan.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their efforts to review our work and for their insightful comments. In general, omissions in the presentation were due to the need to capture the work of the six different partners in the limited allotted time. We hope our response provides clarification to the key points raised by the reviewers as follows.

  With respect to the limited number of pathways being evaluated and the fuel selection: The project is attempting to balance the breadth and depth in terms of the number of pathways pursued versus the amount of process development and sample analysis on a given pathway. A significant degree of focus on a specific pathway is required to produce a sufficient quantity of output for the subsequent ASTM testing to be performed, and this limits the number of pathways that can be pursued. We should emphasize that the ATJ and volatile-fatty-acid-to-jet chemistries allow for a range of feedstock compositions, and the presentation may not have made clear enough that these pathways are not restricted to one specific feedstock each. For example, the PNNL process can accept ethanol, wet ethanol, higher alcohols (e.g., propanol), acetaldehyde, ethyl acetate, and acetone-butanol-ethanol as intermediate feedstock. The intermediate can be individual oxygenate or any combination of the mixtures listed. Additionally, the starting feedstock can be MSW, forest and agricultural wastes, industrial off-gas, and biogas. Simply any material that can be gasified can be utilized to produce ethanol. Similarly, the volatile-fatty-acid-to-jet process can accept a range of inputs, and a significant degree of tunability of the outputs can be achieved. Additionally, the team is considering options for analyzing other processes as part of the scope of work for the remaining duration of the project.

  With respect to the status of the tools and processes: At present, there are (1) tools in further development to focus the compositions of pathways to meet ASTM qualification, (2) pathways under development, and (3) methods to quantify the benefit of SAF. (1) Tools to predict properties of SAF compositions exist, referred to by the Commercial Aviation Alternative Fuels Initiative as prescreening; however, much improvement can be made. Properties with significant variance by hydrocarbon class and carbon number are particularly difficult to predict, although tools do exist to produce predictions with their associated uncertainty quantification. The University of Dayton and Sandia National Laboratories are working to develop higher-fidelity prescreening tools. The reason is that SAF candidate evaluation requires substantially higher fuel volumes than typically can be produced in labs, meaning predictive methods with low-volume testing are critical to low TRL. (2) Georgia Institute of Technology is working to quantify the higher energy content of SAFs as they deploy. They take the Pareto fronts for drop-in fuels and propagate those properties to expected benefits in the reduction of fuel burn and increased payload. (3) Los Alamos National Laboratory, PNNL, and NREL are working toward developing SAF technologies. Fuels developed at these labs are sent to Los Alamos National Laboratory and the University of Dayton for prescreening to align compositions and properties to ASTM expectations.

  With respect to clarity around the interaction among partners: Through the monthly meetings and other channels of communication, the project partners share a great deal of information and coordinate activities as appropriate. This communication keeps the partners performing modeling aware of which species and properties are most important to model, and measurements that are being made are fed back to the process developers and modelers for improvement. The process of feeding back information within the project has led to important developments in how to best approach the development of new aviation fuels and how to characterize and model them to facilitate the rapid certification of new SAFs. At subsequent Peer Reviews, we shall focus on more clearly articulating information flow.

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:	04/30/2022
Total DOE Funding:	$1,249,747

This proposal addresses the large problem of particulate emissions for woodstoves through the use of swirling combustion. Emissions from woodstoves are a result of incomplete combustion. Gaseous hydrocarbons released by the wood fuel fail to be fully oxidized, resulting in the emissions of CO, unburned hydrocarbons, and particulate matter. This incomplete combustion is largely a localized phenomenon resulting from inadequate mixing of the fuel gas and oxidizer (air). Swirling combustion is used for mixing combustion air with fuel gasification products to achieve a more complete burn, thereby reducing emissions and increasing efficiency. Never successfully accomplished in wood-burning stoves, this novel innovation involves the swirling of inlet air as described in MF Fire's patent application, US 2018 / 0051886 A11.

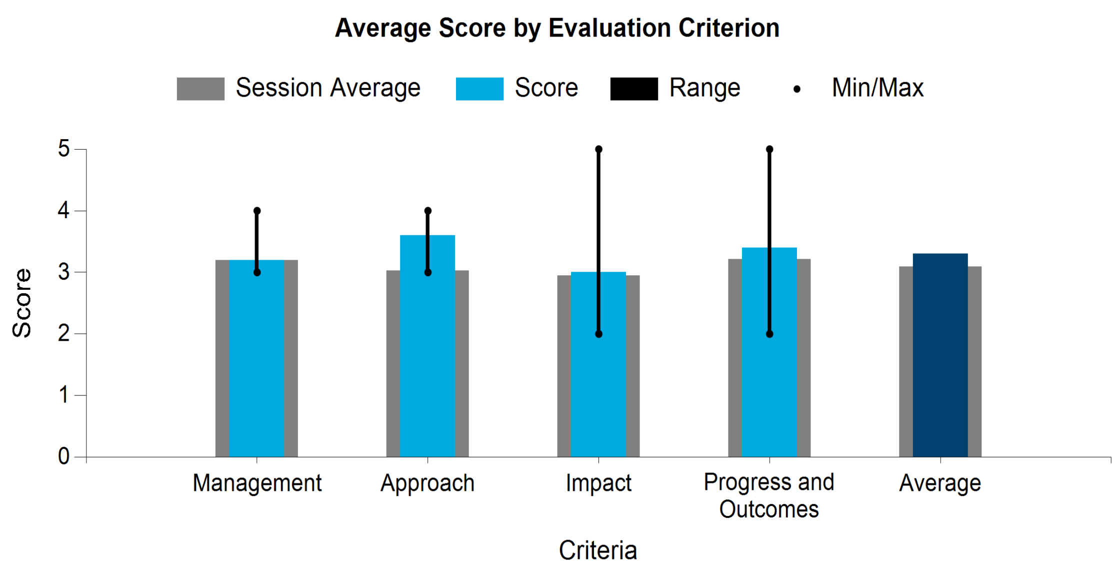


Photo courtesy of MF Fire, Inc.

COMMENTS

- This project focuses on the development of swirl combustion woodstoves for home use. Besides the large question of the appropriateness of combusting biomass for heat, the proposed technology looks to compete with catalytic solutions requiring the use of rare earth metals. There are some questions on focusing on project management versus also looking at CO in the exhaust. It is unclear how the developed CFD models are validated.

- At nearly 50% costed, the progress does not appear to be very good. The entire presentation contained no quantitative information; there is only one slide with some diagrams, apparently from CFD modeling, showing various swirl patterns. It is unclear what, if any, progress has been made toward actual success. The apparent price point of the types of stoves that might be built with this new information is beyond a great many homeowners, especially (I believe) those most likely to do a great deal of home heating with their stove. Also, some of the air quality concerns are likely (and in my experience) a result mostly of fireplaces, not woodstoves. Certainly, stoves play a role, but they could be substantially advanced in many areas without having much salutary effect on winter air quality. Safety concerns with primary/secondary air in a home stove without active monitoring and control were not adequately addressed.

- Safety appears to have been considered for this customer-facing product through adherence to existing standards. Although wood burning is a luxury in some areas of this country, the extent of particulate matter (PM) 2.5 emissions is still an important aspect to study and work on. “Wood” would appear to be specifically pellets because this system would require a feed-metering system, which are common in pellet stoves. It is not clear what the growth of wood-burning stoves is in the United States or how wood-burning stoves could be exempted from new rules being enacted with such items. The project cannot yet sustain the swirl combustion (definition of *sustain*), without which the project cannot proceed. It is not clear how close this project is to project prototyping or if the prototyping is not dependent on unknowns in the design at this stage. It is not clear why formal prototypes are in development if the swirl cannot yet be sustained. An overall project plan would have been helpful to understand the status of this project. Prototypes are being built, the theory is still being studied, and the validation plan is unclear. The project appears to be well aware of the risks involved and is trying to overcome them. I cannot fault the team for the difficult technical hurdles to overcome. Bravo for continued effort.

- The project is well managed and run and is a great example of a project with specific, realistic goals that could have immediate real-world impact. The only things that can be improved would be to better outline how the project is managed, including risks and mitigation strategies, and to see if you could improve on the solids combustion portion of the modeling.

- This is a good project, but it is lacking in detail for project management and implementation. There is no risk assessment and mitigation plan, nor communication with external partners that may be able to help with the complex modeling required. The impact appears limited because the final product will be beyond the budget of most people who use woodstoves for heat. Also, that group represents less than 2% of U.S. households (census.gov).

PI RESPONSE TO REVIEWER COMMENTS

- I thank the reviewers for their questions. I have organized the questions and answers into a single section, largely in order of the reviewers' questions.

  Fuel source: The swirl stove uses standard cord wood for fuel, not pellet fuel.

  Market size, growth, and trends: Woodstove use has been essentially consistent for many years, with 250,000 new stoves sold every year and 12% of U.S. households using a woodstove (2% for primary heat, 10% as a secondary heat source). States located in the Northeast have experienced substantial growth during the last two U.S. censuses, whereas other parts of the United States remain flat or slightly in decline.

  Woodstoves and regulations: All woodstoves are regulated by the EPA. The swirl stove would also be regulated by the EPA under the same regulations.

  Prototyping and definition: The questions around our initial prototype appear to be about the lack of a common definition. The dictionary definition and what we consider a prototype is a first full-scale model or functional form of a new type—in this case, a unit used to test various configurations following successful completion of CFD modeling.

  Project plan: A full project plan was submitted as part of the original application and is used to monitor progress in conjunction with our DOE project managers.

  Project status: The project is on target according to our project Gantt chart and SOPO. The project has met all milestones to date.

  Particulate matter versus CO focus: The BETO FOA objectives are tied to the reduction in particulate matter, not CO. This project looks to help with both, but our main success metric is reduction of PM2.5.

  CFD model validation and expert partner: CFD modeling is a well-known method for modeling complex systems. Cord wood combustion is a chaotic, constantly changing system—every burn is different. Modeling wood combustion using CFD is new. To achieve the best results, MF Fire defined the scope of the modeling to be performed and enlisted the consulting and CFD engineering assistance from a well-known CFD services organization. MF Fire provided the domain expertise for combustion science that fed into the CFD modeling provided by the outside firm to develop SOA combustion modeling for swirling combustion conditions.

Risks and mitigation strategies: A risk assessment and mitigation plan was submitted as part of the original application and is a required component that was evaluated prior to the project award. Little time was spent on reviewing this during the presentation because we focused on discussing the technical approaches, outcomes, and progress thus far.

Project expenditures: A reviewer was concerned with spending to date. The project is on schedule with our published SOPO milestones and project timeline yet 15% under budget.

Quantitative information and results: The project progress and testing produces extremely large 3D data sets that vary over time. The best way to share results is visually. Given the nature of this year's virtual reviews and bandwidth limitations, it was not practical to share time-series models of the results. The team selected images that best illustrate the key phenomena and results from our project thus far.

Price: The commercial price of the resulting product is expected to be consistent with the price of a low- to mid-tier-priced modern woodstove, but with superior emissions and efficiency.

Fireplaces are a bigger problem: Fireplaces were not a focus of this DOE BETO FOA. Woodstoves were the target and what this project was conceived around.

Safety concerns with primary and secondary air monitoring and control: Primary and secondary air inlets for any stove allow air to flow into a stove design, not out. All exhaust gases exit the stove via a venting system and are released into the air according to well-established codes. This stove is no different with respect to air control. Generally, inlet air may be passive or active (forced air). MF Fire is well experienced in both and is considered an expert in the field of woodstove design, having successfully designed several stoves certified by the EPA and UL testing labs using both passive and forced air designs. Part of this project is to determine which approach (passive versus active) and in what ratio (primary versus secondary) air needs to exist to create a sustainable swirling combustion, and if multiple configurations are viable, which is most viable for the commercial market, mostly in terms of cost.

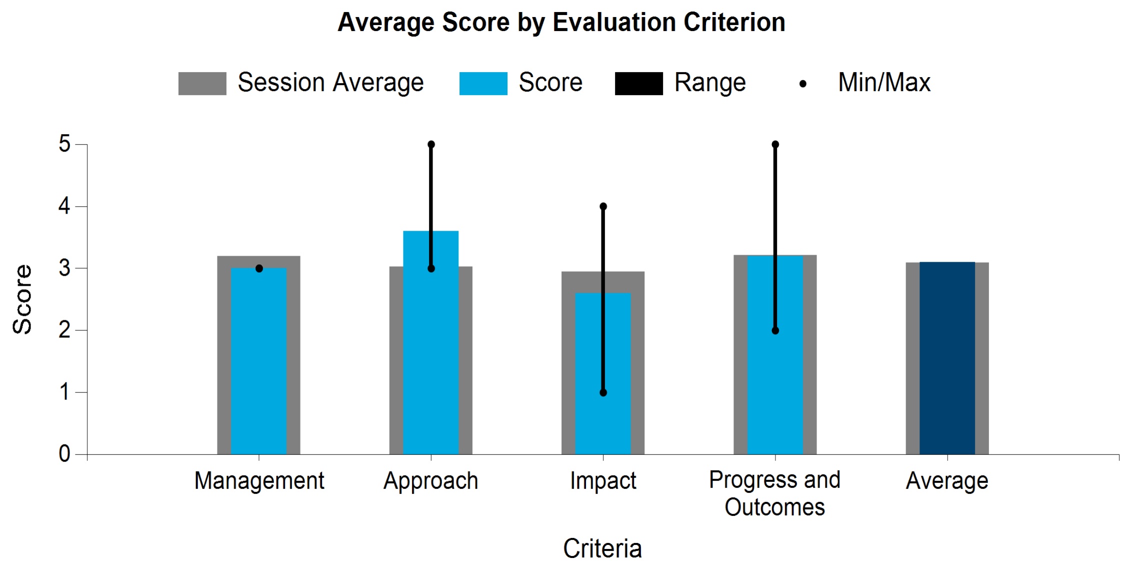
FIRE MAPS

MF Fire, Inc.

PROJECT DESCRIPTION

WBS:	5.5.1.103
Presenter(s):	Paul LaPorte
Project Start Date:	10/01/2019
Planned Project End Date:	07/31/2022
Total DOE Funding:	$1,245,144

The Fire Monitoring, Alerts, and Performance System (MAPS) solves the large-scale problem of user-contributed emissions for woodstoves. MF Fire proposes to create a unique, commercially viable technology for woodstoves, called Fire MAPS. Fire MAPS continuously monitors the performance of key combustion indicators in the woodstove and delivers real-time user guidance and burn status to the user. In turn, the user interactively learns how to properly control the woodstove throughout the life cycle of a fire. Stove users, equipped with timely guidance based on real stove performance data, can optimally operate the woodstove as it was intended, thus resulting in lower emissions and increased efficiency. Based on user-contributed emissions research, we anticipate a 5–8-gram/hour reduction of real-world emissions per stove, a far greater reduction than can be achieved by stove design improvements of new woodstoves.



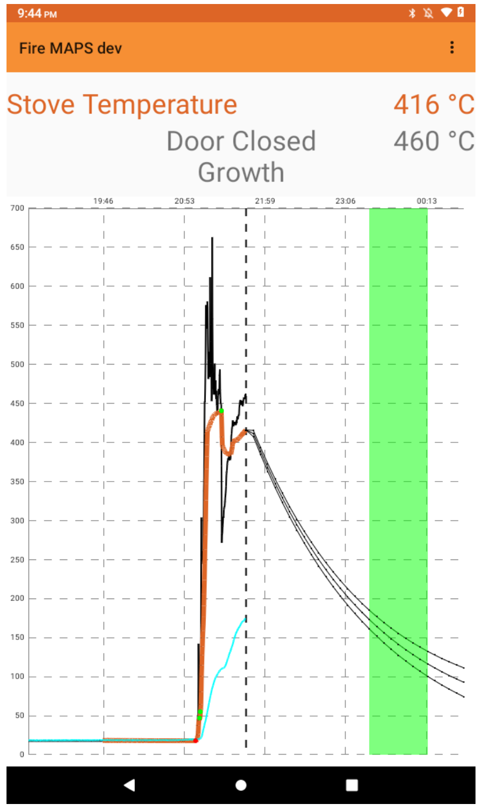


Photo courtesy of MF Fire, Inc.

COMMENTS

- The project is looking to avoid user error and underperformance for household woodstoves via sensors and phone applications. Besides the large question of the appropriateness of combusting biomass for heat, it is unclear at this size and ability whether it will penetrate the target market. The proposed approach relies on advice to the user from passive sensor and data analysis from cloud-based models. It is quite unclear on the impact, even with technical success.

- Twelve million woodstoves, many of which are only part-time/backup, is not a large market segment. The goal of achieving what is possible with the current technology (i.e., match the lab-tested performance) is laudable, but there are several obstacles. People need to *care* enough to make the necessary adjustments, and it needs to be *easy* enough for them to make them. Also, the value of a phone application versus an on-stove system with audible alarms is debatable. At the very least, there should be both. There are concerns about the Internet of Things with regard to privacy and security. A device that could, in the worst case, cause a fire or a CO poisoning event would seem to be especially sensitive. A hacked application could potentially ignore hazardous conditions or even actively advise users to create such conditions. It is unclear if the tests were on a randomized, "blinded" sample. If not, the results as applied to the public could be very different.

- On the surface, this project appears poised to have a significant impact; however, there is not a clear quantification of the market; no clear path to significant impact; zero risk mitigation (communicated); and with all Internet of Things applications, there is a significant privacy risk that may prevent end-user application.

- The product development strategy of the user interface was noted to be in development—with its associated wire frame, clickable prototype, surveys conducted, contextual interviews, etc. The plan has an alpha and beta validation plan that is a future part of this project. The overall validation plan would have been helpful to add to the presentation. The selling point to customers was not made clear, nor was the price point. If the selling point is purely about being "greener," the user interface needs to better reflect that message, similar to a Nest thermostat. The dependence of the product on the technical setup of the unit was not clear. It seems this setup would be required to be preinstalled and could not be sold easily as an aftermarket product. The application of this product could be expanded to pellet stoves and grills. The project has identified the root cause of higher emissions than tested in labs—human interaction—and this product, if utilized, could reduce that difference. The project has not identified *how* to influence users to utilize the product, even if offered. The project appears to have a working prototype of a unit, but the overall product development schedule is significantly longer than normally required. Significant effort is still needed to bring the product to market. The overall status of the project compared to the plan was not provided.

- This is a very well-thought-out plan and with significant achievable goals that are being evaluated in real-world situations with industry. The real-world data will be especially useful, and it is great that it will be broadly shared. Learnings from the process of obtaining, integrating, and interpreting consumer data could be useful in other areas of the program. The management plan with risk mitigation should be outlined better.

PI RESPONSE TO REVIEWER COMMENTS

- I thank the reviewers for their questions. I have organized the questions and answers into a single section, largely in order of the reviewers questions.

  Price: The target retail price is estimated at $149.

  Customer value proposition: The value propositions for consumers are: (1) lower fuel costs with a sub-year ROI; (2) less work chopping, stacking, and moving wood into the home, especially during winter; and (3) for those who value it, improved environmental impact or their own air quality. For air quality groups and government organizations, the value propositions are: (1) reduced emissions, especially PM2.5, in areas with high concentrations of woodstove users or in areas with inversion problems; and (2) achieving program goals.

  Technical setup: Fire MAPS is extremely simple to set up and use. It requires no specific knowledge or tools and takes uses less than 10 minutes to set up.

  Target use case: Fire MAPS is specifically designed and implemented as an aftermarket product, although can be used in conjunction with a new stove as well. The problems we seek to solve are the user-contributed emissions from existing woodstove use in the 100 million existing woodstoves. Only 3%–5% of stoves are replaced every year, making it essential to solve emissions issues in the installed base.

  Influencing user behavior: Influencing user behavior is a key to overall success beyond the technical capabilities of the solution to monitor and provide accurate guidance. Gamification techniques will be incorporated into the application experience and used to aid user adoption. By helping users get engaged and leverage competitive behavior, we can increase the level of participation, directly leading to greater program success and reduced emissions. Example techniques—such as those in review and travel sites such as Tripadvisor and Yelp—will be leveraged, such that participation or adherence to guidance leads to success badges and other emotional reward. Users will see messaging, such as their fuel cost savings and number of trips saved to get more wood; fun, informative, and motivating performance and improvement comparisons to other users and groups; and demonstrated benefits to environment.

Development schedule/overall status compared to plan: MF Fire remains on schedule as agreed upon in our project application, despite a year filled with challenging events that have derailed many other projects. MF Fire has successfully met all major milestones and passed all our go/no-go review checkpoints. The project is on track.

Market size: The total addressable market size is 100 million installed woodstoves, primarily in Europe and North America. The segmentation of this market can be seen in the article "Mapping the Performance of Wood-Burning Stoves by Installations Worldwide" by Ricardo L. Carvalho, using extensive data sets from the World Health Organization, available from the publisher Elsevier. The U.S. component of the overall market is 12 million installed woodstoves, which contribute 40% of all PM2.5 in the United States (cars contribute most of the rest)—the magnitude of the Fire MAPS potential impact is vast.

Ability to penetrate market and make impact: The proposed price point for this product falls in line with those of smart thermostats for use with other home heating, ventilating, and air-conditioning solutions. Adoption rates in that market provide an idea of potential adoption rates and challenges. The potential of the product to make a material difference in PM2.5 and other pollutants make Fire MAPS a candidate for various subsidies, further accelerating adoption. Up to 34% of total U.S. PM2.5 output comes from woodstove users operating stoves improperly or suboptimally. This user-contributed pollution is the single largest user-controllable source of PM2.5 in the country, one that Fire MAPS has the potential to eradicate. Even fractional adoption moves the needle, and we believe Fire MAPS can be widely adopted.

Real-world data and use: Fire MAPS represents a new, untapped source of data about woodstove burning habits. The data set will be unique and more comprehensive than any available in public or private. The existence of these data will provide government and academic researchers with unparalleled insights into how to improve outcomes, guide program dollars, or foster legislative activities.

Risk mitigation: We have completed substantial risk mitigation prior to and during the project, including the development of device security and privacy plans, third-party lab testing, phased rollout through two different test groups, and 6 years of operational performance of a similar digital system that monitors and automates stove operations without incident.

Ease of use/access: A reviewer commented about whether our use of a phone application versus an on-stove audible system is preferable, suggesting both at a minimum. This is a good observation, and although it is not covered in the review, it is a proposed component of the go-to-market planning. For the project, our focus was on a phone application to deliver the guidance and alerts because it provides guidance while the user is away from the line of sight or hearing of a stove-based notifier. The phone screen also provides for a richer user experience and can provide the gamification elements that likely would be absent from a simplified audible system. We are evaluating sound and light-emitting diode indicators for stove users who are not interested in using a phone or who live in an off-the-grid or no-cell-service area.

Security and privacy concerns: All Internet of Things devices must adequately address security concerns. Connected tools—such as Internet of Things devices, cell phones, computers, home security systems, or connected medical devices—must identify threat vectors specific to potential use cases and account for them as part of a security protocol. As part of our project application and verification process, we developed and provided a security and privacy plan. Our team's domain experience with online and cloud security helped us address this and plan for potential threats and concerns. We do not plan on Fire MAPS collecting or using personally identifiable information, but rather information about the frequency of use and types of stove-specific behavior that will allow us to steer a user to better operational habits. All information we are collecting falls outside of the definition of personally identifiable information and cannot readily be used to determine a person's identity. Fire MAPS provides access to real-time fire state information for users, which our solution uses to deliver guidance. Fire MAPS does not operate or automate the stove—a person continues to control the stove. Operational guidance is consistent with best practices in woodstove operation. We help a woodstove operator be more precise and timely with actions that have beneficial results. As with many guidance delivery systems, the user is ultimately responsible for basic operational knowledge. Fire MAPS is not intended to teach a novice user how to use a woodstove; rather, it will be clearly marketed as a decision aid to provide users with additional information to which they currently do not have access.

ADVANCING WOOD HEATER EVALUATION METHODOLOGY FOR ACCELERATING INNOVATION

Brookhaven National Laboratory

WBS:	5.5.1.105
Presenter(s):	Tom Butcher
Project Start Date:	09/30/2019
Planned Project End Date:	09/29/2022
Total DOE Funding:	$360,000

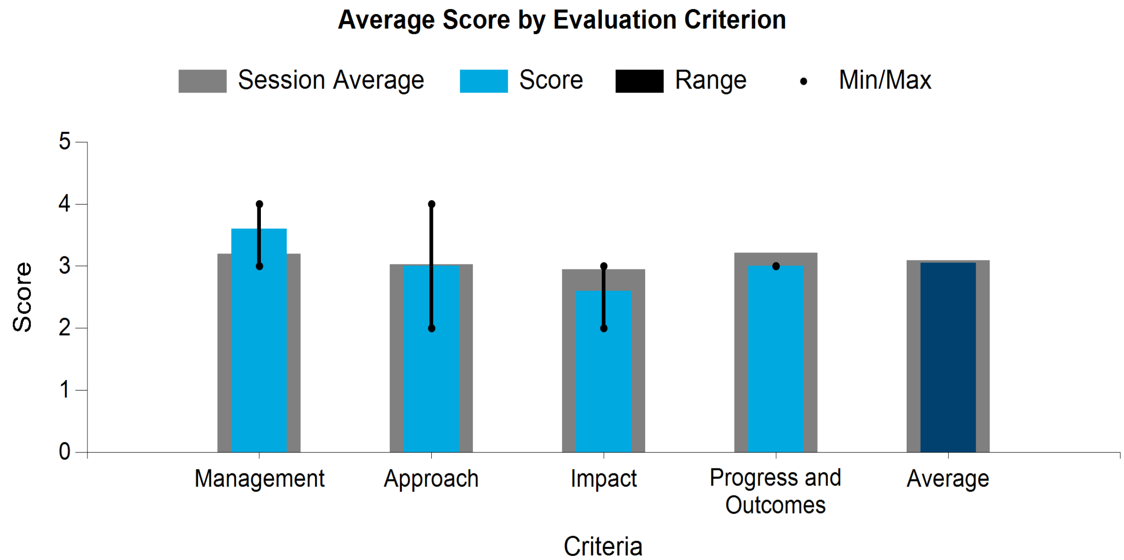


Photo courtesy of Brookhaven National Laboratory

COMMENTS

- This is an interesting project on low-cost methodologies to test woodstoves in their development. Higher-level analysis on the resource effects of using woody biomass for residential heat is needed from BETO. More context on drivers for testing (policy?) are needed.

- This is an interesting project, but the presentation does not clearly answer who will benefit the most: Is this guidance for an external/third-party lab? Is this a roadmap for industry to do their own (preliminary) tests? It seems to be more about accelerating preliminary testing for new wood heater designs than directly impacting BETO's goals.

- Great job obtaining multiple industry representatives in this work. The project recognized the inherent need to get buy-in for what they are proposing so that the goal of increased innovation can be realized in industry. The project is addressing a first-principles-based problem that innovation is lacking (in part) due to the expense of testing required for said innovation. Remove the barrier. Great approach. Although particulate matter emissions reduction is not the direct goal of BETO, it still fits within the overall mission to replace oil and gas with cleaner energy sources. Woodstoves may become banned if particulate matter emissions cannot be reduced. The result of such a ban would be more oil and gas furnaces. The overall state of development was not made clear in the presentation. It is unclear if the group is actively presenting work and working with ASTM and other groups. It is unclear how many innovations have been stalled by the cost of testing or how many are underway. Really, no examples are provided that demonstrate the hurdle discussed as the issue. The typical cost of ASTM testing ($25,000 is noted, but how many are typically required per invention?) was unclear in its typical total cost compared to the overall cost of development for these innovations. Additional focus would be beneficial to highlight the impact.

- The project has a very good overall objective. The impact of this work is difficult to assess because although it is noted that certification tests are expensive and time-consuming, there is no documentation of the impact of this—e.g., cost, number of new stoves that do not come to market due to difficulty. This information would help underscore the impact of this work. The management plan should also be better developed. The risks shown appear to be the reasons for the work, not the risks in the work being performed. It would also have been good to see more of the overall project plan. The team has made good progress, but the information from the working group will be critical to ensuring that the path and results are on target. It seems that an online workshop could be held prior to the end of 2021, and I would ask the team to consider moving this forward as far as possible.

- This presentation had the worst audio quality of the entire Peer Review. It was unintelligible, so my review had to be completed from the slide deck alone. Was the audio reviewed in advance of the meeting? The management plan is superficial. Where is ASTM involvement? There should be consultation/review at least, even if not active collaboration. It is unclear how the air quality issues depend on woodstoves versus ordinary fireplaces. In my experience, the latter are often more of the problem, in which case addressing the former may have limited benefits. It was hard to assess, especially with the garbled audio, exactly how much progress had been made. The only actual data presented (slide 13) appear to come from a 2017 publication.

PI RESPONSE TO REVIEWER COMMENTS

- On behalf of the entire project team, we thank the reviewers for their efforts and many helpful comments. Several comments addressed the development process in industry and the impact our work could have on that development. In the United States, a few manufacturers are relatively large, but most are small. Until recently, the development of new products has been influenced by an approach that it is at least as much art as science, and the industry has not, for many years, faced strong regulatory challenges to produce low-emissions products. In relatively recent changes, however, the industry now faces new challenges because the EPA has recently set new emissions limits on products while also expanding emissions limits into classes of biomass-burning appliances that have not been regulated in the past. Further, states increasingly recognize that direct biomass thermal systems contribute strongly to their failure to meet ambient air quality standards. States also recognize that current emissions testing methods are not leading to the differentiation of products that are always actually cleaner. There is presently considerable pressure for new test methods that are more representative of how these stoves, furnaces, and boilers are actually used in the field. As pointed out by the reviewers, unless manufacturers begin to offer cleaner products, an expansion of current regulations that ban or limit the use of these systems is likely to occur. Also, European manufacturers, which have faced low-emissions limits for a longer time, have developed new products that can perform better than traditional U.S.-made products, and this presents somewhat of a competitive challenge. In response to all these challenges, U.S. manufacturers will need to improve their understanding of how to economically burn these fuels with lower emissions. Part of this will be more research on combustion processes, and the DOE BETO FOA process for wood heater innovation is helping manufacturers partner with universities and other groups not traditionally engaged to develop new technologies. The new measurement tools being developed in this project complement the FOA and will help all manufacturers involved with biomass thermal heaters better understand the impact of their innovation concepts on emissions and on potential scores in both existing and emerging test methods. This will reduce the cost and accelerate the pace of innovation. As noted by the reviewers, the project team is deliberately engaged with industry to ensure that this work will provide the support that they need, and in a manner suitable for their use. One reviewer suggested that an industry workshop be held in 2021, even if virtually, and we are planning to move forward with this excellent suggestion. Another comment suggested we work with ASTM. This organization develops formal certification test methods. Although it is the case that we are using some of these methods in our own work, and that we have collaborated in the past with ASTM on test methods, we have made the conscious decision to avoid direct involvement in the formal certification test method process because this is really an area the EPA oversees. This is an area that is now in transition, and we realize that our tools must be flexible enough to work with essentially any test method. Finally, we would like to strongly apologize to the reviewer who had problems with the audio on our presentation. We understand this is annoying and makes it very difficult to follow the subject being presented. These types of prerecorded presentations are being used increasingly at virtual conferences, and we will strive to minimize such issues in the future.

U.S. DEPARTMENT OF ENERGY

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DOE/EE-2576 · June 2022