SYSTEMS DEVELOPMENT AND INTEGRATION: SCALE-UP

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

The Systems Development and Integration – Scale-Up Portfolio (SDI-SUP) Technology Area is one of 12 technology areas reviewed during the 2023 Bioenergy Technologies Office (BETO) Project Peer Review, which took place April 3–7, 2023, in Denver, Colorado. A total of 28 presentations were reviewed in the SDI-SUP session by five external experts from industry and academia. 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 (www.energy.gov/eere/bioenergy/systems-development-integration-scale-portfolio).

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $93.7 million, which represents approximately 17% of the BETO portfolio reviewed during the 2023 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 approach, impact, and progress and outcomes. This section of the report contains the Review Panel Summary Report, the Technology Area Programmatic Response, and the full results of the Project Peer Review, including scoring information for each project, comments from each reviewer, and the response provided by the project team.

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

SYSTEMS DEVELOPMENT AND INTEGRATION – SCALE-UP PORTFOLIO REVIEW PANEL

Name	Affiliation
Ray Miller*	Verdecute Consulting
Joaquín Alarcón	Catalyxx Inc.
Susan van Dyk	University of British Columbia; SVD Consulting
Mary Dinh	Avangrid Renewables
Siva Sivasubramanian	Independent consultant

* Lead Reviewer

SYSTEMS DEVELOPMENT AND INTEGRATION – SCALE-UP PORTFOLIO REVIEW PANEL SUMMARY REPORT

Prepared by the Systems Development and Integration – Scale-Up Portfolio Review Panel

INTRODUCTION

The SDI subprogram was reviewed by a team of industry subject matter experts at the request of BETO management. The projects reviewed covered a wide range of areas, including:

- Project risk management
- Biomass pretreatment equipment improvements
- Adding value from lignin market development
- National laboratory process development and demonstration facilities
- Algae deployment
- Bio-based alcohols to advanced fuels
- Biomass processing to advanced fuels
- Biogas processing to advanced fuels.

STRATEGY

The BETO 2023 plans and strategies across the portfolio are strongly consistent with the current national goals for climate-impacting carbon emissions. The primary concern of this review panel centers on the robustness of the technologies being developed, which need to be both effective and economic to ensure implementation. This concern points to the need for a critical assessment of the funding and probability of success for each program so that a go/no-go decision can be promptly made before the demand for resources starts to dramatically ramp up.

The SDI portfolio has a clear set of goals and targets. It has significantly benefitted from industry and stakeholder input during the past few years, and now it is focused on greenhouse gas (GHG) emissions reduction projects that will greatly impact the development and scale-up of technologies to produce sustainable aviation, rail, heavy-duty transport, and maritime fuels versus light-duty vehicle transportation fuels, especially gasoline. That seems to be an appropriate shift due to the increasing emphasis on more widely available and effective electrification technology for cars and light-duty trucks; however, it should not be at the total exclusion of gasoline replacement and use reduction opportunities to improve average passenger car fleet mileage through other means, such as light-weighting, that use more mature technologies and do not require the extensive infrastructure investments that large-scale electric vehicle employment will require. Fuel additives and engine improvements would also fall into that category because the return on investment would be quicker.

Another important gap that is being addressed in the future is the decarbonization of chemicals and materials. There are many challenges in attempting to convert traditional plastic and chemical products into renewably sourced materials, especially matching the cost and quality of existing products; however, some newer bio-based materials are under development or are recently launched that combine renewable content with advanced performance. Examples include Sorona (polytrimethylene terephthalate) as a partially renewable replacement for nylon 6 and polylactic acid as a renewable replacement of disposable packaging and implements from polystyrene. There are other valuable bioproducts/chemicals in development, and if at all possible, they should be supported during their early stages.

Funding for these new, first-of-a-kind technologies has always been a challenge, so the selective use of both funding opportunity announcement (FOA) and annual operating procedure funding mechanisms is necessary to support and leverage developments in that area. In addition, feedback from industry and subject matter experts should continue to be a critical assessment tool to ensure that progress is made and that projects that are not performing are curtailed.

There is clear evidence that most, although not all, the projects currently funded in this technology area are making good progress toward the established goals, although meeting them on the desired timeline will be quite challenging. More focus on the projects that are nearer to implementation may be needed, even at the expense of some of the more innovative but less probable for success projects. Active management of the programs is necessary to ensure that short-term deliverables are obtained considering the looming crisis of global warming.

There should be increasing focus on selecting and scaling up new technology to address major gaps in sustainable fuel production as well as bioproducts, and implementation is necessary to meet climate change goals. Leveraging public and private investment in developing and proving out these technologies is an effective way to fund them. Pilot and precommercial demonstration units are critical to proving that these technologies are robust and to meeting the goals of these projects. These projects must be encouraged to use the resources of the national labs to capitalize on the already developed infrastructure and experienced resource pool. Using outside expertise to evaluate progress is an essential tool to objectively critique programs. The SDI portfolio is a good start.

STRATEGY IMPLEMENTATION AND PROGRESS

Detailed comments on each project are included in the body of this report. Selected comments on each major area are summarized in the following overview. The portfolio of projects is quite comprehensive, and good progress is being made in most areas.

Project Risk Management

The SDI's project success rate can likely be improved by implementing a uniform framework that focuses on risk identification and mitigation as well as maintenance of a risk register for BETO's scale-up projects. The framework should consider various types of risks—such as technical, implementation, unforeseen events, and the identification and allocation of resources—along with cost (on-budget) and timeline (on-schedule) risks. Standards used by the chemical, engineering, and aeronautical industries could be incorporated into the calculation methodology. Based on the risk score, only projects with acceptable risk levels should be selected for implementation. SDI has supported "Risk Management Program for BETO Scale-Up Projects" to develop a uniform process for risk management. After the completion of this project at the Pacific Northwest National Laboratory (PNNL), the developed tool should be made available to all FOA submitters, and funding should include a contingency budget (e.g., 15% of the requested budget) for any unforeseen risks. As identified risks are mitigated, the contingency budget could be accordingly reduced. Additionally, tasks should be included in this project for technology transfer efforts, especially to the SDI team. BETO would greatly benefit from the implementation of this risk management framework to ensure the successful scaling up of projects.

Biomass Pretreatment Equipment Improvements

Modeling the disc refiner is very useful and informative, provided that the operation of the disc refiner can be tested at conditions that would be used in a biorefinery, such as with actual feedstocks and solids concentration. This will identify whether the improvements in sugar yield and energy consumption will still be achievable at relevant conditions. Also, it would be useful to observe disc deterioration and performance over lengthy periods of time.

Similarly, a very systematic approach to selecting and improving the materials of construction of the Szego Mill rollers to improve wear and corrosion resistance is proving useful. An additional benefit of this work might be noise reduction for this unit operation. This kind of analysis would be useful for any other pretreatment unit operations that are subject to mechanical wear or corrosion damage. It might also be useful to consider other materials of construction, such as advanced ceramic composites, which are both tough and unaffected by corrosion; however, several questions still remain about this unit operation, for example, whether the conditions of high speed and tight clearances are causing cavitation, which might impact wear and noise. A different configuration might allow for higher residence time, thus allowing for slower and less damaging speeds.

Added Value from Lignin Market Development

Adding value above fuel value to the lignin can significantly increase the investment return for biomass-fed processes; however, separation of solid lignin from the cellulosic components presents a significant operational challenge. The deacetylation and mechanical refining (DMR) process is showing promising results in laboratory and pilot-scale studies. The separation of sugars and solids before fermentation may be necessary to optimize the fermentation process efficiency because lignin can hinder the fermentation process by binding to microorganisms and thus inhibiting their growth. Additionally, sugars in the solid fraction will not be readily available for fermentation, resulting in lower product yields. Although there is a potential loss of sugar during the washing of solid lignin, efficient separation processes can minimize this loss. The concentration step following the washing can increase the sugar concentration of the feed to a fermenter, resulting in higher product yields. Clean lignin isolation opens possibilities to convert cyclohexanes from phenolic compounds in the lignin fraction of corn stover after DMR, providing an important blending component for sustainable aviation fuel (SAF) in place of aromatics. In another project, a pilot-scale hydrothermal process produced high-value biocarbon and carbon nanofibers. These are all promising options for adding value to lignin after extracting the sugars from biomass.

National Laboratory Process Development and Demonstration Facilities

The national laboratories reported on efforts to expand their equipment and expertise in biomass sorting, processing, and conversion processes. Consistent feedstock handling and feeding remain significant challenges in biomass projects, and leveraging the expertise of engineering firms and equipment vendors in collaborative engagement projects will improve feedstock preprocessing, particularly in the area of densification, to ensure a consistent and stable feed for end users. PNNL's hydrothermal process development unit (PDU) provides a valuable facility for testing, scaling, and commercializing hydrothermal projects and valorizing wet waste feedstocks. PNNL has learned from tar sands for solids separation and wastewater treatment plants to eliminate heat exchangers and their associated fouling problems. Similarly, the National Renewable Energy Laboratory's (NREL's) Thermal and Catalytic Process Development Unit (TCPDU) is a valuable resource that enables research and development (R&D) for developing, de-risking, and scaling thermochemical conversion processes, which are capital-intensive steps. Continued investment to maintain the TCPDU as a state-of-the-art (SOA) facility is a key component of developing large-scale biofuels and the biochemicals industry. Idaho National Laboratory's (INL's) Biomass Feedstock National User Facility (BFNUF) provides a valuable facility for feedstock testing, handling, scaling, and de-risking the commercialization of biochemical conversion. Continued investment to upgrade all these facilities with SOA technologies is a well-spent investment to continue innovations and the commercialization of biochemical conversion processes.

Algae Deployment

The use of algae as a means to capture carbon dioxide (CO_2) and generate feedstock for biofuels and bioproducts has gained significant interest due to an improved algal growth rate, higher lipid content, and ability to grow in a variety of environments. New technology to dry and extract lipids and meal from algae are also helping to grow this approach; however, there are still concerns with respect to water use, water recycle after separation, and land use that remain to be answered. Also, the cost of producing biofuels from algal biorefineries is currently prohibitively expensive, which limits the impact as well as the widespread adoption of this technology. These challenges will need to be addressed to ensure that the industry is sustainable and does not negatively impact other sectors, such as agriculture.

Bio-Based Alcohols to Advanced Fuels

Meeting the goals of the advanced fuels, such as SAF, or other sustainable advanced fuels, such as low-sulfur diesel, will require the development of low-cost cellulosic ethanol. One option being explored is using energy-dedicated feedstocks, such as miscanthus, grown on marginal soils. Another option being worked on involves upgrading the alcohol to 2,3-butanediol (BDO) and then converting it to SAF. The lack of success of previous commercialization of cellulosic ethanol has spurred the development of the DMR process, which has been demonstrated with clean feedstock of consistent quality, but this is an ideal situation. It is well documented that feedstock harvesting, storage, handling, high contaminants, and inconsistent quality caused some of the most important challenges and impediments to the commercialization of cellulosic ethanol.

Biomass Processing to Advanced Fuels

Various projects are exploring thermal processing to break down biomass into fractions that can be upgraded to advanced fuels or other products. For example, the integrated hydropyrolysis and hydroconversion (IH^2) process appears to have been successful for the feedstock used (wood). Another project using wood builds on the pulp and paper industry by separating clean cellulose and hemicellulose to make nanocellulose and clean sugars for biochemicals. Still another project is developing fast pyrolysis of municipal sludge to create syngas and biochar for land remediation. All these are exploratory in nature, and some may result in value-added applications.

Biogas Processing to Advanced Fuels

There is a large and growing effort to produce and/or convert biogas or equivalent into syngas for the production of liquid fuels, particularly advanced fuels, such as SAF or diesel. Some of these projects focus on smaller conversion technologies compatible with distributed sources of biogas, such as anaerobic waste digesters or landfill gas. Novel electric reformers, cooler-operating catalytic Fischer-Tropsch reactors, and other catalytic reactors that combine several steps into significantly fewer unit operations are all being proposed and tested. Some of these processes have the potential to make a significant contribution to gas-to-liquids (GTL) options from waste gases.

RECOMMENDATIONS

The review team had a number of questions for the project leaders, and those are captured in the individual remarks by project. In addition, the review team offers a number of recommendations for consideration by BETO management in evaluating and funding future projects in this area.

Recommendation 1: Add more resources to programs designed to more effectively recover and recycle plastic waste.

One major area of opportunity that seems to be under-resourced is in the reclamation and recycling of plastics. The sources of these plastics could come from municipal solid waste (MSW) and recycle collection centers. Only a minor portion of these materials are recycled today, and there is a growing problem of microplastics in the environment, in addition to the growing use of new fossil carbon to manufacture plastics. In addition, there are decades of MSW buried in landfills, which represent a significant opportunity.

Recommendation 2: Put more resources into recovering CO_2 from concentrated sources for use as feedstocks.

Another area for GHG reduction would be to separate CO_2 from concentrated emission sources, point sources, and collection points at landfills (in addition to CH_4) and effective utilization of the recovered carbon (CO_2 and CH_4) into materials, thereby replacing those currently produced from fossil sources. There should be emphasis on using renewable electricity for these projects.

Recommendation 3: Require biomass-to-fuels programs to use real feedstocks from multiple sources and during the course of a harvest cycle.

Many of the biomass-to-fuels projects are not yet addressing the fact that biomass is highly variable and very unstable for mid- to long-term storage. All the large-scale failures for cellulosic fuels hinge in part on the fact that the feedstock had significant handling characteristics and contamination or integrity (stability) during the course of an annual operation year. It should be a requirement for future funding that these projects conduct their testing and scale-up as soon as practical on real feedstocks sourced from many different locations and of different ages.

Recommendation 4: Devise funding approaches that make national labs more affordable for smaller users.

With all the national laboratories, the full cost of using their facilities and personnel for testing is quite expensive and is a barrier for smaller startups. It is recommended that the labs use formulas based on the ability to pay to make these resources more accessible to entrepreneurs and startup companies.

Recommendation 5: Implement high-level analyses of programs and their potential impacts to enable BETO management to have a more succinct and objective view of commercial viability to assist in ongoing funding decisions.

To gain a true perspective of BETO's programs as they relate to the advanced biofuels and bioproducts being targeted, it would be helpful to see a fairly complete mapping of all of the programmatic pathways that are potentially known or are being funded. In addition to a visual map, a spreadsheet of those pathways with the current state of completion, potential impact on total GHG targets, and financial metrics, such as net present value (NPV) and internal rate of return for investments, along with a technology readiness level (TRL) status and probability of success, would be helpful to the reviewers and especially to BETO management to facilitate a clearer picture of options, status, time, and money needed to ensure commercial viability. That approach will also help make decisions about how to distribute taxpayer funds toward projects in the portfolio, with projects that have a higher probability of achieving success gaining higher priority for funding.

SYSTEMS DEVELOPMENT AND INTEGRATION – SCALE-UP PORTFOLIO PROGRAMMATIC RESPONSE

INTRODUCTION

The SDI team would like to thank the SDI-SUP review panel for providing their time and expertise throughout the 2023 Project Peer Review process, including the critical and helpful interaction with presenters at the Project Peer Review, the Review Panel Summary Report, and the valuable project comments. We appreciate the review panel's comments that the SDI portfolio has appropriately shifted to technologies producing SAF and other off-road transportation fuels. The review panel commented that there are still means of improving light-duty vehicles. Activities like light-weighting are within the DOE Vehicle Technologies Office. Other solutions, such as bio-based fuel additives and engine improvements, are presently beyond the scope of BETO. From 2016–2022, BETO worked with the DOE Vehicle Technologies Office on supporting the Co-Optimization of Fuels & Engines (Co-Optima) consortium, which identified solutions, such as boosted spark ignition engines combined with bio-blendstocks with certain properties such as high octane, that could deliver 10% engine efficiency increases; with multimode engines, an additional 14% engine efficiency could be provided. These activities have been communicated to the private sector through meetings and webinars. Ultimately, DOE has decided that, to reach nationwide net zero by 2050 and considering that there is a limited amount of sustainable biomass, the pathways for decarbonization are electrifying the light-duty sector and using biofuels along with other solutions, such as hydrogen and batteries, for the medium-duty/heavy-duty on-road and off-road sectors. The focus on electrification for light-duty vehicles has been described by the recently published *U.S. National Blueprint for Transportation Decarbonization*. As an R&D office that cannot immediately deploy commercial solutions, BETO seeks end uses for sustainable liquid fuels that have the greatest long-term opportunity.

The SDI-SUP review panel noted that there is a gap in the SDI portfolio with a limited amount of attention paid to bio-based chemicals and materials. The SDI team notes that the 2021 SDI peer review panel commented that there may be too much attention paid to specialty coproducts; however, the primary reason for the shift away from bioproducts is an intentional BETO program move to prioritize biofuels for hard-to-decarbonize sectors—specifically for aviation as the highest priority and secondarily for marine, rail, and other transportation applications. The nuance of maintaining a portfolio with the appropriate balance for fuels and chemicals has long been a challenge for BETO. FOAs typically still allow for bioproducts, but there is clearer language designating a high priority for SAF and other strategic fuels; for example, often there is a project requirement that at least 50% of the carbon from the feedstock must be converted to fuel.

The SDI team appreciates the SDI-SUP review panel's detailed analysis of portfolio features such as project risk management, biomass pretreatment equipment improvements, lignin valorization, the national laboratory PDUs, algal deployment, alcohol-to-jet (ATJ) technologies, preprocessing and pretreatment with thermochemical conversion, and biogas upgrading to liquid fuels. The SDI team will act on the SDI-SUP review panel's concerns that some cellulosic ATJ projects are not sufficiently considering feedstock variability.

Following are the SDI team's responses to the review panel's recommendations. A common theme is that the review panel would like to see a wider range of feedstocks in the SDI program's portfolio. The SDI team is attempting to focus on feedstocks with the potential for delivering the largest resulting biofuel volumes from the wide range of available feedstocks across the U.S. biomass landscape.

Recommendation 1: Add more resources to programs designed to more effectively recover and recycle plastic waste.

In the SDI program's most recent FOA, which was released in Fiscal Year (FY) 2022, with selections announced in January 2023, sorted MSW, defined as organic and plastic constituents of the MSW stream going to the landfill, was an allowable feedstock. This was not always the case. For example, the SDI program's FY 2016 FOA did not allow MSW except for post-sorted MSW, where all recyclables and non-biomass components were removed. Nevertheless, despite the trend in allowing plastic waste feedstocks, the SDI team understands that the SDI-SUP review panel would be concerned that there is a lack of program activity focused on recovering and recycling plastic waste. BETO has focused these activities in the conversion program, which stood up the Bio-Optimized Technologies to Keep Thermoplastics out of Landfills and the Environment (BOTTLE) consortium to develop bio-optimized technologies for reducing thermoplastic waste. BOTTLE presented separately from the SDI program at the Project Peer Review. The SDI team will seek more engagement with BOTTLE to understand the TRL of the technologies under development.

Recommendation 2: Put more resources into recovering CO_2 from concentrated sources for use as feedstocks.

In the SDI program's FY 2022 FOA, waste carbon dioxide produced as a byproduct from fermentation or the combustion of biomass or other biopower processes was an allowable feedstock. Nevertheless, the SDI team understands that the SDI-SUP review panel would be concerned that there is a lack of program activity focused on carbon dioxide recovery and utilization. In terms of carbon dioxide capture from non-biogenic sources, the SDI teams notes that other DOE offices have led large efforts in recent years toward these activities. For example, the DOE Office of Clean Energy Demonstrations announced plans for $2.5 billion for carbon dioxide capture from natural gas and coal power plants and industrial facilities. In terms of using carbon dioxide as a feedstock, the SDI program recently awarded a project that will use biogenic carbon dioxide from ethanol fermentation as feedstock for biological upgrading. This award was made in 2023, so it was too soon for presenting at the Project Peer Review. Further, BETO has relied on the Conversion Technologies program to stand up the CO_2 Reduction and Upgrading for e-Fuels Consortium (CO_2RUe). The SDI program will seek more engagement with the consortium to understand the TRL of the technologies under development.

Recommendation 3: Require biomass-to-fuels programs to use real feedstocks from multiple sources and during the course of a harvest cycle.

The SDI program greatly appreciates the recommendation for projects to use feedstocks with wide variability. The SDI programs notes that typically projects acquire all feedstock early in the project and then store it until use. If it is possible and pending appropriations, the SDI program will consider that future FOAs stipulate that projects acquire feedstock throughout the project lifetime and from multiple sources/sites. The SDI program is actively responding by engaging with relevant projects and facilitating more collaboration with the national laboratories. Additionally, the SDI program is working with the Feedstock-Conversion Interface Consortium (FCIC) to facilitate conversations between the FCIC and pilot and demonstration projects using agricultural residues or woody feedstocks. The FCIC is jointly managed by the Renewable Carbon Resources, Conversion Technologies, and SDI programs. The FCIC is actively conducting R&D in feedstock variability and its impact on preprocessing, pretreatment, and conversion.

In addition, the SDI program is funding a new project at the national laboratories to explore the opportunities and challenges for envisioning a cellulosic sugars depot strategy to commoditize preprocessed agricultural residues. This project will include national laboratory experts to reach out and engage with industry experts on the SOA in managing agricultural residues.

Recommendation 4: Devise funding approaches that make national labs more affordable for smaller users.

Though this is an important recommendation, there may be limits to what BETO can do about making national labs more affordable for smaller users. BETO has conducted some limited funding opportunities that provide relatively small amounts of funding to be made available to assist small companies and local government entities. Further, BETO’s competitive FOAs often have clear language encouraging engagement with the PDUs at the national laboratories. If awarded, the project would then include funds awarded to the external user (applicant) as well as funds contracted to the national laboratory.

BETO also supports directed funding opportunities where funds are awarded to the national laboratory for solving a problem identified by an industry partner and where the industry partner supplies a cost share. The directed funding opportunities are often in other programs besides SDI, so the SDI-SUP reviewers did not see these projects. The SDI program will keep the directed funding opportunity approach in mind for future use.

Recommendation 5: Implement high-level analyses of programs and their potential impacts to enable BETO management to have a more succinct and objective view of commercial viability to assist in ongoing funding decisions.

In the last year, BETO supported an internal portfolio analysis led by the office’s chief scientist and chief engineer. The results have not been publicly shared, but this information provided a mapping of projects supported by BETO and their features, such as feedstocks, conversion process, and TRL. The SDI program also maintains other internal analyses to track project development. The review panel recommends including metrics such as NPV, internal rate of return, and GHG reductions. Under SDI FOAs, the project recipients are required to present forward-looking *pro forma* and environmental analyses. And the SDI program will seek to have these analyses updated and reviewed as the project progresses.

MODELING FLOW BEHAVIOR IN A DISC REFINER FOR DMR PROCESS

National Renewable Energy Laboratory

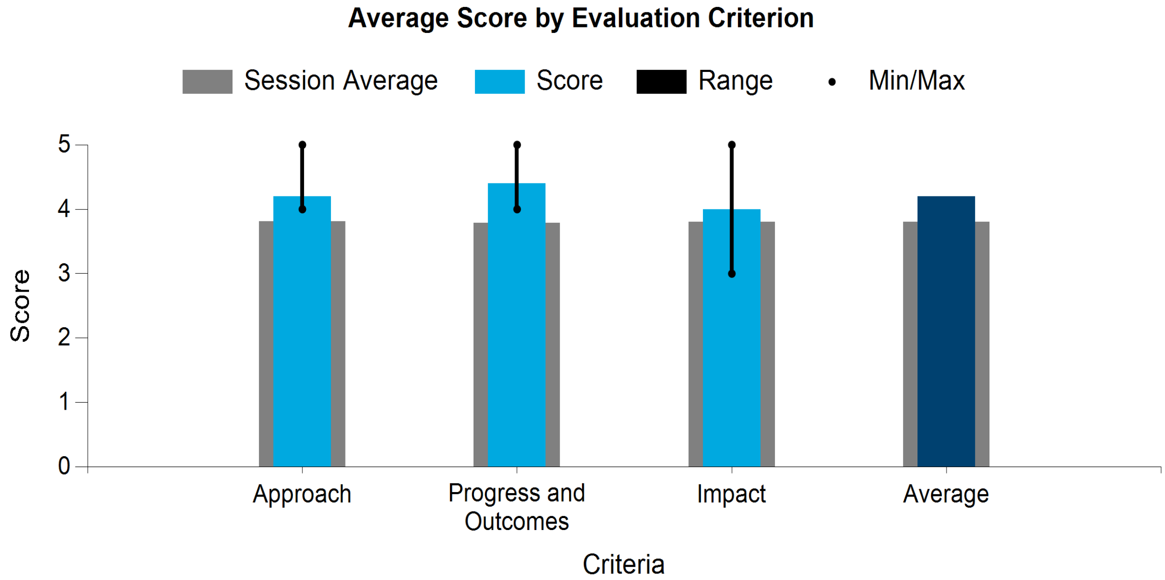
PROJECT DESCRIPTION

WBS:	3.1.1.012
Presenter(s):	Xiaowen Chen
Project Start Date:	09/03/2019
Planned Project End Date:	09/30/2023
Total Funding:	$750,000

The objective of this project is to develop 3D computational fluid dynamics (CFD) models that can accurately forecast refining power during disc refining. These models can then be used to guide future disc plate designs and process parameter selections, resulting in reduced energy consumption and GHG emissions in the DMR process; however, reducing the energy intensity of the mechanical refining-based pretreatment process while maintaining enzymatic hydrolysis sugar yields is challenging. To tackle this challenge, the research team examined the impact of different refining conditions on energy consumption, enzymatic sugar yields, minimum sugar selling price, and environmental impacts.

The team found that when changing the refiner gap, a positive proportionate correlation between specific energy consumption and enzymatic sugar yields was observed, which was consistent with other published works; however, changes in refining rotational speed and refiner plate design made the correlation between specific energy consumption and enzymatic sugar yields less straightforward. The team observed that by decreasing the rotation speed for low-consistency disc refining, specific energy consumption decreased by more than 50% without affecting enzymatic sugar yields. By changing refiner plate designs, the team achieved a 45% reduction in specific energy consumption without affecting glucose yield, although there was a negative impact on xylose yield.

Using a high-fidelity disc-refining model, the team could predict the energy consumption for different refiner plate geometry designs and operating conditions. The techno-economic analysis (TEA) and life cycle analysis (LCA) showed that the plate design and operating conditions have a direct impact on process power consumption and sugar yields, with sugar yields strongly influencing the minimum sugar selling price, the life cycle GHG emissions, and fossil energy consumption. To minimize environmental impact and maximize process economics, the mechanical refining process optimization should focus on maintaining high sugar yields while reducing refining energy consumption.



COMMENTS

- The DMR process is a promising technology NREL developed, and the disc refiner modeling work looks good. The obtained results in the modeling and the experimental results are very close; however, the DMR has not continuously worked with the DMR processing, and the difficulties of integrating two different systems (and, lately, the downstream processing) have not been considered.

  I believe that DMR is a promising technology, but NREL has not worked on the process's integration, which poses a question about the solution's scalability. I fear previous failures in scaling biomass treatment technology have not been considered. I want to encourage NREL to review what happened in the past and learn from it. The big issue is ensuring that you can process any corn stover and handle all types of impurities. Please be sure that you do not encounter the same issues as before.

  Another question is whether working with 3% solids in the disc refiner will demand high energy to separate products from the water. The disc refiner will need to work with much higher solid content.

- The project has successfully developed a CFD model that accurately predicts refining power (as shown by the validation against experimental data) and can be used to inform future disc plate designs. The impact of this project is reducing energy consumption and thus GHG emissions and economics of the DMR process for SAF/biofuels production. The CFD model will be useful for determining the optimal plate design for different feedstocks.

- This modeling approach to rotating equipment used in size reduction is unique and has produced good results, as verified by the actual enzymatic production of fermentable sugars as a function of milling energy use. A nearly 50% reduction in energy used with the same sugar production is very significant for biomass feedstock pretreatment. This modeling approach should be useful for studying different types of feedstocks being processed in different types of equipment to reduce costly and time-consuming empirical approaches, subject to experimental verification. It could also be useful to reduce noise in the processing area, assuming energy input reductions also lead to somewhat lower noise production.

- The modeling approach used in this study is unique and has resulted in a predictive model that has been validated against experimental data. Further work is encouraged to assess the model's accessibility and ease of use for a wider range of users. Friction generated during the refining process can contribute to the cooking of polymeric sugars, which may pose a challenge. Additional investigation is suggested to understand the extent of this issue. Most refiner plates have been developed for the particleboard industry, and their suitability for handling various agricultural and woody feedstocks, particularly those with high ash and silica content, remains uncertain. Additional testing will be required to assess their wear and tear under these conditions. Disc refiners have traditionally been used in the pulp and paper industry with wood chips containing up to 50% moisture as well as with softened wood; however, using corn stover with a moisture content of 15% and without precooking may impact the wear and tear of the refiner discs, and this needs to be investigated further. It is important to encourage greater industry participation in the development and implementation of biorefinery-specific plate manufacturing technologies.

- This project tackles an important component of the DMR process and involves the optimization of the disc refiner to achieve maximum sugar yields. The work that has been done has shown a clear improvement in sugar yields with an optimization and reduction in energy use. The experiments were carried out at low solids concentration (3%), which does not represent the industrial conditions under which the disc will be operated. Although it is outside the scope of the goal to model and optimize design and flow behavior, it would be very useful and informative if the operation of the disc at the optimized conditions can be tested at actual conditions, such as solids concentration, that would be used in a biorefinery. This will identify whether the improvements in sugar yield and energy consumption will still be achievable at relevant conditions. Further, although it is not part of this project, it would be useful to be provided with information on the disc deterioration and performance over lengthy periods of time.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate and value the feedback provided by the reviewer concerning our disc-refining modeling project. We strongly agree with the majority of the reviewer's comments, which highlight the significance of this project in reducing disc-refining energy and the associated GHG emissions for SAF production through DMR processes. As the project progresses, we plan to implement the reviewer's suggestions. One comment we received was that our experiment was conducted with low solids and does not accurately represent industrial conditions. Unfortunately, due to our current 12-inch disc refiner, we are unable to increase the solids; however, the installation and commissioning of the new 22-inch disc refiner at NREL will enable us to conduct experiments at higher solids with continuous flow. This will enable us to model the process with more realistic industrial conditions. Regarding the other comment on the integration of the disc refining with other process units—we are closely collaborating with the Sustainable Aviation Fuel From [i] Renewable Ethanol (SAFFiRE) project to integrate the disc-refining process with other unit operations to establish continuous operation. This will allow us to identify and address any potential scalability issues. Addressing the issue of disc plate wear is another important aspect that we plan to tackle in future iterations of the project. To achieve this, we will work closely with the FCIC to develop solutions that characterize and mitigate the effects of ash content present in agricultural waste, which has been identified as a leading cause of wearing problems during disc refining.

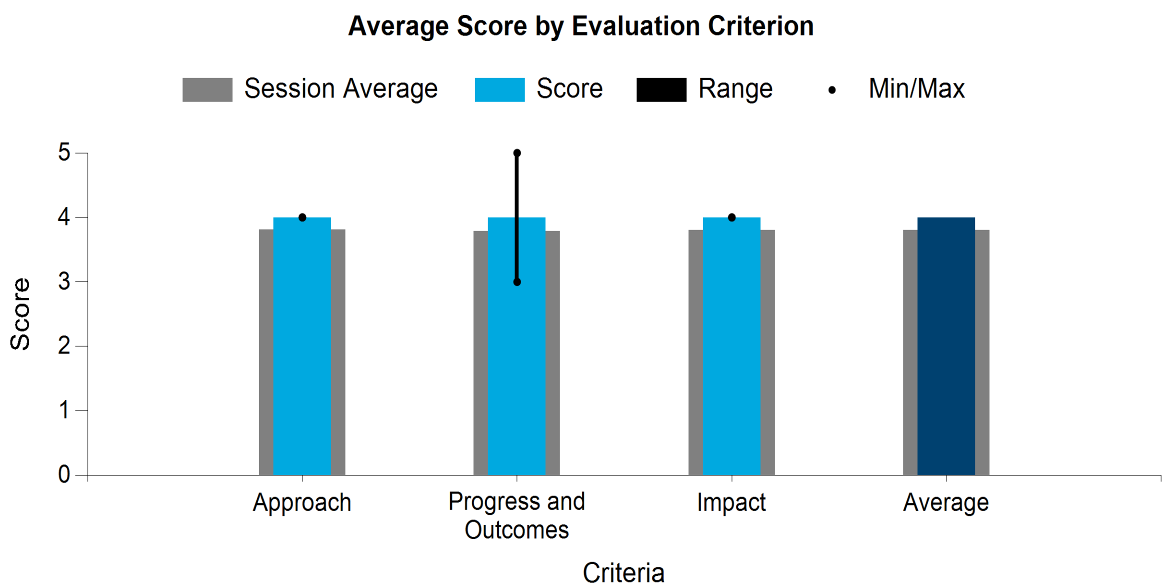
RISK MANAGEMENT PROGRAM FOR BETO SCALE-UP PROJECTS

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	3.2.4.001
Presenter(s):	Hannah Rabinowitz
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$1,400,000

Scaling up bioenergy projects presents challenges, often resulting in significant cost and schedule overruns or even project failure. Identifying risks that could lead to cost and schedule impacts is a critical part of project planning and execution to ensure proper risk handling. Based on industry consensus standards as well as many years of experience, PNNL has developed a risk management process to help scale-up projects identify and manage risks and to help BETO track and manage risks across its portfolio. To create a consistent and best-practice risk management process, PNNL developed a Risk Management Plan Guidance (RMPG) document that serves as a template for projects to write their own risk management plan (RMP). Additionally, PNNL delivered training on risk management topics as part of a technical assistance effort with one pilot BETO Phase 1 scale-up project, and a second pilot is planned for 2023. PNNL will facilitate risk elicitations to help the pilot projects identify, characterize, and capture risks in a project risk register. The Excel-based risk register is the principal tool to help the project track risks, manage risks through handling actions, and support risk reporting to BETO. Supporting the development of pilot project RMPs and risk registers will inform the finalization of the RMPG to allow its application across the BETO portfolio of scale-up projects.



COMMENTS

- Risk management is a must exercise that any project needs. The concept and approach are consistent with industry standards; however, I am afraid that the project team is developing the tool from scratch. There are many tools out there to do project risk management. The risk assessment is translated to the level of contingency. You should recommend BETO to allow a certain level of contingency in the budgets. I will not recommend requesting a full risk analysis during the FOA application because it is cumbersome and requires significant time, but it should be one of the first tasks once the project has been awarded.

- This project provides guidance and a consistent, uniform process for the risk management of BETO projects, and I am glad to see it. The overall framework looks good. From the presentation, it is not clear when projects begin the quantitative risk assessment—before or after being funded for Phase 2?

  Because budgets are developed during the proposal development, would teams perform the quantitative risk assessment during the proposal development for Phase 2 and provide their risk register and contingency budget as part of their proposal? Would project teams need to provide a contingency budget?

  Generally, in industries (nuclear, oil and gas, etc.) where risk management is a standard practice, risk management professionals are brought in to facilitate risk workshops to ensure a comprehensive, efficient, and inclusive risk assessment process and to manage any challenging personalities. Does the RMPG provide guidance on facilitating a risk workshop? Does the RMPG provide guidance on how to write good risk statements?

- The audience for a clear risk analysis should be both the project leaders as well as BETO program management. The best time to do that initial analysis is before the project even starts. The approach being developed in this project is semiquantitative, and it leans on experiences in the nuclear power and oil and gas industries, among others, which could lead to a more objective assessment of the risks and mitigation strategies being planned for each project. That analysis depends to a great extent on the background and experience of the technical advisory board members, so the choices for those roles should be consistent with the type of project being considered. It will be more useful as a managing tool if clear standards can be set for each criteria and then consistently applied. It may also be helpful to use financial metrics tempered with probability of success—for example, an NPV that is risk adjusted, as is commonly used in industry. Also, it might be useful to do a lookback on projects that underwent risk analysis to see if the analysis was useful and if the methodology can be improved in the future.

- The SDI project's success rate can be improved by implementing a uniform framework that focuses on risk identification, mitigation, and maintenance of a risk register for BETO's scale-up projects. The framework must consider various types of risks, such as technical, implementation, unforeseen events, identification, and allocation of resources, along with cost (on-budget) and timeline (on-schedule) risks. To ensure accuracy, industry standards used by the chemical, engineering, and aeronautical industries must be incorporated into the calculation methodology. Based on the risk score, only projects with acceptable risk levels should be selected for implementation. After completion of this project at PNNL, the developed tool should be made available to all FOA submitters, and funding should include a contingency budget (e.g., 15% of the requested budget) for any unforeseen risks. As identified risks are mitigated, the contingency budget could be accordingly reduced. Additionally, tasks should be included in this project for technology transfer efforts, especially to the SDI team. In conclusion, BETO would greatly benefit from the implementation of this risk management framework to ensure the successful scaling up of projects.

- Risk management is critical for project success, and this framework will assist projects to identify risks and have contingencies in place. This will be important to successfully scale up.

PI RESPONSE TO REVIEWER COMMENTS

- The project team thanks the review panel for their time and thoughtful comments. We appreciate the reviewers reinforcing the importance of conducting formal risk management for BETO's scale-up projects. In the following, we clarify several items brought up in the review panel's comments.

The review panel mentioned a concern about developing a tool from scratch given the large number of processes already available. The framework that we have put together does, indeed, follow industry standards and is not intended to reinvent the wheel. We have put together an RMPG as a template that projects can use as a starting point to create their own RMP, but the RMPG heavily draws from previous RMPs developed in a range of industries. In terms of the risk register tool, the intent for creating a risk register, Excel-based tool is to ensure that all projects have a risk register available that captures the inputs outlined in their RMP and provides outputs that can be directly used in risk reporting. By developing an Excel-based tool for BETO, this resource is available free of charge to all BETO projects and will help produce consistent results across BETO's portfolio, enabling BETO to manage its portfolio of risks. For projects that progress to a fully quantitative RMP in Phase 2, we expect that existing commercial tools would be leveraged for the risk analysis and that BETO would recommend a software tool to be used by all applicants to help ensure consistency across the portfolio.

The review panel also had questions about the timing of the semiquantitative and fully quantitative risk assessments relative to the BETO scale-up project FOA, Phase 1, and Phase 2 timelines. The intent of providing the RMPG as part of the FOA is to help projects understand the level of effort associated with risk management that they should plan for in their FOA application and budgeting for Phase 1. It is not intended that they complete a risk analysis prior to the project being awarded; rather, this risk management framework can help them to meet one of their Phase 1 milestones related to developing an RMP. The intent is that the quantitative risk assessment will be conducted during Phase 2, but training on how to conduct a fully quantitative risk assessment will be given as part of Phase 1 to enable the projects to plan appropriately for Phase 2. Although, ideally, a robust quantitative risk study would provide the basis for contingency estimates at the outset of in Phase 2, the practicality is that the type of detailed, resource-loaded schedule required to support such a study would not be in place prior to Phase 2. Instead, the anticipation is that the Phase 1 semiquantitative risk study would provide input to a preliminary contingency assessment. We also anticipate that the risk analysis will provide a robust basis for contingency estimation. As a project's methods evolve from semiquantitative to fully quantitative (in Phase 2), the robustness and completeness of the basis for contingency assessment will improve, including collecting data such as discounts that allow for calculating NPV.

In terms of risk scores being a basis for project selection, if such an approach were to be considered, it would be important that the principles of risk-informed decision making be applied and that factors such as risk model quality, detail, and completeness be accounted for so that projects are not incentivized to underreport their risks. The panel also emphasized the importance of leveraging risk professionals when conducting risk elicitations to provide a more comprehensive and efficient risk assessment process that yields a risk register populated with well-structured and well-characterized risks. Although the RMPG that we have developed does not include specifics on facilitation and writing risk statements, it is the topic of two training courses being provided to scale-up project teams. Also, we fully endorse the statement that risk professionals should facilitate risk workshops, particularly for the early sessions. This would provide hands-on training so that, ultimately, the facilitation role could be taken in-house, if desired.

Additionally, the panel noted the importance of incorporating technical advisory board members who are experienced in the industry. The risk management project has established a technical advisory board to provide bioenergy industry perspectives in the development of the risk management framework. The board includes a member of the independent engineering team that supports BETO and another industry expert. Additionally, the RMPG lays out the role for a project-specific risk advisory committee that comprises both industry and risk technical experts and can support the project in reviewing risk documentation and reporting. For the current pilot projects, the risk advisory committee comprises PNNL risk experts and the technical advisory board. It is intended that each project should create their risk advisory committee to include members with expertise relevant to their particular project, but additional guidance can be added to emphasize the types of people who should be included.

Finally, the panel noted that it could be useful to do a lookback and compare the success of projects that followed the formal risk management process with projects that did not. We agree that a lookback on project success with and without formal risk management would be useful, though that is likely to be a more successful endeavor in a few years, once several projects have implemented the risk management process and have been subsequently completed. Also, the RMP is a dynamic process with continual improvement based on experience with each project. We anticipate that BETO will play a key role in ensuring that general programmatic risk insights gained across the portfolio will be shared with all scale-up projects.

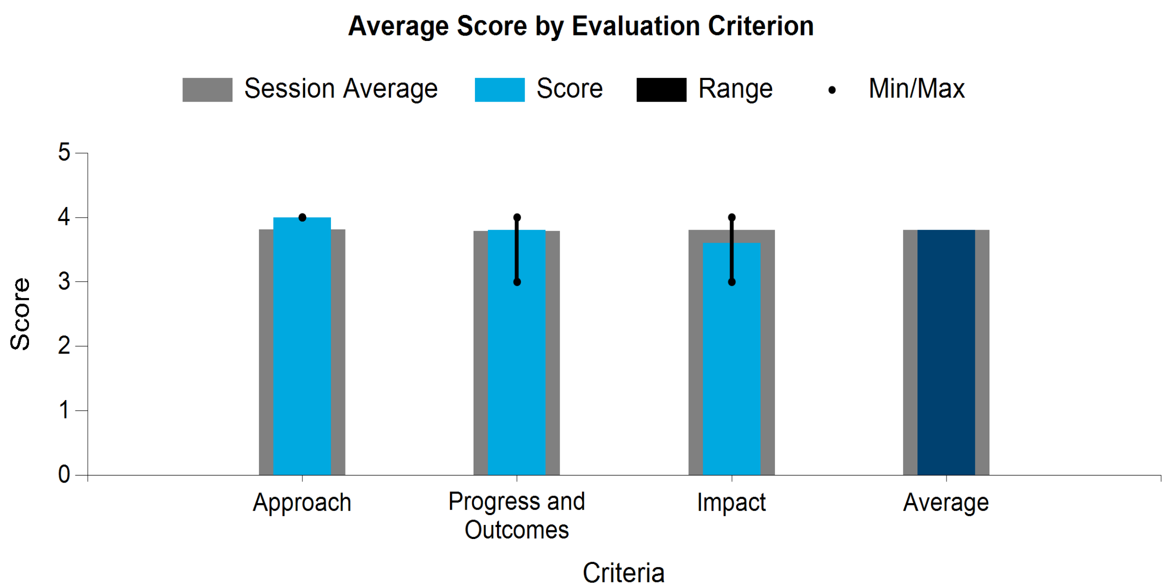
SOLID LIGNIN RECOVERY

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.3.4.601
Presenter(s):	Dan Schell
Project Start Date:	09/03/2019
Planned Project End Date:	09/30/2023
Total Funding:	$600,000

Valorizing the lignin residue remaining after 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 with good sugar recovery using commercially available, solid-liquid separation equipment, particularly for lignin derived from the DMR process or caustic-based pretreatments. 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 using either flocculation or a non-flocculated separation process. Based on a TEA completed in December 2020, both decantation (decanter centrifuge) with multiple-stage washing and cross-flow filtration produced a minimum fuel selling price (MFSP) of $0.21/gallon gasoline equivalent (GGE) and $0.03/GGE, respectively, below the flocculation-based process. This outcome generated a go/no-go decision to further explore and optimize the performance of these later non-flocculated processes. We generated enhanced data sets for cross-flow filtration and dynamic cross-flow filtration, and we will do the same for decantation in FY 2023, leading to a final economic evaluation at the end of FY 2023.



COMMENTS

- NREL tested and analyzed different alternatives to filter lignin solids coming from DMR pretreatment. It seems that the best system uses a decanter like in 1G ethanol production for thin-stillage separation.
- This project takes a sound approach to finding and evaluating solutions for recovering solid lignin to increase biomass conversion for more cost-effective SAF production. These are the types of

investigation that will enable improvements in the techno-economics of SAF production. The TEA will be important for the selection of the best method and for quantifying the economic improvements.

- Solid/liquid separations are an often troublesome unit operation in many processes. The need for lower-cost and more effective separations became obvious while evaluating the DMR enzymatic pretreatment process at increasing scale, and this study identified a few approaches that appear to be effective without the expensive addition of flocculants. When the final experimental work is completed and the data are evaluated, a TEA should elucidate the best approach for this feedstock and this pretreatment system. More work may be useful to investigate other feedstocks and their pretreatment and separations to broaden the potential applicability generally.
- The aim of this project is to improve the solid-liquid separation process in the DMR process, specifically for the separation of solid lignin. This separation process presents a significant operational challenge. When scaling up from the pilot to commercial scale, it is essential to consider the process's technical and economic feasibility. In this case, it is crucial to assess the efficiency of the separation process at larger scales and the potential cost implications of implementing the necessary equipment and infrastructure. The DMR process has shown promising results in laboratory and pilot-scale studies; however, further research is necessary to fully determine its commercial viability. This assessment should include a comprehensive evaluation of the technical, economic, and environmental aspects of the process. The separation of sugars and solids before fermentation may be necessary to optimize the fermentation process's efficiency. Solids, such as lignin, can hinder the fermentation process by binding to the microorganisms and inhibiting their growth. Additionally, sugars in the solid fraction will not be readily available for fermentation, resulting in lower product yields. Although there is a potential loss of sugar during the washing of solid lignin, efficient separation processes can minimize this loss. The concentration step following the washing can increase the sugar concentration of the feed to the fermenter, resulting in higher product yields; however, it is essential to consider the increased water load for the process due to the washing step and evaluate the process's environmental impact.
- The economics of a cellulosic ethanol facility are linked to the ability to valorize all coproducts or byproducts. Lignin valorization has been a significant challenge, and most cellulosic ethanol facilities have burned the lignin for energy generation. This project looks at lignin recovery after the DMR process (still undergoing development and optimization). The characteristics of the lignin make it challenging to separate and recover, and various methods are evaluated. The project can significantly impact the viability of cellulosic ethanol facilities based on coproducts derived from the lignin. Switching to lignin separation before fermentation makes sense to prevent the inhibition of the fermentation organism because sugars can be concentrated. There does not appear to be a clear winner among the investigated approaches, with the cost reduction against the baseline being quite small for a few alternatives. It would be useful to show the difference in wash water consumption between the most promising approaches. Which option achieves the highest sugar concentration? What is the impact of different recovery approaches on the proposed lignin valorization approaches?

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 be generally applicable to any aqueous-phase pretreatment process; however, additional work could look at other pretreatment/feedstock combinations, but we have found that DMR-derived lignin is the most difficult to separate, and for this reason, this material was used in this work. TEA is being extensively used in the project to assess the relative economic performance of the various separation options being analyzed in this study. The separation performance data for each option—including wash water usage, solids and sugar recovery, and extent of solids dewatering—are being generated in pilot-scale equipment. The TEA analysis is being performed by the NREL process analysis team using previously established models. These models include DMR and lignin utilization process designs and economics as documented in NREL's 2018 design report (doi.org/10.2172/1483234), which has been reviewed and vetted by industry and other external reviewers. The TEA will identify the optimum operating conditions (e.g., water consumption) as well as the relative cost of each separation option.

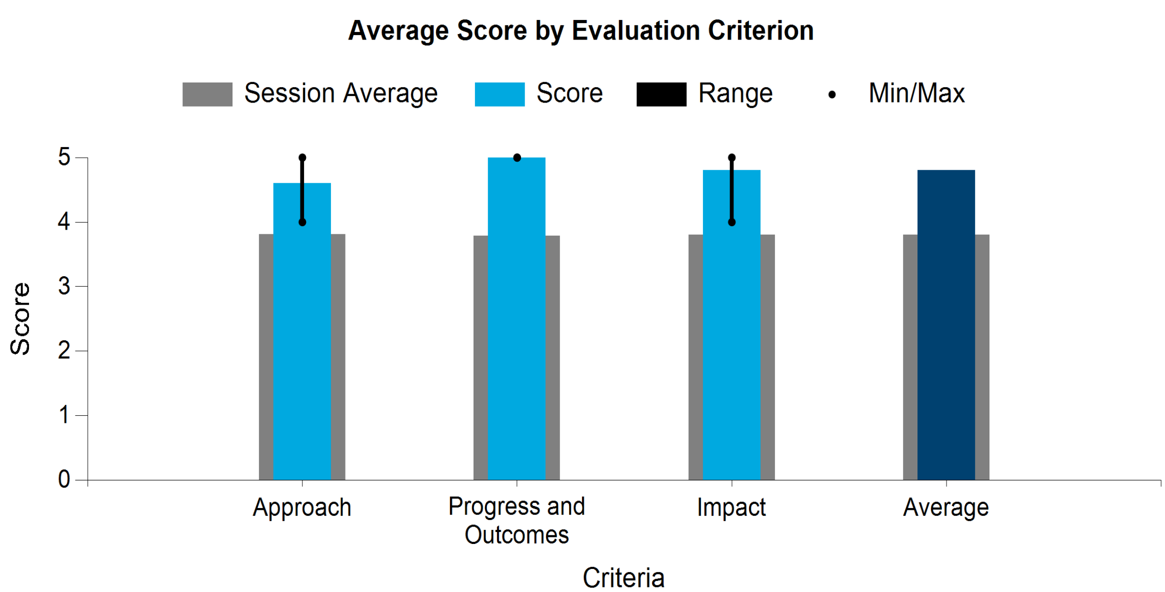
BIOMASS—FEEDSTOCK USER FACILITY

Idaho National Laboratory

PROJECT DESCRIPTION

WBS:	3.4.1.202
Presenter(s):	Neal Yancey
Project Start Date:	07/03/2008
Planned Project End Date:	09/30/2024
Total Funding:	$6,000,000

Variability for low-value carbon feedstocks continues to create challenges during storage, preprocessing, and conversion. The purpose of this project is to ensure that feedstocks are procured and prepared for all BETO-funded research projects as well as industry and academia. Part of that involves maintaining equipment and reconfiguring to meet customer needs. The project has advanced the TRL of new technologies with the aim of moving promising technological developments from the bench scale to the pre-pilot scale. Three BFNUF projects were selected to develop processing methods for corn stover, forest residue, and MSW. Each specifically addressed variability in moisture, particle size, and ash. Upgraded BFNUF equipment was used to fractionate, remove contaminants, and create a product with significantly reduced variability. The targets were met using screening, advanced milling, and contaminant-removal operations, which were also part of the BFNUF equipment upgrade. This project supplied feedstocks to more than 100 requests from industry, academia, and national laboratories during FY 2022 and will exceed that number in FY 2023. One technological challenge of this project is the integration of the BFNUF upgrade equipment, the inclusion of that equipment in the current operating system, and data acquisition. A desired outcome from this project is to increase the inclusion of underrepresented companies and individuals in the development of technology solutions.



COMMENTS

- INL is doing excellent work helping companies and other national labs to address biomass handling and pretreatment issues. They had 73 projects funded in 2022–2023 and have worked with various feedstocks, covering the whole spectrum. Keep on working as you have until now!

- Feedstock handling and preprocessing continue to be a challenge. INL's BFNUF is a valuable resource to companies and researchers in the bioeconomy to work through feedstock challenges and assess the techno-economics of different preprocessing options. It is great to see additional investment being made to expand the capabilities of the BFNUF. Because feedstock drying is often required for the conversion process, BFNUF should consider how it can support that.
- A multipurpose, multiunit operation, multi-feedstock facility to facilitate scale-up the front end of various processes has become a very useful investment. This is very attractive to industry users, as indicated by the many collaborative projects.
- Because consistent feedstock handling and feeding remain significant challenges in biomass projects, this project has the potential to make a meaningful impact. This project has made excellent progress, underscoring the critical role of producing dependable feedstocks for successful project outcomes. To leverage the expertise of engineering firms and equipment vendors, are there any plans to collaborate with them? Are there any ongoing or planned projects to improve feedstock preprocessing, particularly in the area of densification, to ensure a consistent and stable feed for end users? In addition to air classification for cleaning, is a washing step included to clean the feedstocks, similar to those used for cleaning wood chips in pulp and paper facilities? What plans are in place to share lessons learned, including dos and don'ts, with other project developers to help them avoid common pitfalls?
- INL performs a vital function in commercializing technologies for biofuel and bioproducts production. The cleanup and processing of feedstocks is critical for any biorefinery, and the expertise and equipment at INL can achieve this. The most important part of this role is the feedback to companies to translate these data into industry decisions for pilot, demonstration, and commercial-scale facilities. Based on the presentation of their work, INL has a good communication strategy, which includes the collection of data on TEA and LCA to help companies with decision making. Keep up this excellent work.

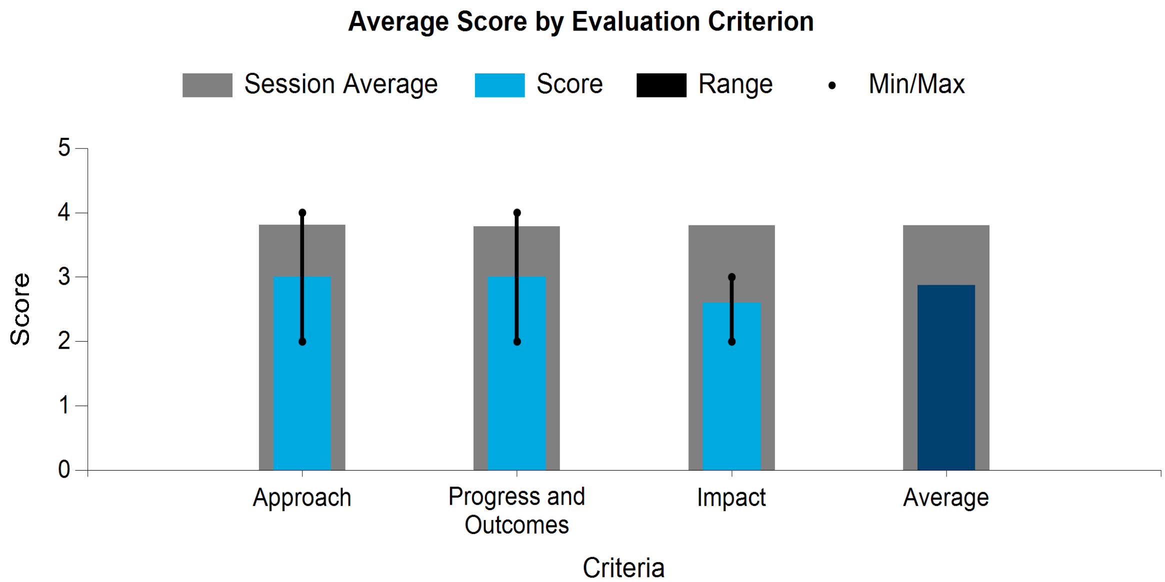
PI RESPONSE TO REVIEWER COMMENTS

- Thanks for the comments; they were beneficial and insightful. The BFNUF continually seeks engagement with equipment manufacturers. Some examples are the partnership with Warren and Baerg Manufacturing in developing the new bale processor. In May 2023, INL hosted a ribbon-cutting ceremony where university partners, industry partners, and our DOE customer came and participated in an open-house demonstration. This along with conference attendance and publications have led to added customer interactions with the BFNUF. Specifically, the BFNUF is working with air classification vendors and milling manufacturers, such as Forest Concepts. But, to your point, improvements can always be made to include more partnerships with industry and manufactures alike. We routinely seek partnerships with industry to improve preprocessing and material handling/flowability. Densification is also of particular importance; most recently, we engaged with companies such as Fulcrum, Enerkem, and Lignetics in conducting densification research. INL is in the process of establishing additional partnerships with industry in developing densification research with both MSW and corn stover as well as other feedstocks as the opportunity arises. Washing capabilities are also an ever-increasing need. The BFNUF has multiple laboratory-scale washing capabilities where research is being completed but not as much at the PDU scale. Certainly, that is an area that may increase in need in the future. INL produces many papers/publications each year to help get the word out on the research being conducted. But, to your point here, it would be beneficial to develop a lessons-learned publication on an annual basis to highlight those types of issues, both positive and negative.

SCALE-UP OF NOVEL ALGAE DRYING AND EXTRACTION UNIT OPERATIONS

Global Algae Innovations

WBS:	3.4.2.101
Presenter(s):	David Hazlebeck
Project Start Date:	10/01/2020
Planned Project End Date:	08/31/2024
Total Funding:	$5,000,000



COMMENTS

- The project we are reviewing is for drying and extraction operations; however, the presentation does not specify how the process will be done. The final product portfolio has changed from oil and meal to various higher-value products that may positively impact the project's economics. Considering that the project started very recently, I will need to wait for further development of the project to have a better assessment of its performance.

- This project aims to enable economic algae-based biofuel by developing high-value coproducts and new drying and extraction unit operations that are less energy intensive. Although the lipid coproducts are valuable bio-based chemicals, biofuels production is reduced by 66%.

  Global Algae Innovations has also selected a non-genetically modified organism (GMO) algae, which allows the algae to be produced in open ponds without concerns of GMO algae being unintentionally dispersed into the wild. The feasibility of the large-scale production of algae is still in question in regard to the land and water requirements. Water makeup needs to account for not only evaporation but also water entrained in the algae when harvested.

It is not possible to provide a technical evaluation of the project due to the lack of information on the new drying and extraction technologies.

- This algal project differs from other approaches in that they are using selected algae to produce increased amounts of lipids and proteins and employing novel unit operations to reduce the cost of algal isolation and drying, the latter dramatically reducing energy costs. The lipids and algal meal are separated, and the lipids are further separated into value-added streams for different applications. More process analytical controls are used to increase the security of the algal pond and manage nutrients for growth. A key question about the cost-effectiveness of microalgae for fuels remains, but coproduct value appears to help. Although the usual questions remain about land and water use, this seems to be a smart approach for this type of platform.

- The use of algae as a feedstock for biofuels and bioproducts has gained significant interest due to its improved growth rate, high lipid content, and ability to grow in a variety of environments; however, the cost of producing biofuels from algal biorefineries is currently prohibitively expensive, which limits the impact as well as the widespread adoption of this technology. Despite this, ongoing R&D efforts are being made to improve the efficiency and reduce the costs associated with algal biofuels. This project focuses on the use of a novel drying and extraction method for the separation of algae (lipids and meal) for downstream processing to produce algal oil and products. Several questions and challenges with respect to water use, water recycling after separation, and land use (does it impact agricultural land?) remain to be answered. To better understand the various projects from Global Algae Innovations, it would be helpful to have a clear illustration of the similarities and differences between the projects. Additionally, understanding how the project team members collaborate, particularly during the execution phase, can provide valuable insights into the success of these projects.

- The production of lipids from algae and commercialization has proven to be quite difficult over the years, and many companies have failed; however, the high demand for low-carbon-intensity lipid feedstocks will keep growing, and algal lipids have been identified as a potentially significant source.

  The project reviewed here focused on the scale-up of a novel drying and extraction technique rather than the overall process, although these are definitely some of the most critical components. We were not provided with any information on the actual technologies because patents are still pending; however, the results in terms of energy consumption and yields were very good.

  The 50% lipid production in a naturally occurring organism seems very impressive, but it is not clear whether contamination of the ponds, and therefore lipid yields overall, were a problem. At a broader level, there are some concerns about land use change and water consumption that will affect the sustainability and carbon intensity of the lipids. This should be investigated in terms of scale-up and location because it will be an important consideration for the offtake of lipids by a biofuel producer, such as Neste. The impact of fertilizer consumption (and the source of the fertilizer, likely from fossil fuels) will also be a consideration for carbon intensity.

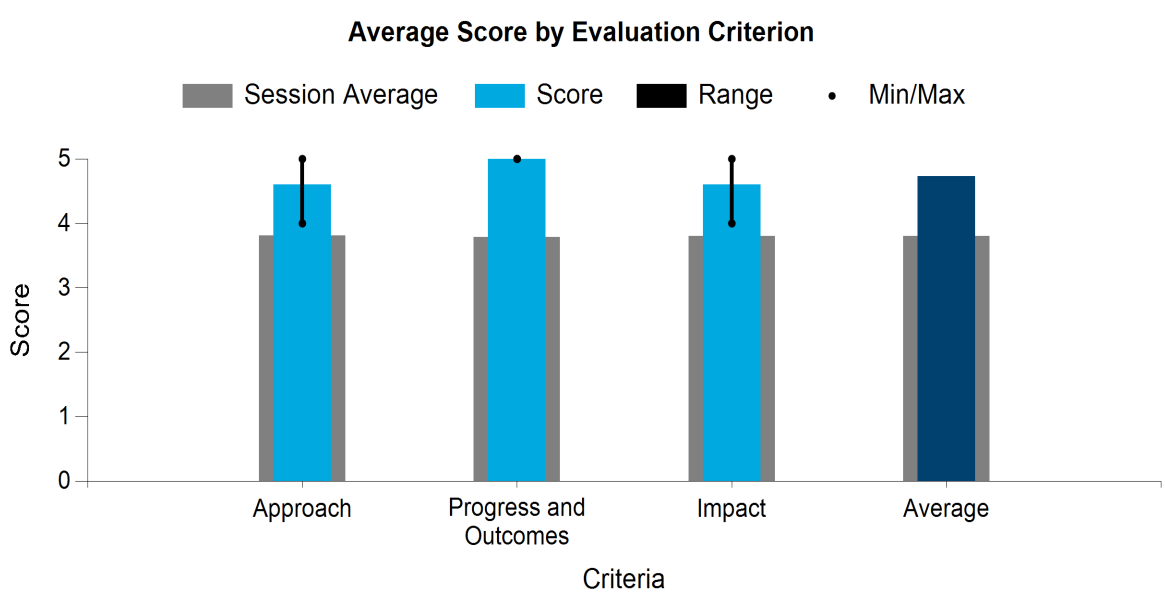
BIOCHEMICAL PILOT-SCALE SUPPORT AND PROCESS INTEGRATIONS

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.201
Presenter(s):	Dan Schell
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2024
Total Funding:	$4,468,000

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 and evolve its capability to perform process-relevant testing or integration work for BETO and industry clients. We also encounter and solve unknown scale-up issues that usually manifest only at the pilot scale prior to technology deployment; however, processing biomass feedstocks remains a challenge at the pilot scale, particularly handling a variety of raw biomass materials. In the past 2 years, we completed the modernization of 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., automated data storage to a Structured Query Language (SQL) database. We developed and implemented a data management system that effectively captures and logs all pilot-plant sensor data associated with experimental runs into an easily retrievable format including sample tracking. This year, the plant's aging boilers and air compressors will be replaced using non-project funds, and we will install a new 22-inch disc refiner to support a new pretreatment technology. The pilot plant continues to be used by BETO projects as well as by industry clients, with 11 new industry-based projects begun in FY 2021/2022.



COMMENTS:

- NREL is known worldwide as a reference for biomass treatment, utilization, and upgrading. During the last 30 years, NREL has worked with multiple stakeholders trying to solve the intricacy of sugar liberation in biomass feedstocks. I think NREL has outdated facilities, and the $39 million they have just started will revamp and bring back their facilities to SOA. This investment is really needed.

NREL is expensive for small businesses, and it is necessary to find formulas to make it more accessible to entrepreneurs. NREL should seek more feedback and participation from the industry.

- The Integrated Biorefinery Research Facility (IBRF) provides a valuable facility for testing, scaling, and de-risking the commercialization of biochemical conversion. Continued investment to upgrade to SOA technologies is a well-spent investment to continue innovations and the commercialization of biochemical conversion.

  As with all national labs, the cost for testing at the IBRF is expensive and is a barrier for smaller startups. DOE BETO FOAs enable smaller, resource-constrained companies to partner with NREL and conduct testing, but FOAs are limited. Otherwise, access to the TCPDU is limited to large corporations and startups with early-stage venture capital funding.

- Adding data retrieval and process control management to the already existing biochemical piloting facility provides a significant improvement to its capabilities. In addition, generating process hazards analyses and procedures is very important, along with sample generation and product analysis. This is a very important tool for investigating and scaling up biochemical conversions to de-risk unit operations, provide real-time process characterization, and generate data for scale-up. As evidenced by the many industrial collaborations in these facilities, there should be strong support for continued investment to keep up with new technologies for this application area. I would like to see additional pilot unit operations for biochemical separations.

- Biochemical conversion is a promising technology used to convert biomass feedstocks into useful products. The operations involving various feedstocks have helped to modernize the IBRF, and the insights gained are being used by industry clients for process development and scale-up, tailored to their specific needs. Over the years, the IBRF has evolved into an SOA facility. What type of change management (control) mechanism is implemented to ensure that modifications made to the facility do not adversely affect its operations? This mechanism should be designed to carefully evaluate and approve any changes to the facility to ensure that they are safe, effective, and do not violate any regulations. Understanding this mechanism can help differentiate any work performed before and after modifications to the facility. Can the IBRF operate 24/7, making it feasible to conduct experiments or runs that span multiple days? This allows for a more thorough analysis of the processes and a more accurate understanding of their potential for commercial-scale deployment. In addition to tracking the utilization of the facility, does the IBRF maintain a record of projects that have been performed and have resulted in commercialization? This information is essential for understanding the success of the IBRF and the impact of its research on the industry. The results and efforts of the IBRF project are expected to significantly contribute to the successful deployment of biochemical projects at commercial scales.

- The work of the unit is important for facilitating the commercialization of biochemical technologies for biofuels production.

PI RESPONSE TO REVIEWER COMMENTS

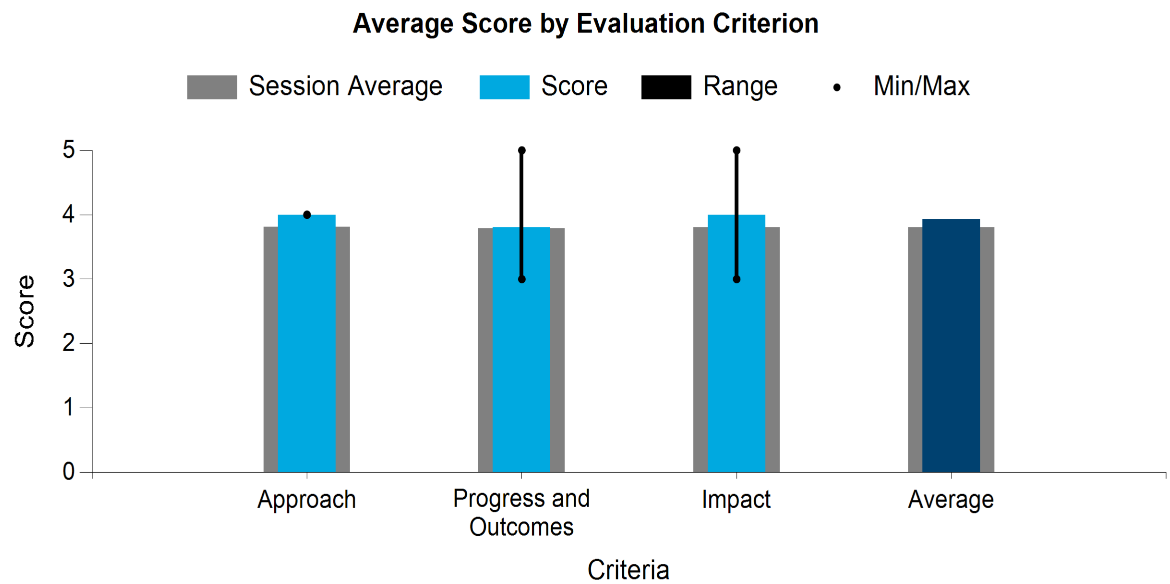
- We appreciate the reviewers' comments and their assessment of this work, and we have provided clarifications and answers to the comments in the following. The project's primary goal is to maintain a safe and process-relevant biochemical-based pilot plant that is made available to others to use including industry partnerships and BETO research projects. Regarding 24/7 operations, the facility has been used in the past and currently can conduct work requiring 24/7 operations. With respect to change management, we follow guidelines from the Occupational Safety and Health Administration and the

American Institute of Chemical Engineers' Center for Chemical Process Safety, and we document the change and its impact on operations, provide expert reviews of design and safety prior to system use, and verify that the changes were satisfactorily completed. Regarding separations, we are continuing efforts to upgrade the facility to perform biomass-to-finished fuel processing, and we will likely acquire additional separations capabilities to support this effort as well as more generic downstream processing requirements. The challenge is identifying the most versatile equipment to support multiple projects, all typically with unique downstream processing needs. We understand and share the concerns regarding the cost of doing business at NREL and other national laboratories. But beyond the FOA process and associated DOE cost sharing and other limited programs at NREL, there is currently no mechanism to reduce or provide cost shares for a project using our facility. Finally, we do not maintain good records of the fate of companies and technologies used in the plant; however, we would like to initiate work on this suggestion and develop a database to begin tracking this information and mine previous work to the extent possible.

INNOVATION AND OPTIMIZATION OF THE SZEGO MILL FOR RELIABLE, EFFICIENT, AND SUCCESSFUL UPSCALING OF THE DEACETYLATION AND MECHANICAL REFINING PROCESS FOR BIOFUEL PRODUCTION

University of Alabama

WBS:	3.4.2.203
Presenter(s):	Luke Brewer
Project Start Date:	10/01/2020
Planned Project End Date:	01/31/2026
Total Funding:	$3,816,102



COMMENTS

- The University of Alabama is performing a very thorough analysis of the metallurgy required for manufacturing the Szego Mill for biomass processing after the DMR disc refiner. The lab-scale mill has suffered corrosion and very quick degradation of the internals. The University of Alabama is trying to identify the causes and provide a metallurgical solution to avoid those problems. The University of Alabama has proven different types of stainless steel and has identified two promising alloys and two possibilities for material filling. The mill rotates at 1,200 rpm, and water with a 3% solid content is inside. I am sure the team has considered cavitation as the source of material degradation, but nothing was mentioned in the presentation. I think that this should be studied. Please keep working as you have done in the past and bring a feasible solution.

- The team has developed a sound approach to selecting better steels for the Szego Mill to address the wear and vibration issues with corn stover. The project will make the Szego Mill viable for commercial use with the DMR process. The Szego Mill improves sugar yield in the DMR process and thus enables better economics of commercial SAF production via the DMR process. A TEA should be included as part of this project to quantify the economic improvements.

- This is a very systematic approach to selecting and improving the materials of construction of the Szego Mill rollers to improve wear and corrosion resistance. The additional benefit will be noise reduction for this unit operation. A cost-benefit analysis would be helpful in making the final decisions on how to proceed. This kind of analysis would be useful for any other pretreatment unit operation that is subject to mechanical wear or corrosion damage. It might also be useful to consider other materials of construction, such as advanced ceramic composites, which are both tough and unaffected by corrosion. Several questions still remain about this unit operation, however—for example, whether the conditions of high speed and tight clearances are causing cavitation, which might impact wear and noise. A nearly horizontal configuration might allow for higher residence time, thus allowing for slower and less damaging speeds.

- The reliability and robustness of process operations using high wear-and-tear equipment for biomass applications is a crucial consideration that needs to be addressed. Equipment that shows signs of wear and tear after only 30 hours of operation is not scalable in an industrial setting. Although the Szego Mill may have been used in the pulp and paper industry with wood chips containing up to 50% moisture, as well as with softened wood, using corn stover with a moisture content of 15% and without precooking may affect the wear and tear of the equipment. Further investigation is necessary to understand the impact of these conditions on the equipment. At present, the results of this project may satisfy academic curiosity, but the commercial implementation of the findings will be limited until the reliability and robustness of the process operations are established.

- The addition of the Szego Mill to the DMR process can increase sugar yields from enzyme hydrolysis by 10%, according to the data presented. This would have a clear impact on the yield of fermentation product and potentially improve the economics of a facility based on this technology. The principal investigator (PI) presented the approach that was taken to identify problems with wear and corrosion on the metal in the Szego Mill, and the research approach is sound; however, the impact on the metal seems different for this type of feed, and it might be useful to identify the conditions under which wear and corrosion will be minimized. For example, pH adjustment before the Szego milling step to the pH required for enzyme hydrolysis might minimize the problems encountered. Moving to expensive metals or metal treatments will likely add costs to the overall process, which could be avoided or minimized. It will also be useful to include some cost data on metals and treatments to get an idea of whether the increased costs would be warranted for the inclusion of the Szego milling step.

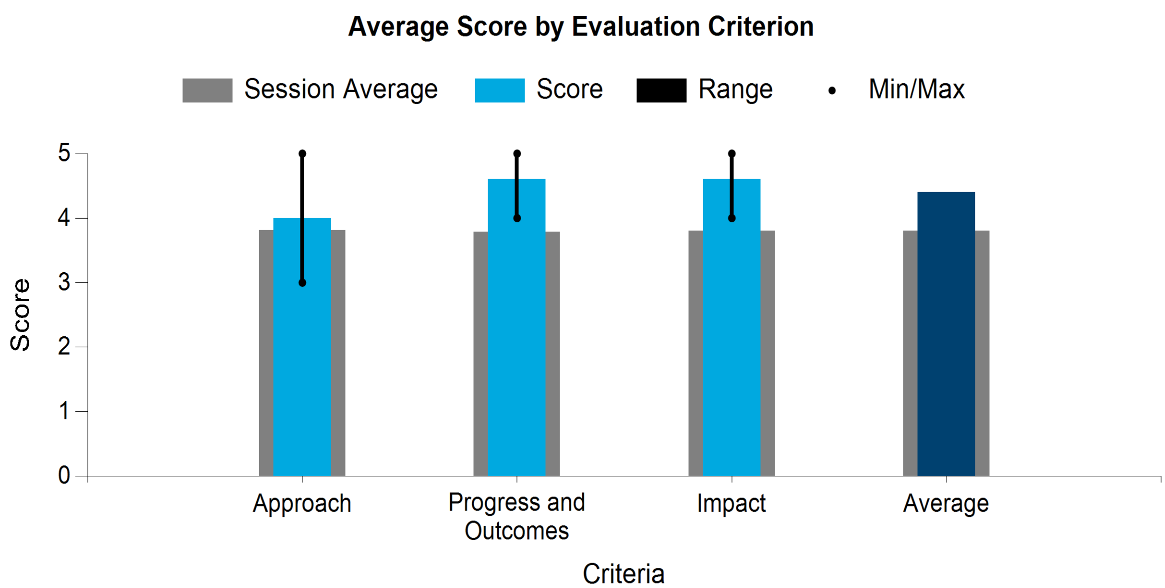
PNNL HYDROTHERMAL PDUS

Pacific Northwest National Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.301
Presenter(s):	Mike Thorson
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2024
Total Funding:	$5,055,000

The PNNL hydrothermal PDU project is focused on adapting and applying hydrothermal PDU capabilities (hydrothermal liquefaction [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 testing and the 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, cooperative R&D agreements, the development of intellectual property for improved HTL processing and upgrading, and licensing agreements with commercialization partners.



COMMENTS:

- The PNNL has developed a promising technology to produce biocrude from wastewater biosolids. They have designed a plant, tested it at a small pilot-plant scale, and developed an engineering package for technology scale-up. The escalation factor from pilot to demonstration is 30–40 times, which is reasonable. They have addressed the fouling issues in high solid-liquid by eliminating heat exchangers. PNNL is focused on only one type of feedstock (biosolids from wastewater treatment plants), and I think they should also look at other available feedstocks. Licensing the technology is a great business concept, but the PNNL, as a national lab, should also dedicate its resources to providing feedback to other potential technology users.

- PNNL's hydrothermal PDU provides a valuable facility for testing, scaling, and commercializing HTL projects and valorizing wet waste feedstocks. PNNL has been clever in taking lessons learned from tar sands for solids separation and wastewater treatment plants for eliminating heat exchangers and associated fouling problems; however, the PDU does not have the capabilities to identify and solve contaminant issues besides for per- and polyfluoroalkyl substances (PFAS). Given that sewage sludge is the target feedstock, it seems that contaminants are an important issue to address.

- This wet waste-to-liquid fuels installation represents a good collection of feedstock sources and comprehensive unit operations. Building on collaborations involving Canadian tar sands is a good idea, and it led to the conclusion that avoiding heat exchangers makes sense when dealing with heavily fouling processes. Investing in this capability should accelerate many programs involving recalcitrant feedstocks. I would like to see more effort on in-line analytical capabilities.

- The primary focus of this project is to develop processes for HTL, scale up unit operations, and build industry partnerships. These efforts have a direct impact on the commercialization of HTL projects. HTL is an appropriate technology, especially for processing feedstocks with high moisture content. The project is well managed, with clear goals and accomplishments; however, note that achieving GHG emissions reduction greater than 81% compared to fossil sources depends on the feedstocks used. Regarding the production of biocrude, it is important to address the potential presence of PFAS. If PFAS are detected, what measures will be taken to handle and mitigate their impact? Additionally, what assistance does this project aim to provide to end users in tracking biogenic carbon in the final product? This methodology will enable end users to accurately report the carbon footprint of the biocrude produced and biogenic carbon in the final product, contributing to the overall sustainability of the project.

- HTL is an important technology for the production of drop-in biofuels, and the commercialization of this technology is a priority. As a process that can, uniquely, use wet feedstocks, HTL can access niche feedstocks and can be used for the treatment of waste. The work done at PNNL is therefore very important. The only comment/concern is that there is a focus on sewage sludge alone. Many projects and research efforts also focus on solid feedstocks that may contain high moisture content, and these feedstocks can pose unique challenges but make a significant contribution in the biofuel sector to expand the access to feedstocks without the energy inputs associated with drying that is needed with pyrolysis or gasification. As a national lab, advancing a broader feedstock utilization would be beneficial to industry and research efforts.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to express our appreciation for the valuable feedback and thoughtful comments on our project. We are pleased to hear that the reviewers have recognized the potential and significance of our efforts in developing HTL technology for producing biocrude from wastewater biosolids. We appreciate the following positive feedback: "PNNL has developed a promising technology to produce biocrude from wastewater biosolids," "PNNL's Hydrothermal PDU provides a valuable facility for testing, scaling, and commercializing HTL projects," "Investing in this capability should accelerate many programs involving recalcitrant feedstocks," "The project is well managed, with clear goals and accomplishments," and "Hydrothermal liquefaction is an important technology for the production of drop-in biofuels."

  Diversification of feedstocks: We appreciate the suggestion to explore other available feedstocks beyond wastewater biosolids. Although our current focus has been on advancing the robustness of HTL using biosolids from a water resource recovery facility as the design case, we understand the importance of considering a broader range of feedstocks, and we have carried out extensive work on a variety of feedstocks, ranging from woody material, to algae, to a variety of organic wet waste. We agree that by diversifying our feedstock sources, we aim to enhance the versatility and economic viability of HTL for different waste materials.

Addressing contaminant issues: We appreciate the concern raised regarding the identification and mitigation of contaminants, particularly beyond PFAS. As part of our ongoing conversion R&D, we are addressing contaminant destruction around PFAS/perfluorooctyl sulfonate species, we and have historically looked at the destruction of a wider range of contaminants.

In-line analytical capabilities: We agree with the reviewers regarding the importance of in-line analytical capabilities for real-time monitoring and process optimization. This is a valuable area of consideration, and we will assess options for the integration of advanced in-line analytical techniques within our HTL processes. Such capabilities would enable us to enhance process control, improve product quality, and ensure the efficient conversion of wet waste feedstocks into valuable biofuels.

GHG emissions reduction and carbon footprint tracking: We appreciate the reviewer’s acknowledgment of HTL as an appropriate technology for reducing GHG emissions. Addressing the specific feedstock-dependent GHG reduction potential is indeed a critical aspect of our research. Regarding the carbon footprint tracking, we are partnered with Argonne National Laboratory (ANL) for detailed LCA analysis that models GHG reduction exceeding 80%. Again, we sincerely appreciate the reviewer’s feedback. We remain committed to collaborating with industry partners and to actively engaging in knowledge sharing to ensure the broadest impact of our work. We are dedicated to advancing the field of biofuels production, improving sustainability, and contributing to a more environmentally friendly energy landscape.

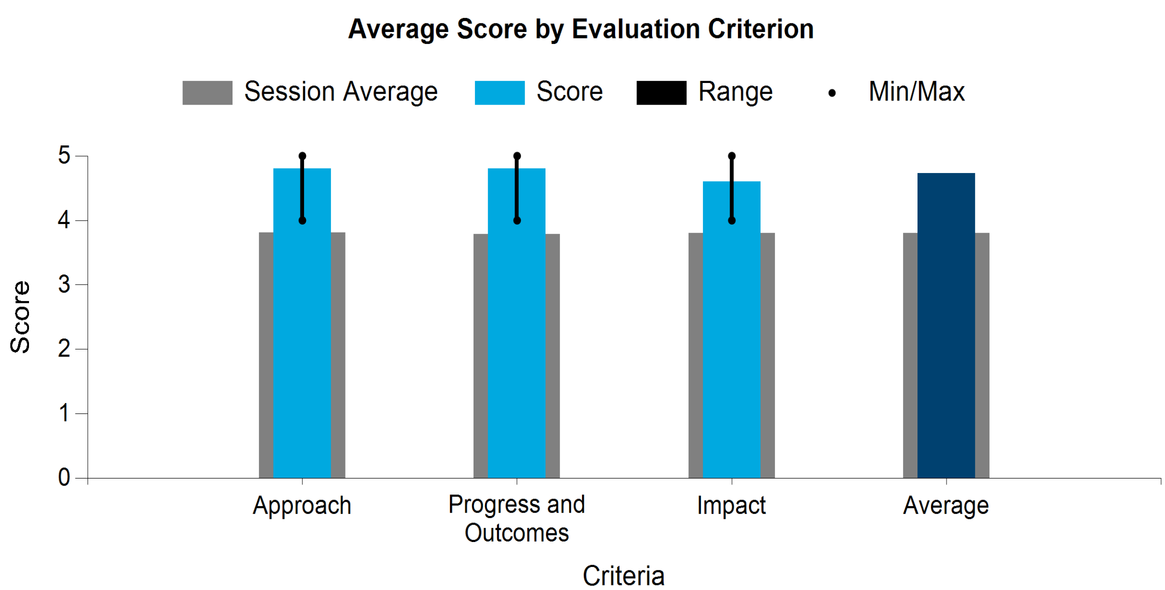
TCPDU - CATALYTIC CARBON CONVERSION CENTER OF PILOTING AND EXCELLENCE (C4PE)

National Renewable Energy Laboratory

PROJECT DESCRIPTION

WBS:	3.4.2.302
Presenter(s):	Mark Still
Project Start Date:	10/01/2018
Planned Project End Date:	09/30/2024
Total Funding:	$5,307,000

The Catalytic Carbon Conversion Center of Piloting and Excellence (C4PE) maintenance and upkeep project supports facilities that address key technical and economic risks of biofuels production. The industrial relevance of these facilities is maintained through industry engagement, internal evaluation, and implementation. Maintenance and upkeep of C4PE facilities helps generate industry partnerships and accelerate progress toward BETO's renewables production goals.



COMMENTS

- NREL is known worldwide as a reference for biomass treatment, utilization, and upgrading. During the last 30 years, NREL has worked with multiple stakeholders trying to solve the intricacy of sugar liberation in biomass feedstocks. I think NREL has outdated facilities, and the $39 million they have just started will revamp and bring back their facilities to SOA. This investment is really needed. NREL is expensive for small businesses, and it is necessary to find formulas to make it more accessible to entrepreneurs. NREL should seek more feedback and participation from the industry.

- NREL's TCPDU is a valuable resource that enables R&D for developing, de-risking, and scaling thermochemical conversion processes, which are capital intensive. Continued investment to maintain the TCPDU as an SOA facility is a key component of developing large-scale biofuels and the biochemicals industry. Interviewing industry experts and holding bioeconomy listening sessions are great approaches to ensuring that additional investments and improvements align with industry interest and needs; however, the cost for using the TCPDU is expensive and is a barrier for smaller startups. DOE/BETO

FOAs enable smaller, resource-constrained companies to partner with NREL and conduct testing, but FOAs are limited. Otherwise, access to the TCPDU is limited to large corporations and startups with early-stage venture capital funding.

- This facility is a valuable resource to de-risk multiple pathways from the bench scale to piloting for commercial basic data. It has many essential elements—from heat and mass transfer data collection, to solids handling, to data collection for TEAs, to modeling and sample generation. It is a very good example of how government and industry can work together to collaborate on big challenges. I support continued funding to keep up with the SOA on new technologies.
- Thermochemical conversion is a vital technology for converting biomass feedstocks into valuable products. This project is making excellent progress toward its defined goals, with significant achievements and industry participation and collaboration. The project's primary focus is on conducting R&D for process development, scaling up unit operations, and fostering industry partnerships. The project's methodology should include a robust system for tracking biogenic carbon in the final product, ensuring the sustainability and environmental integrity of the process. I suggest the allocation of resources to process modeling work, particularly in the development of reaction kinetics. These models are essential for simulating the process, and they help to optimize operations, increase efficiency, and reduce costs. By using process simulators, the project team can evaluate different scenarios and identify areas for further improvement, leading to more effective and profitable thermochemical conversion processes.
- The NREL TCPDU performs an important function in the advancement of thermochemical technologies, such as pyrolysis, catalytic pyrolysis, and upgrading. Continuous upgrading of the facilities is critical to provide advances in the area and a relevant service to industry.

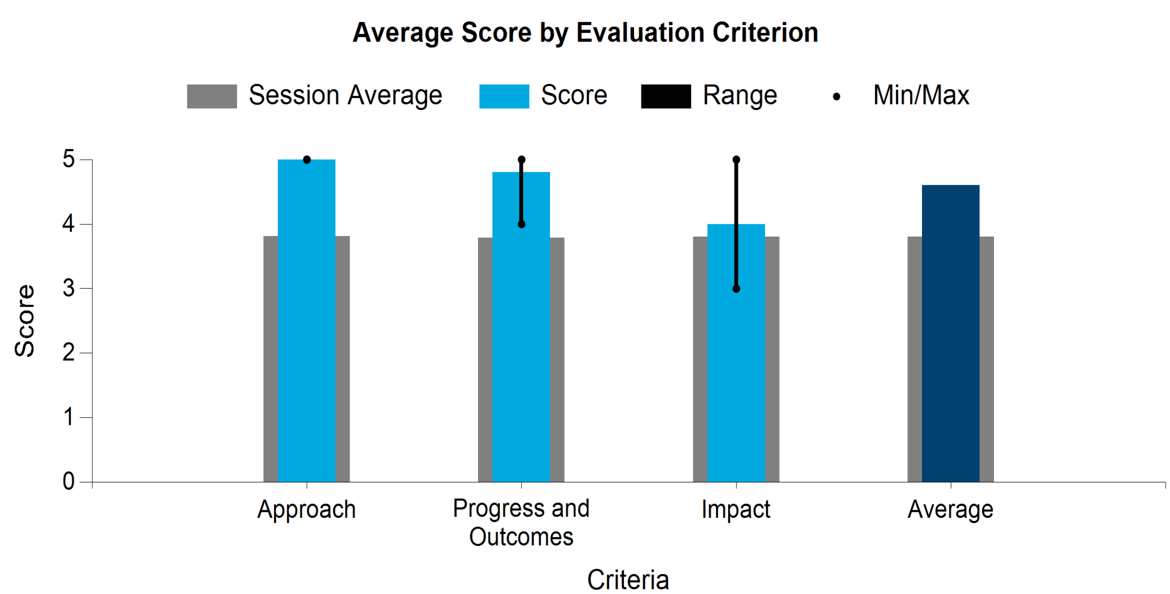
CONVERSION OF 2,3-BUTANEDIOL TO BIOJET FUEL: SCALE-UP AND TECHNO-ECONOMIC ANALYSIS OF ENERGY-EFFICIENT SEPARATIONS AND FERMENTATIVE DIOL PRODUCTION

Georgia Institute of Technology

PROJECT DESCRIPTION

WBS:	3.4.2.501
Presenter(s):	Sankar Nair
Project Start Date:	10/01/2020
Planned Project End Date:	09/30/2024
Total Funding:	$3,754,356

This project targets key process scale-up, modeling, detailed evaluation, and TEA LCA issues in the conversion of 2,3-BDO to kerosenic biojet fuel blendstocks. This goal will be achieved by collaborative advancement of five project elements:. (1) We will demonstrate the scale-up of BDO enrichment to 85+ wt % from clarified fermentation broths by a continuous adsorption pilot plant to produce 100 kg BDO at more than 1 kg/day. (2) We will demonstrate the construction and operation of a pervaporation membrane module for the last-mile dehydration of BDO. Each scaled-up system will be operated for 500 hours cumulative and 100 hours continuous on-stream time. (3) We will demonstrate the scale-up of fermentative BDO production at the 1,000-L scale to obtain at least 100 kg BDO with at least 100-g L concentration. (4) Laboratory-scale catalytic conversion work will optimize catalyst properties and conditions for enriched BDO feeds and produce biojet fuel samples that meet ASTM biojet blendstock standards. (5) The entire project will be tied together by a process modeling, TEA, and LCA framework that will produce accurate, well-parametrized separation process models, and we will integrate them with an overall process TEA to meet (modeled) throughput, MFSP, and CO_2 emissions reductions. The separation and fermentation technologies scale-up levels will be 100–1,000 times the present bench scale, and they would constitute the highest scale-up for BDO production to date.



COMMENTS

- The project will produce SAF from corn stover using 2,4-BDO as the sugar fermentation product (instead of ethanol). The novelty is that BDO can be separated from water without boiling it, and it is already a C4, which improves the oligomerization process. Extensive work is required in all aspects of the process: (1) BDO production, (2) BDO-water separation and purification, (3) BDO dehydration, and (4) olefines oligomerization. This is not an easy process, and it requires that various subsystems that have not yet been developed are integrated and can economically produce the fuel. The project has been ongoing for almost 3 years, and the presenter has reported good results in BDO fermentation and bench-scale BDO-water separation. The catalytic conversion of BDO to olefins still needs significant in-catalyst screening, kinetic modeling, and characterization. It is a high-risk project because of its complexity.

- The project had a sound, systematic approach to developing the conversion of BDO from corn stover to SAF. The team understands the technical challenges to be addressed. The team seemed to work together and coordinated well. Given the complexity of the process, the TEA and LCA will be important to evaluate the commercial feasibility.

- The approach used by this team is classic applied chemical engineering. Experimental work, modeling, and TEA are used to guide the selection of process conditions and evaluate outcomes. Communications between member organizations across the country are seamless and are clearly moving the project along. Already the team is seeing improvements to adsorption media stability, BDO isolate concentrations, and the reactivity of metal/zeolite catalyst for BDO-to-olefin conversion. The result is lower energy consumption, higher=quality intermediates, and improved separations. Although it remains to be seen if 2,3-BDO to SAF is the preferred route, this is an excellent team effort.

- The project team consists of highly experienced members from academia, national labs, and industrial companies who are working in excellent coordination to ensure that the project progresses smoothly. Please explain the reasoning behind using pervaporation membranes for BDO dehydration? When it comes to producing jet fuels, how does the BDO process compare with the ethanol route? Additionally, what is the justification for producing jet fuels from BDO instead of other bioproducts? Note that although the jet fuel produced from ethanol is ASTM certified, producing jet fuel from BDO would require a new certification from ASTM before it can be used in airplanes.

- This project targets the production of 2,3-BDO as an alternative to ethanol as an intermediate for conversion into SAF. A novel separation method is proposed using adsorption and enrichment of 2,3-BDO, thus avoiding energy-intensive methods required for ethanol removal from the fermentation broth. Comparing this process with an ethanol production and conversion process will be useful based on titer, yields, productivity, energy inputs, economics, etc. Specifically, the comparison should be assessed for the production of ethanol/BDO, the separation process, and the ATJ process. The BDO-to-jet process will require more steps, which would impact the economics of this stage. It is not clear whether any jet fuel has been produced from BDO and the characteristics of the jet fraction, and this should be provided. ASTM approval for BDO to jet will need to be obtained.

PI RESPONSE TO REVIEWER COMMENTS

- Overall, the five reviewers have given very positive comments on this project. In the following, we have excerpted the questions/concerns of the reviewers and answered them. Similar comments from different reviewers have been grouped.

  Comments: The catalytic conversion of BDO to olefins still needs significant in-catalyst screening, kinetic modeling, and characterization. It is a high-risk project because of its complexity. Response: The catalytic conversion element in this project involves bench-scale work only, targeted at proving the entire corn stover-to-SAF process flow. Our latest results (available after the peer review and included in the most recent quarterly report) show excellent performance of zeolite-based catalysts for both the BDO dehydration and oligomerization steps. We have thus successfully completed the catalyst screening and initial characterization, which greatly de-risks this project element. This project element will now focus on improving the SAF blendstock fuel quality and collecting systematic reaction data on the specific selected catalysts for use in updating our process model and TEA/LCA.

Comments: Given the complexity of the process, the TEA and LCA will be important to evaluate the commercial feasibility. Response: We agree. TEA/LCA update tasks are continually present in the project. Two iterations of the TEA/LCA have already been performed and show a positive delta NPV with respect to the prior state of technology. We will continue to refine the TEA/LCA using the detailed experimental data being generated in the project.

Comments: Although it remains to be seen if 2,3-BDO to SAF is the preferred route, this is an excellent team effort. When it comes to producing jet fuels, how does the BDO process compare with the ethanol route? Additionally, what is the justification for producing jet fuels from BDO instead of other bioproducts? Response: The project is responsive to the DOE goal of reducing the MFSP of bio-based aviation fuels to less than $3/GGE, and preferably less than $2.5/GGE, by 2030. Our current TEA indicates that the proposed route can meet these targets with comparable modeled costs to other routes based on ethanol. The catalytic conversion processes for BDO versus ethanol are somewhat different, including effects on catalyst longevity and efficacy in producing the required hydrocarbon slate. Our hypothesis is that starting from a C4 intermediate will have positive impacts on the catalytic processes. These aspects are not as easily captured in TEA and will require further detailed catalyst testing (which is planned in our project), which will then enable a better comparison with ethanol-based routes.

Comments: Note that although the jet fuel produced from ethanol is ASTM certified, producing jet fuel from BDO would require a new certification from ASTM before it can be used in airplanes. ASTM approval for BDO to jet will need to be obtained. Response: Our project, which proposes to produce SAF blendstock (ASTM D7566), has specific tasks in Budget Period 3 and Budget Period 4 to assess and continually improve the fuel quality using ASTM D7566 tests. Detailed hydrocarbon product analysis is being conducted (and the first results were reported in our most recent quarterly report). This work will be performed in close collaboration with our industry partner.

Comments: Please explain the reasoning behind using pervaporation membranes for BDO dehydration? Response: The adsorption (simulated moving bed) process and the vacuum distillation column together remove the vast majority of the water (mainly the simulated moving bed) and recycle the ethanol desorbent (vacuum distillation). This produces a stream of approximately 85% BDO and 15% mostly water. The pervaporation membrane downstream performs last-mile dewatering of this stream to 90%–95% (this can be controlled); therefore, it is an important de-risking operation and is electrified (uses very little thermal energy). For example, if water content is found to have a significant long-term impact on downstream catalyst function, then the capability to control the last-mile water removal independently of the simulated moving bed and vacuum distillation will be a significant factor.

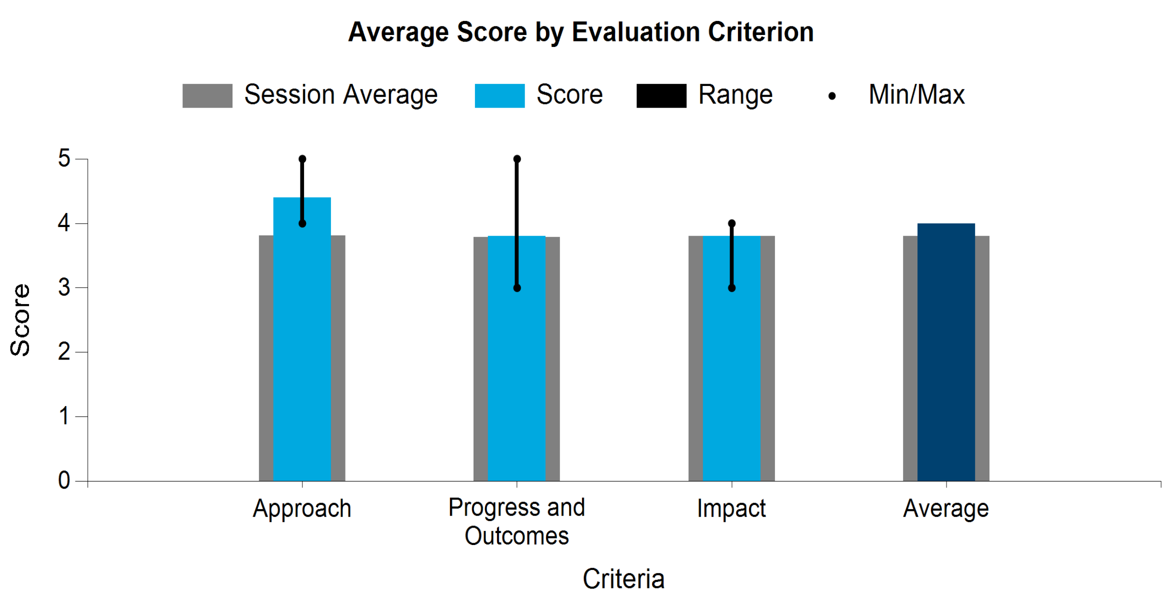
SCALE-UP OF THE PRIMARY CONVERSION REACTOR TO GENERATE A LIGNIN-DERIVED CYCLOHEXANE JET FUEL

University of North Dakota

PROJECT DESCRIPTION

WBS:	3.4.3.501
Presenter(s):	Wayne Seames
Project Start Date:	10/01/2020
Planned Project End Date:	06/30/2025
Total Funding:	$4,778,359

The goal of this project is to translate lab-scale reaction technology to produce cyclohexanes from corn stover-derived reactive lignin to the engineering scale and to determine the technical, economic, and environmental feasibility of producing jet fuel and byproducts from this technology. Corn stover is preprocessed by INL and shipped to NREL, where the deacetylation step of NREL's dilute alkali DMR process followed by evaporation is used to generate 10 wt % reactive lignin in a 10+ pH NaOH/water solution and shipped to the University of North Dakota. The lignin is then non-catalytically fragmented. The fragments are recovered by solvent extraction and hydrogenated into cyclohexanes using an Ru-based catalyst developed at Washington State University and pelletized by Advanced Refining Technologies. The conversion system is being optimized at the bench scale and then upscaled to the engineering scale, where it will be demonstrated with operation for at least 100 continuous hours and 500 total hours. Secondary objectives are to develop a less expensive, more efficient hydrogenation catalyst and improved analytical methods for comprehensive reaction product evaluation, plus production/testing of the prototype jet fuel. The technology is also being assessed via TEA and sustainability analyses.



COMMENTS

- Interesting concept, and the project progresses. Good work so far. There are a lot of challenges in the future, but the teams have demonstrated their capabilities. The project was not presented at the Project Peer Review; the presenter was not able to travel due to weather. This evaluation is based only on a review of the slides. The team has taken a sound, systematic approach to scaling from the lab scale to the engineering scale and evaluating the technical, economic, and environmental feasibility of the technology to produce SAF. So far, the team has been able to address multiple challenges as well as coordinating the work to meet tight schedules during the constraints of the pandemic. Biomass-derived cyclohexanes jet fuel/blendstocks would provide a renewable solution for the seal swell requirement and enable higher renewable content in jet fuels, especially Fischer-Tropsch jet fuels. The TEA will be important for evaluating the commercial viability, given that the preliminary TEA showed that the original process is not commercially feasible.

- The presenter was not able to be present for this review. The comments are based on the published charts. This seems like a comprehensive approach to experimental testing and modeling of the reaction conditions leading to catalyst improvement opportunities, including TEA to guide choices. Although the optimum set has not yet been identified, this approach holds promise to find a set of conditions that allow lignin in alkali media to be directly converted to cyclohexane that can be used to make jet fuel. This approach may also be useful to explore other feedstocks and other pathways to advanced biofuels.

- The following comments are solely based on the information obtained from the slide deck because the presenter was unable to attend the Project Peer Review. The main objective of this project is to produce cyclohexanes, which can be used as fuels, from the lignin fraction obtained during the biochemical processing of corn stover. The project team has demonstrated excellent coordination and has successfully modified the execution strategy to overcome challenges encountered during the implementation phase. The modified approach identified for the conversion of lignin to cyclohexanes holds promise; however, the efficient recovery and reuse of ethyl acetate may dictate the economics of this approach. It is unclear, however, if the team has revised the TEA to account for the alternative strategy identified. It is also uncertain how feasible it is to scale up the fragmentation of lignin and the extraction of solubles for conversion into jet fuel for commercial operations. Further analysis will be necessary to determine the commercial viability of this process.

- This project produces cyclohexanes from phenolic compounds in the lignin fraction of corn stover after DMR. If this can be done economically, it can have a very favorable impact on lignin valorization in cellulosic ethanol production while providing an important blending component for SAF in place of aromatics. Only preliminary results were shown, and the crucial TEA and LCA were not completed at the time of the presentation and will be critical to evaluate the potential success and commercialization potential. Switching to a multistep process will likely result in increased costs and added complexity. What is the hypothesis regarding the inability to hydrodeoxygenate the pH 10 NaOH solution? Is removal of the Na required? Is reduction of the pH required, or is the NaOH used as a basis for decomposition of the lignin? How is the lignin non-catalytically decomposed, and how effective is recycling of the non-decomposed lignin for achieving greater decomposition?

PI RESPONSE TO REVIEWER COMMENTS

- Thank you to the reviewers for their thoughtful and encouraging comments. In reference to Comment 4, we have demonstrated that more than 96% of the organics can be extracted from the fragmentation reactor outlet NaOH/water solution, that more than 99% pure ethyl acetate can be recovered by a single-stage distillation, and that the resulting organics have less than 0.1% ethyl acetate. A more comprehensive TEA is being prepared based on the current process scheme and the preliminary data obtained. This TEA will help us to focus future lab- and bench-scale research tasks while we are scaling up the process to the engineering scale. In reference to Comment 5, although the multistep process will be more complicated, the quantity of Ru-based catalyst is reduced by more than an order of magnitude, so we do not expect this version to be more expensive than the original single-step reaction scheme. We postulate that at high hydroxide concentrations, as the hydrogen disassociates, it quickly reacts with the hydroxide to form water instead of hydrogenating the lignin fragment compounds. The purpose of the NaOH is to increase the pH to increase the solubility of lignin in water. Other bases will also work and may eliminate this effect. These will be explored at the lab scale in the upcoming year. Complex organics like lignin are too large to fit in the pore of most catalysts, so the first step in any complex organic decomposition is most likely non-catalytic even when a catalyst is present. This is also when oligomers and other tarry compounds are formed that can foul catalysts. By separating the fragmentation and hydrogenation steps, these issues will be minimized, which may be more important operationally than having to use more unit operations. Preliminary results suggest that once the leftover lignin solution is concentrated back to its original concentration, that fragmentation comparable to the initial fragmentation can be achieved. We will be exploring this in more detail during the upcoming year.

FIELD-TO-FUEL PRODUCTION OF CARBON-NEGATIVE SUSTAINABLE AVIATION FUEL FROM REGENERATIVE-AGRICULTURE BIOMASS

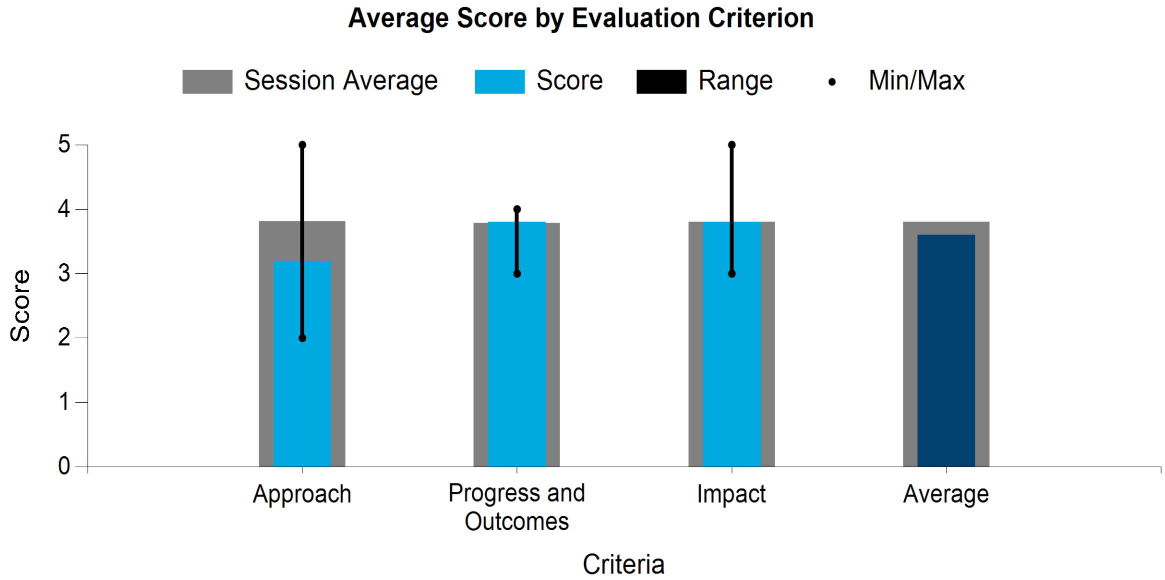
Alder Energy

PROJECT DESCRIPTION

WBS:	3.4.3.603
Presenter(s):	Derek Vardon
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$5,920,596

This project will scale Alder Energy's proprietary Alder Renewable Crude (ARC) technology to convert 0.5 tons per day (TPD) of biomass and produce SAF with negative carbon intensity from regenerative-agriculture miscanthus. Alder's ARC technology addresses the challenge of refinery hydrotreater plugging with commercial fast pyrolysis oils (FPOs) by employing solvent fractionation to generate two process streams for downstream upgrading. This allows ARC to undergo continuous hydrotreating to produce high C-yields of SAF that meets ASTM specs. We will evaluate regenerative-agriculture miscanthus biomass as the feedstock, which has the potential to produce SAF with negative carbon intensity due to the net carbon sequestered in the soil during cultivation. This project will provide key data to baseline woody biomass ARC performance against miscanthus ARC and conduct hydrotreating with iterative SAF fuel property testing for meeting ASTM specs. Success will provide the data needed to accelerate Alder's SAF commercialization.

To advance Alder's ARC technology, our team brings together world-class expertise across the entire SAF value chain. Our expertise includes FPO fractionation technology into ARC, regenerative-agriculture miscanthus field trials and carbon intensity quantification by AGgrow Tech and the University of Illinois, biomass preprocessing know-how by INL, commercial fast pyrolysis expertise by Biomass Technology Group (BTG), ARC hydrotreating and refinery integration expertise by Honeywell UOP and RPD Technologies, SAF fuel property testing expertise by Washington State University, TEA and LCA skill sets by NREL and the University of Illinois Urbana-Champaign (UIUC), commercial and business aviation industry insight for SAF by United Airlines and Gulfstream, and SAF flight test capabilities by United Airlines and Boeing. As the capstone, if target metrics are successful, we will conduct the world's first carbon-negative flight demonstration on Alder SAF produced from regenerative-agriculture miscanthus. If realized, this technology will spur the creation of new U.S. jobs for decarbonized energy and regenerative agriculture.



COMMENTS:

- The project has a significant number of participating partners. Managing them is complex and requires great effort. The company has not explained how they are handling it and whether they are having issues with the coordination. It is unclear why the team is using miscanthus when it seems to work with woody biomass. The presence of ashes in the feedstock may represent a very significant problem downstream and could prevent the use of pyrolysis oil in a hydrotreater. The company has not provided either TEA data to evaluate the economic feasibility of the technology and check the targeted production cost of $2.75/gallon or any LCA data.

- Alder is expanding its feedstock options to miscanthus, which has the potential to play an important role in regenerative agriculture. The presentation identified major risks for the project and provided sound risk mitigation strategies. Due to the higher nitrogen content in miscanthus, the miscanthus greencrude would have a higher nitrogen content than a wood greencrude. Does Alder plan to remove the nitrogen from the miscanthus greencrude? Could miscanthus greencrude and wood-based greencrude be processed together into SAF at the same refinery? The presentation has only a high-level overview of the process. What does Alder's core technology consist of?

  For the go/no-go decision in FY 2023 Q4 on slide 9, if metrics are not met for miscanthus, pivoting to wood-based pyrolysis oil is proposed. Has Alder and/or Honeywell UOP conducted the remaining project campaign with wood-based pyrolysis oil? If so, what new information would be gained?

  Feedstock harvesting, handling, processing, storing, and feeding are often overlooked and not given appropriate attention. What challenges in miscanthus handling and processing has the team encountered or anticipate that would require solving to successfully operate a continuous process at a commercial plant?

- The proposed process uses a relatively smaller biomass supply (miscanthus, which is usually grown on marginal land) as the feedstock, does a fast pyrolysis to a biocrude, then solvent extracts the lighter products from the heavier products. It seems that a hydrotreating step should follow that fast pyrolysis to remove oxygenates. After extraction, the lighter products proceed to another hydrotreating step for conversion to a mix of fuels. The heavier fraction goes to a cracker to make lights and heavies. It uses fairly well-proven unit operations, and the team has a lot of experience with those unit operations. Concerns include the feedstock not being a larger agriculture byproduct like corn stover, the multiple processing steps with their capital charge, and the usual concerns about feed composition variability. A detailed TEA and LCA needs to be done to determine if the claimed economic benefits are sustainable as the process is scaled up. The approach has merit if the feedstock mix can be expanded and the value of products offsets the cost of equipment and operation.

- The challenge for this project will be to coordinate a number of diverse partners and successfully deliver their deliverables. This will require effective communication, collaboration, and project management skills to ensure that everyone is working toward the same goals. The proposed approach for this project is the ARC pilot, which aims to leverage the conditions established with wood pyrolysis oil. A go/no-go decision will be made to determine whether to move forward with wood pyrolysis oil if necessary; however, if miscanthus were to replace woody biomass as the commercial feedstock, it would likely require significant modifications to the project plan and potentially result in a different project altogether. One potential issue with using nitrogen-rich feedstock is that it could increase the nitrogen content in SAF when the biocrude is inserted into the hydrotreater. To address this, the project team may need to explore different processing methods to reduce the nitrogen content or consider using a different feedstock altogether. It is unclear from the provided information how deoxygenation will be performed to remove the oxygen present in the ARC. This will need to be further explored and defined as part of the project planning process to ensure the successful implementation of the project.
- The expansion of SAF production will have to shift to lignocellulosic feedstocks that are more abundant, and pyrolysis-type technologies will play a very important role to deliver SAF volumes, provided that SAF production can be successfully commercialized and ASTM approval can be obtained. Commercialization of the Alder technology will play an important role in this regard. Although I have several concerns about the technology approach, this project is limited to an evaluation of miscanthus as a feedstock and an assessment of the carbon intensity of the feedstock. The development of energy crops for SAF production will be critical to deliver the high SAF volumes required to meet the climate targets for the sector, and this project is very relevant. Although the carbon intensity of a feedstock is critical, the overall sustainability based on Carbon Offsetting and Reduction Scheme for International Aviation (CORSIA) sustainability criteria should also be assessed. Carbon intensity and LCA must also be assessed based on CORSIA methodology, which will be relevant for SAF. This may differ from an assessment based on Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (GREET), and differences could provide important information to the improvement of the CORSIA method. The higher ash content in miscanthus (structural) will have an impact on the yield of the bio-oil (ARC and residual pyrolysis oil [RPO]) and impact the techno-economics. The miscanthus will likely also impact the fractionation of the bio-oil to ARC and RPO, and this will be relevant for the future suitability of miscanthus as a feedstock for this process. "Careful" harvesting of miscanthus to limit nonstructural ash content was proposed (in addition to winter harvesting to reduce ash from leaves), but the potential for these approaches to work at a commercial scale should be considered. Harvesting and processing at a small scale will not expose logistics and supply chain challenges such as storage to the scale-up of feedstock use.

PI RESPONSE TO REVIEWER COMMENTS

- Comments: The project has a significant number of participating partners. Managing them is complex and requires great effort. The company has not explained how they are handling it and whether they are having issues with the coordination. It is unclear why the team is using miscanthus when it seems to work with woody biomass. The presence of ashes in the feedstock may represent a very significant problem downstream and could prevent the use of pyrolysis oil in a hydrotreater. The company has not provided either TEA data to evaluate the economic feasibility of the technology and check the targeted production cost of $2.75/gallon or any LCA data. Response: We thank the reviewer for their comments.

This project leverages partnerships and diverse expertise from leading institutions across the bioenergy value chain to advance critical goals for the realization of carbon-negative SAF from regenerative agriculture. Joint milestones are used to ensure data integration and achieve project goals through coordinated contributions from all partners. Further, the communication strategy consists of project team meetings every 2 months to track progress, monthly small-group discussions centered on upcoming deliverables (e.g., field-to-gate miscanthus LCA), in addition to six-month project review meetings that include feedback from original equipment manufacturers and industry partners. Alder aims to enable process flexibility for feedstocks beyond woody biomass, and this project explores a regenerative-agriculture feedstock, miscanthus, and its potential for carbon-negative SAF production. Miscanthus holds significant promise for soil organic carbon sequestration relative to woody residues or annual crops like corn stover and sugarcane. Higher-ash-content biomass was identified as a key risk factor with possible impacts to pyrolysis, ARC, and SAF quality in this project. With this in mind, and with guidance from AGgrow Tech partners, the project team leveraged supply chain opportunities for managing feedstock quality, employing approaches for miscanthus harvest and timing to limit ash accumulation from soil contamination (nonstructural ash). In this study, structural ash content (inherent to biomass) was measured at approximately 0.7%, with accumulated ash at approximately 1.5% (dry matter). Ash content in corn stover often exceeds 5% (ranging from 5%–25%), with some reports of soil-derived, nonstructural ash exceeding 7%. In addition, preprocessing approaches were employed through the BFNUF housed at INL to further reduce feedstock ash content with selective preprocessing and fines removal of particles less than 500 microns. We appreciate the reviewer's feedback, and we will continue to closely track ash propagation and metal contaminants from feedstock through conversion to pyrolysis oil and fractionation to ARC and RPO to assess the impacts on hydrotreating and the final SAF product. The field-to-biorefinery gate LCA is currently underway and will combine high-quality data collected from field research sites with geospatial mapping and data-driven approaches developed by UIUC for evaluation of the miscanthus footprint. Miscanthus harvested from field research sites was characterized through compositional analysis and used for the production of FPO and fractionation to ARC at the bench and 10-gallon batch scales for hydrotreating and SAF production. During the next 6 months, the project team will scale to 20-metric-tons miscanthus for the production of FPO and continuous operations for ARC production at the barrel-per-day scale. These data will inform the TEA and LCA, allowing for the refinement of the final SAF product cost and field-to-fuel carbon intensity.

Comments: Alder is expanding its feedstock options to miscanthus, which has the potential to play an important role in regenerative agriculture. The presentation identified major risks for the project and provided sound risk mitigation strategies. Due to the higher nitrogen content in miscanthus, the miscanthus greencrude would have a higher nitrogen content than a wood greencrude. Does Alder plan to remove the nitrogen from the miscanthus greencrude? Could miscanthus greencrude and wood-based greencrude be processed together into SAF at the same refinery? The presentation has only a high-level overview of the process. What does Alder's core technology consist of? For the go/no-go decision in FY 2023 Q4 on slide 9, if metrics are not met for miscanthus, pivoting to wood-based pyrolysis oil is proposed. Has Alder and/or Honeywell UOP conducted the remaining project campaign with wood-based pyrolysis oil? If so, what new information would be gained? Feedstock harvesting, handling, processing, storing, and feeding are often overlooked and not given appropriate attention. What challenges in miscanthus handling and processing has the team encountered or anticipate that would require solving to successfully operate a continuous process at a commercial plant? Response: We thank the reviewer for their comments. Miscanthus harvest timing occurred after plant dry down and senescence—during which a significant translocation of nutrients, including N, occurs from the plant tissue back to the soil. Miscanthus used in this study had a measured N content of approximately 0.3%, comparable to softwood feedstocks evaluated in the ARC process. Experiments to date have not encountered high nitrogen, which is attributed to these steps taken during feedstock harvesting. It is anticipated that miscanthus and wood-derived ARC/greencrude can be processed in the same refinery.

Alder's core technology for renewable transportation fuel production links commercial fast pyrolysis technology with existing refinery infrastructure. Alder's proprietary technology fractionates FPO into two streams for renewable energy production: (1) ARC/advanced pyrolysis oil that can be shipped off-site for cohydroprocessing with fats, oils, and grease in existing refineries and (2) RPO that has the potential to be used as a boiler fuel for renewable electricity, upgraded to biogas, or hydrocarbon fuels via fluid catalytic cracking. Honeywell UOP has completed the first phase of development for ARC first-stage hydrotreating with woody biomass. Also, Alder has worked closely with partners at AGgrow Tech, UIUC, INL, and BTG to identify and mitigate challenges related to feedstock variability and supply chain and impacts to conversion. As discussed, miscanthus was harvested in late winter/early spring 2022 after plant dry down, senescence, and leaf fall to reduce moisture and limit ash content, improve feedstock quality, and provide material to meet pyrolysis infeed specifications. Moisture at harvest was approximately 10%–12% to ensure storage stability, and miscanthus was harvested with a standard forage chopper and blown directly into a wagon, so stems never touch the ground, further limiting ash contamination from soil (as discussed). Chopped miscanthus was stored in Ag-Bags (like silage bags) to preserve material at less than 15% moisture until further processing. The team has encountered minor challenges related to material feeding and handling of miscanthus biomass for pyrolysis. Alder is working with partners at BTG and INL to identify size reduction approaches that offer more uniform particle size distributions and a reduced particle aspect ratio to improve flowability, feeding, and handling and facilitate conversion. The team is also working to identify opportunities to reduce the carbon intensity of biomass size reduction required for pyrolysis infeed specifications. In batch studies, lower ARC mass yields were obtained due to the reduced lignin content in miscanthus relative to woody biomass. For successful operation at the commercial scale, reductions in ARC yield must be balanced by RPO, which can be upgraded to value-added fuels and chemicals.

Comments: This proposed process uses a relatively smaller biomass supply (miscanthus, which is usually grown on marginal land) as feedstock, does a fast pyrolysis to a biocrude, then solvent extracts the lighter products from the heavier products. It seems that a hydrotreating step should follow that fast pyrolysis to remove oxygenates. After extraction, the lighter products proceed to another hydrotreating step for conversion to a mix of fuels. The heavier fraction goes to a cracker to make lights and heavies. It uses fairly well-proven unit operations, and the team has a lot of experience with those unit operations. Concerns include the feedstock not being a larger agriculture byproduct like corn stover, the multiple processing steps with their capital charge, and the usual concerns about feed composition variability. A detailed TEA and IRR (internal rate of return) needs to be done to determine if the claimed economic benefits are sustainable as the process is scaled up. The approach has merit if the feedstock mix can be expanded, and the value of products offsets the cost of equipment and operation. Response: We thank the reviewer for their comments. Please see the brief description of Alder's proprietary fractionation technology in the response to Reviewer 2. Alder's technology separates the "bad actors" and reactive components, including small oxygenates, from FPO into an aqueous phase, and it significantly reduces the reactive oxygenates in ARC prior to hydroprocessing. The aim of this project is to evaluate ARC yields achievable through regenerative-agriculture miscanthus and integrate field-scale carbon flux data with modeling approaches to quantify the carbon intensity of the ARC-SAF pathway and potential for carbon-negative SAF. The results of this project will be directly compared with more abundant feedstocks that are also being assessed by Alder, such as woody biomass sources. This project does not consider a first-generation feedstock like corn stover given its variable feedstock quality, high ash content (see response to Reviewer 1) exceeding limits for pyrolysis, and requirement for intensive agricultural practices, which are not carbon neutral. With a purpose-grown feedstock like miscanthus, there are fewer sources of variability inherent to the biomass given the homogeneity in the vegetative portion of the plant and harvest timing after leaf fall and senescence, further reducing the ash content (see response to Reviewer 1). This project can also contribute insights to how harvest timing and agricultural practices are used in feedstock quality management for sustainable and profitable SAF production. The project is partnered with BTG bioliquids to produce pyrolysis oils, which has processed more than 75,000 tons of biomass into FPOs and evaluated more than 50 biomass feedstocks. Alder is leveraging BTG's vast expertise in feedstock composition variability impacts on both pyrolysis to gain deeper insight into potential impacts on the ARC process and upgrading to SAF. This project began Budget Period 2 execution on Dec. 12, 2022, and a preliminary TEA and LCA for the field-to-gate process will be reported in the FY 2023 Q3 milestone on June 30, 2023. During the next 6 months, the project team will scale to 20 metric tons of miscanthus for FPO production and continuous operations for ARC production at the barrel-per-day scale. These data will inform the TEA and LCA, allowing for the refinement of the final SAF product cost and field-to-fuel carbon intensity. We appreciate the reviewer's feedback regarding the current scale of miscanthus production. Projections from a recent study show promise for miscanthus to contribute 30 billion gallons per year of SAF from marginal lands in the rain-fed United States. This project will combine high-quality field data with geospatial mapping tools to refine estimates for miscanthus yields and sequestration potential under various environmental scenarios. The outcomes of this project can be used as a market pull for regenerative agriculture to produce carbon-negative SAF.

Comments: The challenge for this project will be to coordinate a number of diverse partners and successfully deliver their deliverables. This will require effective communication, collaboration, and project management skills to ensure that everyone is working toward the same goals. The proposed approach for this project is the ARC pilot, which aims to leverage the conditions established with wood pyrolysis oil. A go/no-go decision will be made to determine whether to move forward with wood pyrolysis oil if necessary; however, if miscanthus were to replace woody biomass as the commercial feedstock, it would likely require significant modifications to the project plan and potentially result in a different project altogether. One potential issue with using nitrogen-rich feedstock is that it could increase the nitrogen content in SAF when the biocrude is inserted into the hydrotreater. To address this, the project team may need to explore different processing methods to reduce the nitrogen content or consider using a different feedstock altogether. It is unclear from the provided information how deoxygenation will be performed to remove the oxygen present in ARC. This will need to be further explored and defined as part of the project planning process to ensure the successful implementation of the project. Response: We thank the reviewer for their comments. Alder has extensive experience dealing with complicated team structures. Alder's chief technology officer, Dr. Derek Vardon, formerly led a team within the CO-Optima initiative, and our research director, Dr. Allison Ray, is formerly of the FCIC. Our team is well experienced with multi-institution project management. In our ARC R&D activities related to woody biomass, we have created tools for sample management, executed tolling production runs, and coordinated analysis in collaboration with national lab, domestic, and international business partners. This project leverages diverse expertise from leading institutions across the bioenergy value chain to advance critical goals for the realization of carbon-negative SAF from regenerative agriculture. Joint milestones are used to ensure data integration and achieve project goals through coordinated contributions from all partners. This requires a collaborative, communication strategy that consists of project team meetings every 2 months to track progress, monthly small-group discussions centered on upcoming deliverables (e.g., field-to-gate miscanthus LCA), in addition to six-month project review meetings that include feedback from original equipment manufacturers and industry partners. As noted, miscanthus N content was measured at approximately 0.3%, comparable to softwood feedstocks evaluated in the ARC process. Alder did not identify high nitrogen levels in miscanthus-derived FPO or ARC at the 2-metric-ton scale and batch processing. Miscanthus FPO contained 0.1% N, and advanced pyrolysis oil contained 0.2% N (analysis precision is approximately 0.1%). Alder's proprietary fractionation technology separates the bad actors and reactive components, including small oxygenates, from FPO into an aqueous phase, and it significantly reduces oxygenates in ARC prior to hydroprocessing. Alder collaborates with partners at Honeywell UOP and RPD Technologies for deoxygenation via hydrotreating ARC to fuel products.

Comments: The expansion of SAF production will have to shift to lignocellulosic feedstocks that are more abundant, and pyrolysis-type technologies will play a very important role to deliver SAF volumes, provided that SAF production can be successfully commercialized and ASTM approval can be obtained. Commercialization of the Alder technology will play an important role in this regard. Although I have several concerns about the technology approach, this project is limited to an evaluation of miscanthus as a feedstock and assessment of the carbon intensity of the feedstock. The development of energy crops for SAF production will be critical to deliver the high SAF volumes required to meet climate targets for the sector, and this project is very relevant. Although the carbon intensity of a feedstock is critical, the overall sustainability based on CORSIA sustainability criteria should also be assessed. Carbon intensity and LCA must also be assessed based on CORSIA methodology, which will be relevant for SAF. This may differ from an assessment based on GREET, and differences could provide important information to improvement of the CORSIA method. The higher ash content in miscanthus (structural) will have an impact on the yield of the bio-oil (ARC and RPO) and impact the techno-economics. The miscanthus will likely also impact the fractionation of the bio-oil to ARC and RPO, and this will be relevant for the future suitability of miscanthus as a feedstock for this process. “Careful” harvesting of miscanthus to limit nonstructural ash content was proposed (in addition to winter harvesting to reduce ash from leaves), but the potential for these approaches to work at a commercial scale should be considered. Harvesting and processing at a small scale will not expose logistics and supply chain challenges, such as storage to the scale-up of feedstock use. Response: We thank the reviewer for their comments. As discussed in our previous responses, high ash content was identified as a key risk factor for miscanthus-derived SAF. CORSIA’s default life cycle emissions values, which have been produced partly in GREET, are not yet available for hydrotreated depolymerized cellulosic jet fuels, such as the ARC-derived SAF; hence, we are following the CORSIA methodology for calculating actual life cycle emissions values using GREET. Based on an in-house assessment of the CORSIA sustainability criteria, we expect the ARC-derived SAF from miscanthus to be certified as a CORSIA eligible fuel by an approved Sustainability Certification Scheme in the future. Also, we agree with the reviewer that ash content is a key consideration related to feedstock quality for pyrolysis-based pathways and can significantly impact FPO yields. The impacts of ash content on FPO yield will be dependent on the elemental composition, in particular the concentration of alkali and alkaline earth metals relative to inert species (like silicon). Detailed characterization of miscanthus for this project has revealed that ash was significantly reduced (approximately 2%) when compared to agricultural residues like corn stover. In the first phase of the project, batch experiments with miscanthus (approximately 2 metric tons) resulted in FPO yields comparable to previous experiments with woody feedstocks. We agree with the reviewer that the scale-up of feedstock logistics and supply chain challenges are an important consideration for technical feasibility and economic viability in de-risking ARC technology with miscanthus regenerative agriculture for SAF. Given that feedstock quality and availability are central to this project, Alder has established key partnerships with industry, academia, and national laboratories to address the intersections of the feedstock supply chain with conversion to ensure alignment of the technical approach with commercial relevance. Alder is working with a commercial partner, AGgrow Tech, a leader in renewable agriculture that is implementing innovative and sustainable agriculture solutions with miscanthus farms in 11 states and has 8,000 acres under management. UIUC is the world leader in sustainable agriculture analysis and bioenergy crops science, including miscanthus cultivated using regenerative agricultural practices. UIUC efforts also include the Center for Advanced Bioenergy and Bioproducts Innovation, whose goal is to develop and deploy technologies and crops that are economically and ecologically sustainable. INL and NREL are leading national laboratories funded by BETO in feedstock and conversion technologies, respectively, and are the lead labs in BETO’s FCIC to address challenges posed by feedstock variability, material handling, and preprocessing. INL is the lead lab for feedstock and preprocessing technologies, while NREL is DOE’s premier biofuel research laboratory. As noted in the response to Reviewer 3, the team hopes that broader project outcomes can be used as a market pull for regenerative agriculture to produce carbon-negative SAF.

INTEGRATION OF IH^2 WITH THE COOL REFORMER FOR THE CONVERSION OF CELLULOSIC BIOMASS TO DROP-IN FUELS

Gas Technology Institute

PROJECT DESCRIPTION

WBS:	3.5.1.101
Presenter(s):	Terry Marker
Project Start Date:	10/01/2019
Planned Project End Date:	12/31/2023
Total Funding:	$1,596,065

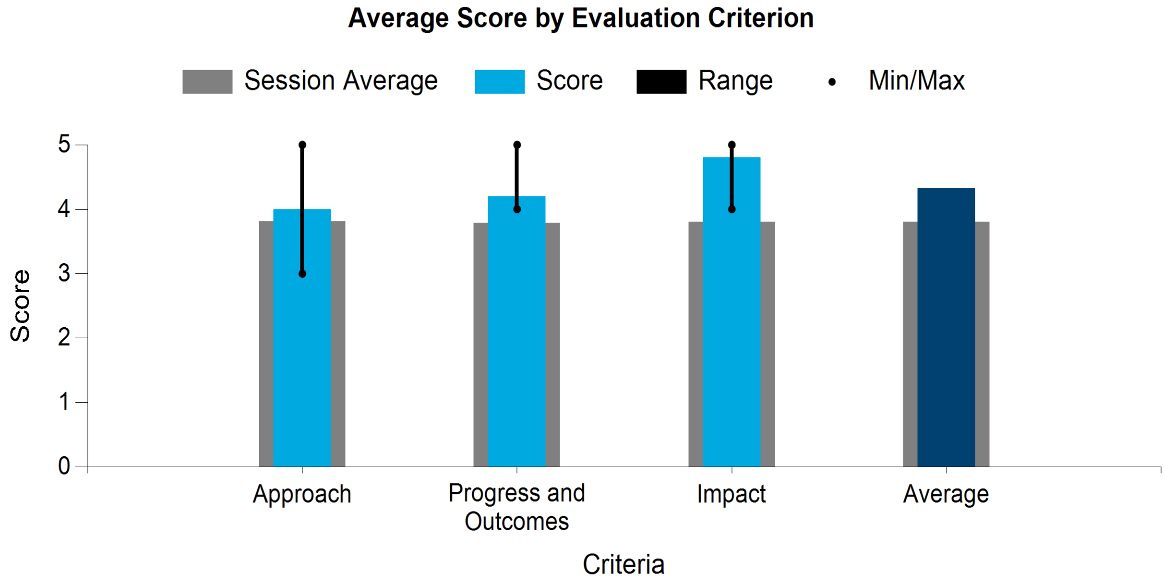
In this project, we will integrate the IH^2 pilot plant with the Cool Reforming pilot plant to show that the IH^2 process is hydrogen self-sufficient and that the systems can be integrated in a simple, low-cost way. The goal of the project is to:

- Make drop-in fuels from cellulosic biomass for less than $2.5/GGE.
- Show that the integrated system is hydrogen self-sufficient.
- Show that the integrated system is simple and low cost.
- Run the integrated system for more than 1,000 hours and more than 100 continuous hours, and produce more than 100 gallons of drop-in biofuel with less than 0.4% oxygen.
- Demonstrate that the integrated system can convert more than 50% of the biogenic carbon from a wood feed into biofuel.
- Develop a skid-mounted modular design for IH^2 based on the Cool Reformer integration along with innovative new technologies for all peripheral equipment, and reduce the capital cost by more than 30% and the operating cost by more than 40%.
- Confirm that the improved design reduces GHG emissions by more than 70% compared to petroleum fuels.

The IH^2 process uses hydropyrolysis followed by hydroconversion to convert cellulosic biomass directly to high-quality drop-in fuel. The IH^2 process produces 86 gallons per ton of high-quality gasoline and diesel from wood. Cool reforming can convert the biogas from the IH^2 process to make all the hydrogen required in the IH^2 process in a simple, low-cost process.

This project will lead to the rapid commercialization of the IH^2 process in compact modular plants. These modular plants will be used to produce bio-renewable drop-in fuel for less than $2.5/GGE.

Major participants in the project are Gas Technology Institute (GTI) Energy, Shell Catalysts and Technologies, KBR, Michigan Technological University, and SynSel Energy.



COMMENTS

- The project's objective is to demonstrate that there is no need for makeup hydrogen. Shell owns all the rights to IH^2. The catalyst is provided by Shell (ICR). The project is almost finished and has demonstrated its main objective: Show H_2 self-sufficiency with the integrated Cool Reformer, and verify there is no need for makeup hydrogen in the integrated process. The IH^2 process consists of biomass hydropyrolysis and a hydroconversion to produce liquid fuel. The current project will use the incondensable gases produced in the hydrocracking reaction to generate hydrogen in the Cool Reformer to demonstrate that both integrated systems can self-produce enough hydrogen for the IH^2 process. The project has demonstrated its feasibility in a short-term run, and in its final step, it will run for 250 hours continuously. GTI invented the IH^2 technology, but Shell has purchased all rights to commercialize it.

- The project has successfully demonstrated short-duration integration of the IH^2 with the Cool Reformer and reduction of the number of unit processes, which should reduce capital expenses (CapEx), operating expenses (OpEx), and operational complexity. It is good to see slide 26 identify specific process improvements that provide for improved techno-economics. The presentation did not provide any information on feedstock used in the testing and the preprocessing requirement for biomass feedstock. For forest residue, would bark and needles/leaves need to be removed?

- Combining hydropyrolysis and hydrogenation to make up the IH^2 process appears to have been successful for the feedstock used (wood). The program needs to demonstrate this with corn stover and other biomass to mitigate the concern that those might be much less clean and consistent, especially over storage time. The partner (Shell) is bringing expertise on fluid bed reactor and catalyst design to the hydropyrolysis step, a significant unit operation in the process. It looks promising, but I would like to see the TEA and IRR work.

- This project, the first of its kind of the integration of the IH^2 process with reforming, has shown promising progress toward achieving its objectives. To fully evaluate the success of this project, a comprehensive table outlining the final cost and TEA, environmental impact, and GHG reduction achieved should be presented as the project nears completion. Additionally, a section detailing lessons learned and how unanticipated changes were effectively addressed during the project's execution would be beneficial. To better understand GTI's various projects, it would be helpful to have clear illustrations that highlight similarities and differences between them. This will allow stakeholders to better evaluate the potential impact of each project and identify best practices that can be applied to other initiatives. Moreover, learning how project team members from different departments collaborate during the execution phase and how they share learnings from various projects can provide valuable insights into the success of these projects.

- The IH^2 process has significant potential to advance drop-in biofuels production through the hydropyrolysis of cellulosic biomass. This project demonstrates the potential to use the gas from the IH^2 process to produce hydrogen for upgrading the liquid product (presumably to remove oxygen and produce saturated hydrocarbons). This could potentially reduce the production cost of the IH^2 fuels and reduce the carbon intensity. This information needs to be provided. One of the project objectives is stated as a reduction in the cost of gasoline, jet, and diesel to less than $2.50/GGE; however, no TEA results were shown to demonstrate that this will be achieved. What is the current cost of gasoline, jet, and diesel with the IH^2 process, and how much does this integration reduce the cost?

PI RESPONSE TO REVIEWER COMMENTS

- GTI has tested the IH^2 process for a variety of feedstocks, including some that include bark and corn stover. Corn stover and bark have lower liquid yields than wood, but they are acceptable feeds for IH^2 as well. The final project report will include the techno-economics for this improved reformer system; however, the techno-economics for the current IH^2 were done previously, which were very promising. Because of limited funding, we were unable to include an LCA analysis in this project; however, earlier studies of IH^2 LCA have also shown a very favorable LCA, with more than a 70% CO_2 reduction.

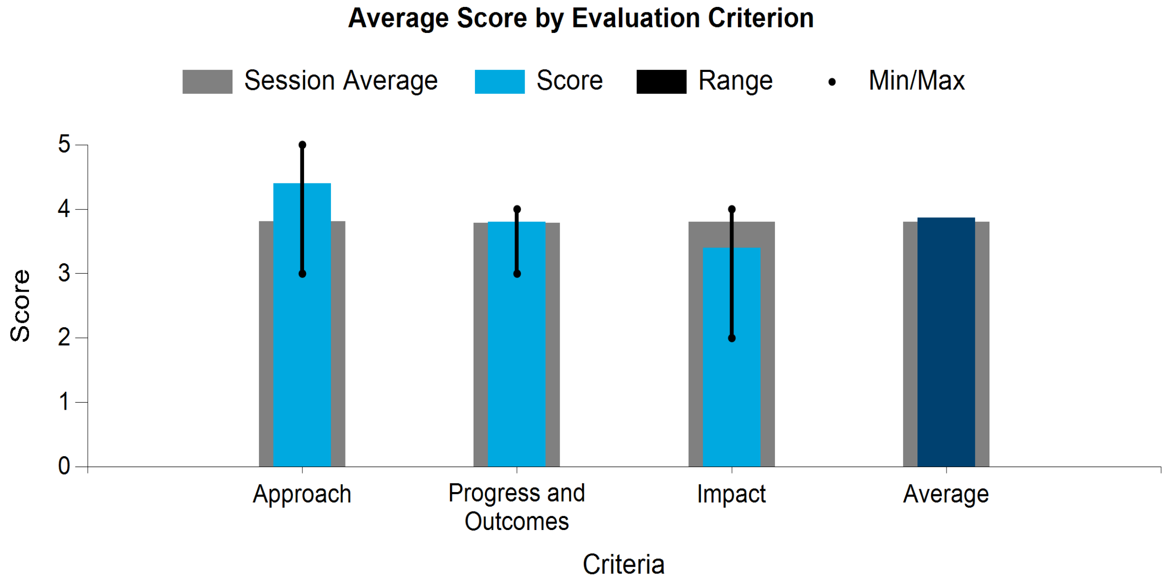
TRIFTS CATALYTIC CONVERSION OF BIOGAS TO DROP-IN RENEWABLE DIESEL FUEL

T2C-Energy

WBS:	3.5.1.201
Presenter(s):	Devin Walker
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2023
Total Funding:	$2,909,698

PROJECT DESCRIPTION

There are 2,451 landfills, 1,241 wastewater anaerobic digester facilities, and 282 agricultural anaerobic digester facilities in the United States. These sites generate more than 800,000 standard cubic feet per minute (scfm) of biogas representing a fuel equivalent of 3.7 billion GGE/year. The biggest challenge to this industry is its largely decentralized nature. Existing biogas projects include direct heating, electricity generation, and enrichment of methane for pipeline use or for natural gas-powered vehicles. T2C-Energy has developed and patented a novel catalytic technology that we have trademarked TRIFTS for the direct conversion of biogas to drop-in transport fuels. This project is focused on optimizing this new TRIFTS technology at a relevant engineering scale capable of using both the CO_2 and CH_4 portions of biogas and incorporating them into the hydrocarbon backbone of the final product of the process (renewable drop-in diesel). This renewable source of diesel resembles its petroleum counterpart both physically and chemically, and it can be used in current-day engines with no engine modifications necessary. Heavy equipment and waste-hauling trucks can therefore unload and refuel at the same landfill or anaerobic digester site with a renewable diesel fuel derived from the very waste they hauled; thus, a closed-loop process is created from feedstock to end point user. 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- to 24-scfm 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 highly profitable manner and at scales that were traditionally not thought economically feasible. The biogas variations, catalytic parameters, process dynamics, system performance, process LCA, and fuel product quality will all be monitored and studied over sufficiently long-term periods (more than 500 hours per site) to optimize the efficiency, productivity, and economics of the TRIFTS process and to incorporated into the scale-up of the TRIFTS plant designs. Economic opportunity; job creation; production of drop-in renewable fuel, fertilizer, and freshwater; and the creation of circular economies within the United States at the rural and metropolitan levels are direct impacts of this project.



COMMENTS

- This is a good presentation. There is a lot of good data. It includes credible information and is a good business concept. It can survive with no subsidies. Well done. I have concerns about the catalyst life. The presenter said it would last at least 6 months, but no proof was provided. There is very little information about the type of catalyst, cost, and regeneration procedures. It is not clear how the company is going to deploy the technology. Will it be in large biomass-producing sites, building large facilities, or installing mobile units and running campaigns?

- This project presents an investigation of a new catalytic process that removes five unit processes and thereby simplifies the GTL process platform while also using the CO_2 to maximize production. The capture and use of waste heat and Fischer-Tropsch synthesis (FTS) water helps to create a self-sufficient process and is a best practice for sustainability, and it may be key to making this process economically feasible at the commercial scale. The project seems to replicate actual commercial operation conditions by using raw biogas as the feedstock and using the FTS water in the process (with results showing a lack of impact on the process and products).

  Slide 8 shows that the TRIFTS system produces the jet fraction. A distillation system, which is a well-proven technology, would be needed. The project team has chosen to produce only renewable diesel to minimize the number of unit processes and associated costs and to keep the number of products to one.

  The presentation indicated an MFSP of $2.91/GGE without subsidies or credits, validated by an independent engineer, which is commendable. At what scale was the MFSP of $2.91/GGE calculated? It would be helpful to see at what scale this process is economically feasible, given that FTS is generally economic at large scales.

  Can the catalysts (for tri-reforming and FTS) be regenerated, and if so, how many times? How long does it take to regenerate? Would the catalyst be regenerated in place, or would it be removed from the reactors and regenerated off-site? How would the catalyst be disposed? Does the catalyst contain anything that would make it a hazardous waste that would require treatment or special disposal methods?

  What does the waste industry scale translate to in terms of the range of production volumes of the renewable diesel (in gallons or barrels)?

- The rationale to have biogas to reformers and syngas-to-liquid fuel at small and distributed scales is not elucidated well, if at all. Conceptually, this project can make a significant contribution to the decarbonization of rail and heavy transportation fuels, but success depends both on the widespread use of biomass digestion to biogas and the aggregation to clustered conversion facilities to ensure economy of scale. In addition to the pending verification trials, a TEA and risk assessment is needed to better understand the economic impact and ability to reach the goal $/GGE without renewable identification numbers (RINs).

- Additional data on experimental runs besides the 4 days in October 2021 that were highlighted in the slide deck should be included to provide a more comprehensive picture of the project's performance. Please provide details on how the small-scale FTS operates and if any challenges were encountered during its operation at a smaller scale? Because this project is coming to an end, it would be beneficial to have a summary table that includes information on the final costs, LCA, GHG reductions achieved, and any other relevant economic data. In addition, it would be helpful to compare the actual completion dates of tasks and milestones with the original proposed dates and to get insights on lessons learned and how unexpected changes/challenges were addressed. Finally, a risk register should be integrated into the project deliverables to ensure that all completed projects include an assessment of potential risks that might adversely affect the project's goals and objectives.

- This is an excellent project, and the approach is thorough and comprehensive. The technology has been demonstrated based on different sources of biogas and the quality of the renewable diesel meets standards. The modular approach for testing is very interesting and has potential to access smaller volumes of biogas at multiple locations, a resource that is underused. Although the potential for licensing modular units for small-scale production was stated as one approach in the business plan, it is questionable whether this type of sophisticated technology could be operated without highly skilled technicians. An analysis of the fuel product characteristics versus ASTM specifications should be included. Has the pathway been approved by the U.S. Environmental Protection Agency (EPA) for RIN generation? What are the GHG reductions achieved, and was this measured using GREET?

PI RESPONSE TO REVIEWER COMMENTS

- Catalyst and process longevity studies were done during a seven-month continuous pilot study on-site at the Citrus County central landfill using the raw biogas produced at this MSW landfill. During this pilot demonstration, the plant consistently achieved methane conversions of 88%–92%, at times approaching the theoretical maximum conversions of 99%. CO_2 conversions were consistently between 30%–40%, at times reaching 50%–60% conversions. Conversion efficiencies during the long-term pilot demonstration aligned with bench-scale results as we proved the ability to maintain high conversions throughout the entirety of the demonstration. During the entirety of the demonstration, the reformer was able to produce the ideal syngas composition, with an H_2:CO ratio of 1.7–2.2. This is one of the unique aspects of our tri-reforming capabilities to tune the syngas H_2:CO ratio as needed throughout the demonstration. During this pilot demonstration, the plant consistently achieved CO conversions of 50%–70%. During the pilot demonstration, we intentionally limited the CO conversion to 60%–70% because it is known that higher conversions can lead to high partial pressures of H_2O and deactivate the FTS catalyst; however, there were little to no signs of FTS catalyst deactivation throughout the entirety of the demonstration, and, in fact, we achieved our greatest conversions toward the last few weeks of the demonstration. Typical industrial GTL have lifetimes of approximately 4–5 years. Based on the long-term pilot data at the Citrus County landfill, the catalyst used in this project would meet or exceed industrial catalyst lifetimes. The reformer and FTS catalysts used in this project were produced in-house using a T2C-Energy patented catalyst. Currently, T2C-Energy manufactures the reforming and FTS catalyst at $20.44/kg and $85.59/kg, respectively. Current manufacturing capabilities allow us to produce approximately 10 kg/hour of catalyst. During the pilot demonstration, regenerative studies were performed using two techniques. The first technique involved regenerating the reforming and FTS catalyst while remaining online (*in situ* regeneration). Higher steam flows are fed to the reformer to oxidize the carbon deposits on the catalyst surface. This increases the H2:CO ratio of the syngas product while also removing carbon in the form of methane. The elevated H2:CO ratios feeding the FTS facilitate carbon removal and shift the FTS products to a lighter boiling point fraction, allowing for continuous operations as the FTS catalyst bed is regenerated. This regeneration cycle typically takes approximately 2–4 hours to complete and return to steady-state conditions. The second regeneration technique requires the feed to both reactors to be removed and replaced with a steam/air feed, effectively oxidizing coke deposits on the catalyst surface. This is done over a 1-hour period, followed by a reduction gas mix of hydrogen and nitrogen to reduce the active metal of the catalysts. This second regeneration cycle takes approximately 24–30 hours to complete and return to steady state. The second regeneration technique is more rigorous and done approximately every 2,000 hours of run time or if the catalyst activity drops 10% below the desired conversion efficiencies. Both regeneration methods are performed within the respective reactors for reforming and FTS. Spent catalyst are disposed of according to EPA solid waste regulations (K171). This includes utilization to produce new catalysts and other useful materials, recycling through recovery of metals, and treatment of spent catalysts for safe landfill disposal. The full-scale TRIFTS modular system is designed to accommodate biogas production facilities generating 123–1,750 scfm. This is T2C-Energy's short-term serviceable available market because most commercial technologies struggle to remain profitable within this range. Larger centralized facilities with traditional construction methodologies will be deployed once confidence within the waste-to-energy sector is gained through proven full-scale operational data within the biogas range from 123–1,750 scfm. The average biogas flow rates of an anaerobic digester facility and landfill in the United States are 210 scfm and 1,380 scfm, respectively. At these biogas flow rates using the TRIFTS process, the average size anaerobic digester would produce 230,000 gallons of renewable fuel annually, while an average size landfill would produce 1,470,000 gallons of renewable diesel fuel annually. The MFSP of $2.91 validated by an independent engineer was calculated based on a biogas feed rate of 1,500 scfm and excludes environmental attribute revenues. T2C-Energy has specifically targeted landfills producing more than 300 scfm of landfill gas, farm-based anaerobic digester's producing more than 123 scfm of biogas, and wastewater anaerobic digester's producing more than 275 scfm of biogas. Sites flaring the majority of their biogas and sites producing electricity from biogas with expiring electrical power purchase agreements meeting these biogas flow rate capacities are T2C-Energy's short-term market focus. Stranded facilities where the natural gas pipeline infrastructure does not exist are of particular interest for TRIFTS biogas-to-diesel projects. T2C-Energy has gained interest from these "stranded" facilities and also from developers wanting to avoid the costly gas connection/distribution fees of natural gas pipeline owners. Liquid fuel production simplifies logistics in that it can be stored and transported under ambient conditions; therefore, current freight and rail distribution channels are used, and the project location becomes less relevant than renewable natural gas (RNG) types of projects. TRIFTS landfill projects generate a carbon intensity score of -36 gCO_2e/MJ fuel, and therefore for the project to break even, the flow rate of landfill gas needed is 300 scfm. Whereas TRIFTS farm-based anaerobic digester projects have carbon intensity scores of less than -500 gCO_2e/MJ, and therefore for the project to break even, the flow rate of biogas needed is 123 scfm. Carbon intensity scores are based on the ANL GREET module that was completed under this project for the TRIFTS fuel production pathway.

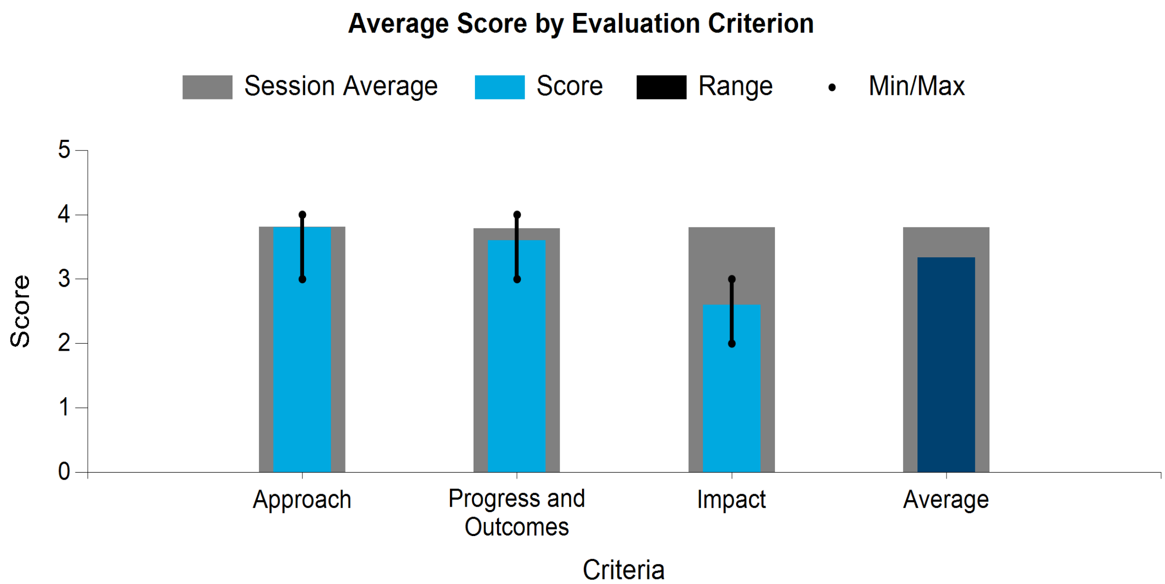
PRODUCTION OF LIQUID HYDROCARBONS FROM ANAEROBIC DIGESTER GAS

OxEon Energy LLC

PROJECT DESCRIPTION

WBS:	3.5.1.203
Presenter(s):	Jessica Elwell
Project Start Date:	10/01/2019
Planned Project End Date:	12/31/2023
Total Funding:	$2,494,236

OxEon proposed a process for the conversion of both CO_2 and CH_4 in anaerobic digester GTL transportation fuels containing three elements. A solid oxide electrolysis cell (SOEC) system converts steam and CO_2 to synthesis gas (CO and H_2) by high-temperature electrolysis. A plasma reformer converts methane to synthesis gas using the plasma to catalyze the reaction of methane with steam and oxygen supplied as oxygen-enriched air. The oxygen enrichment is the result of byproduct oxygen from the electrolysis system. The syngas from the plasma reformer and electrolysis systems are combined to produce liquid fuels in the Fischer-Tropsch reactor. Each subsystem has undergone and completed verification to key targets, and the full system fabrication and integration is underway.



COMMENTS

- The project uses four expensive block components to convert biogas to liquid fuels:

    1. CO_2-CH_4 gas separation
    2. SOEC for CO_2 to syngas
    3. Plasma reactor for CH_4 conversion to syngas
    4. Fischer-Tropsch reactor for the production of liquid biofuels.

This is a very complex approach, and it is difficult to understand if the project economics make sense and whether the technical approach is feasible. The company should clarify if they have worked with real biogas and how they manage impurities that may affect the SOEC. Working with bottled gas is not the same, and they may face big challenges down the road. There have been problems with the Fischer-Tropsch catalyst, but the company has not explained the issues and how they are trying to solve them.

- OxEon seems to have the appropriate approach to developing its three proprietary process units and their integration; however, the combination of the three technologies (SOEC, plasma reformer, and Fischer-Tropsch) into one process platform seems complex and expensive. The technical and market advantages of this process platform are not clear. Has the plasma reformer been tested with biogas or only natural gas? What contaminants and impurities are the processes sensitive to?
- This project relies on large-scale biogas availability and delivery to a conversion plant for success, as do several other similar projects. The conversion technologies envisioned are, to a large extent, relatively unproven at scale, especially in an integrated process, although individually at the pilot scale they appear to be capable. Linking these technologies together into an integrated process at a reasonable scale will be essential to prove that the approach is viable versus other syngas-to-advanced fuels concepts. Of key concerns are the plasma reactor and the electrolysis steps and integrating those with Fischer-Tropsch with high recycle ratios. The hot-gas-side stream is not fully integrated into the process for making fuels. In addition, the team needs to understand the effects of contaminants and composition variability of RNG on catalyst performance and life. A detailed TEA is planned and recommended.
- This project is quite complex because it involves the integration of three unique technologies with recycle streams. Each technology has been independently tested, making this integration project a first of its kind. The process involves separating CO_2 and methane before using them in the solid oxide co-electrolysis and plasma reformers, respectively; however, it raises the question of whether it is necessary to separate them. Is it possible to reform the combined CO_2 and methane instead to produce the necessary syngas for the downstream Fischer-Tropsch reactor? The inclusion of results from the verification tests of individual components has been helpful to understand this project. It has aided in ensuring that each component is properly functioning before integrating them. The biggest risk could be how the recycle streams would impact the performance of the electrolysis cell and plasma reformers when all components have been integrated together.
- This project focuses on the production of liquid hydrocarbons from anaerobic digestion gas, and the goals align with BETO’s goals. The project includes multiple steps with novel and complex (expensive) technologies that have been developed by the applicants, and the project goal is the integration of these units for the production of hydrocarbons. Successful operation of individual units has been demonstrated, and integration will be challenging. But overall, the techno-economics derived from data in this stage will be a critical determinant of the potential of this pathway. Three specific items came to my attention that need to be addressed. As part of the integration, the syngas going into the Fischer-Tropsch reactor may have contaminants that could cause catalyst inhibition in the Fischer-Tropsch. It is not clear whether the syngas has been analyzed and whether a strategy is in place to address this. The current approach is to flare gases after the FTS, which will reduce product yield, and recycling of the gases for syngas production should be considered as part of the integration. Though not specifically important for the integration, the future commercial viability of the technology must address the following: The FTS produces a wide range of fuel products and will require separation and perhaps further upgrading. Although this is not the target of the project, it is very relevant for the future commercialization potential of the technology. At a small scale, this might not be economic. A profile of the hydrocarbons based on carbon chain length should be provided. A strategy and future business approach to product upgrading and separation will be needed. Fischer-Tropsch catalyst development has

been targeting bifunctional catalysts to produce a narrower range of hydrocarbon products, and this could be explored to minimize the number of products.

PI RESPONSE TO REVIEWER COMMENTS

- OxEon appreciates the valuable feedback on this project. We agree that SOEC and Fischer-Tropsch technologies are currently costly at scales matching biogas resources. Recent E.U. mandates for SAF include power-to-liquids SAF, and the expectation is that costs will be substantially reduced through plans currently in development at OxEon (increase in power density of the cells, automation of assembly process for SOEC, etc.). The power-to-liquids SAF approach uses the electrolysis of CO_2 and steam to produce synthesis gas (CO, H_2; commonly "syngas") and then Fischer-Tropsch to fuels. Combining CO_2 and CH_4 to fuels will have better economics for two reasons. First, the biomethane reformation process requires almost no additional energy input (1%–2% electric for plasma), and the reformer is relatively inexpensive to fabricate. Second, the Fischer-Tropsch plant for a combined CO_2 and CH_4-to-liquids process will be close to double the size, giving the opportunity for economies of scale. The separation of biogas CO_2 and CH_4 is widely practiced to upgrade the CO_2-CH_4 mixture from anaerobic digesters to attain the quality of natural gas required for pipeline injection to claim RIN credits. The CO_2 is at a concentration of 30%–40% coming from the digester and needs to be reduced to less than 1% to meet the pipeline standards. The plasma reformer is relatively low cost to build and operate. OxEon demonstrated and the low energy requirement was verified during the verification phase. We have tested the reformer on biogas from an anaerobic digester from a dairy. The reformer is insensitive to sulfur and has shown it can reform heavy, dirty fuels that are high in sulfur and aromatics, such as NATO F-76 (1% S spec. limit). We have also shown that the SOEC, operating as a fuel cell, can be operated with 1,000 ppm of H_2S. We have not tested the cells/stacks in SOEC operation with H_2S, but we anticipate similar performance. Fischer-Tropsch is known to be sensitive to sulfur down to approximately 20–50 ppb, so although the reformer, and possibly the SOEC, are not sulfur sensitive, the Fischer-Tropsch is and will require a sulfur trap. The project will be sited and tested at a digester site to address any impacts of running on biogas (CO_2 and CH_4). There are current gas (methane)-to-liquids systems operating at a profit (e.g., the Shell Pearl plant in the United Arab Emirates). There is a great push in the European Union for CO_2-to-liquids systems. Where both biogenic CO_2 and CH_4 are available, projections are that the combined system will be lower cost than two separate systems. The interfaces between them are of a type and complexity that are believed to be within the bounds of normal industrial practice: Cooling the exothermic Fischer-Tropsch reaction raises steam for SOEC, the SOEC byproduct O_2 is used by the reformer to enhance the amount of oxygen available for the reforming reaction, a small amount of Fischer-Tropsch-produced water is also used in the reformer, and the combined syngas streams from the reformer and SOEC are compressed and supplied to the Fischer-Tropsch. Fischer-Tropsch catalyst development is a highly specialized blend of art and science that has been seeking to improve the distribution of hydrocarbons generated by the Fischer-Tropsch for nearly a century. OxEon has presented data on the product distribution from its systems and has confirmed that this product follows the well-established and accepted Anderson-Schulz-Flory distribution model. Globally, nearly 400,000 barrels/day of Fischer-Tropsch liquids are produced, refined, and sold at a profit into existing markets otherwise served by petroleum. The synthesis of hydrocarbons using the Fischer-Tropsch process has been commercially practiced since its development in Germany before World War II. The difference between biogas-to-liquids Fischer-Tropsch products and the Fischer-Tropsch liquids produced by these existing plants is feedstock. The vast majority of the approximately 400,000 barrels/day of current production uses fossil-based feedstocks that also contain sulfur and other contaminants. These feedstocks are primarily associated gas from oil wells and coal (in South Africa). The challenge is scaling the technology down to a size matched to the disperse and distributed nature of bio-feedstocks. The use of the bio-CO_2 nearly doubles the product potential from biogas, and it at least doubles the potential from biomass gasification. The application of SOEC to bio-CO_2 to produce energy-dense fuels provides an extremely efficient and compact means of storing renewable electric energy. In effect, it shifts the renewable energy from the time and location it is available to when and where it is needed. Once the Fischer-Tropsch liquids have been produced, they constitute a storable and energy-dense material that is transported to refineries as easily as crude oil. This program has been scoped to provide outputs that would feed a TEA in a follow-on effort. The TEA of the integrated system would be used to establish the commercial potential for the technology and provide a cost basis for comparison to other comparable sources of energy on both a capital and operating basis.

COOL GTL FOR THE PRODUCTION OF JET FUEL FROM BIOGAS

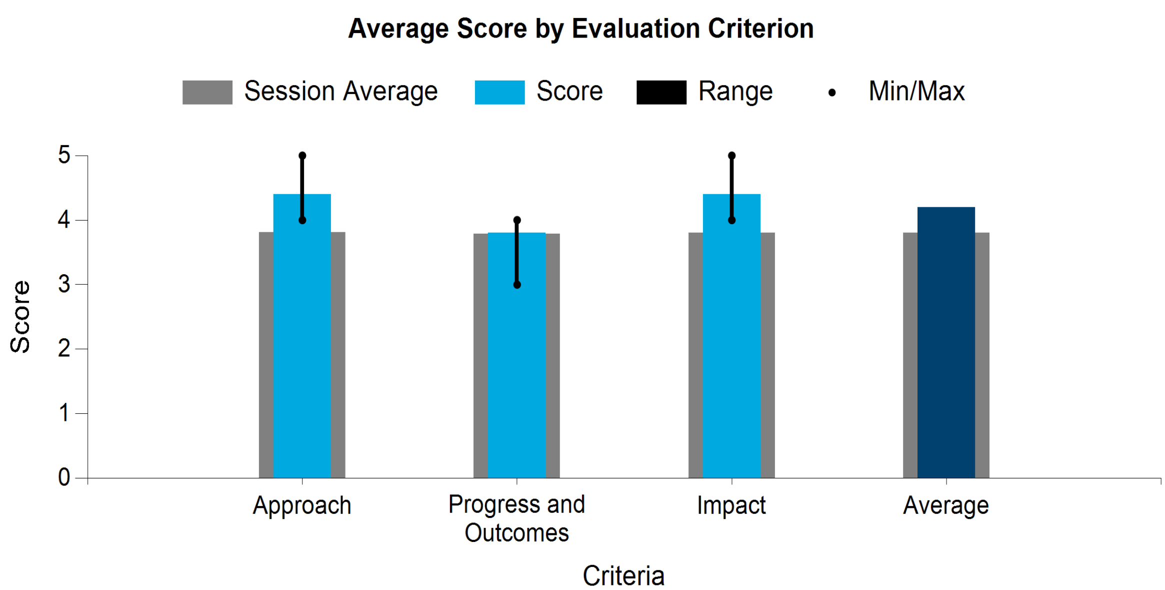
Gas Technology Institute

PROJECT DESCRIPTION

WBS:	3.5.1.405
Presenter(s):	Terry Marker
Project Start Date:	10/01/2018
Planned Project End Date:	07/31/2023
Total Funding:	$3,839,596

Cool GTL is a new gas-to-liquids technology that directly converts high CO_2 and CO-containing C1–C3 gases to jet fuel, diesel, and gasoline. Cool GTL can be used to convert biogas from digesters, IH^2, or gasifiers, so it has a wide range of applications. Cool GTL uses a unique new catalyst for CO_2/steam reforming in the first stage and a unique new catalyst and fluid bed reactor for Fischer-Tropsch plus wax cracking and isomerization in the second stage to directly make jet fuel from biogas.

The goal of this project is to develop the Cool GTL technology for biogas conversion to jet fuel by making 100 gallons of high-quality jet fuel. In this project, we expect to show that the Cool GTL technology can produce drop-in jet fuel for less than $3/gallon and reduce the GHG emissions of jet fuel by more than 60%. As a result of this program, the Cool GTL technology should go from a TRL of 3 to 5. The major participants are GTI, Hatch Engineering, Particulate Solid Research Inc. (PSRI), Michigan Technological University, SynSel Energy, and Veolia Environmental Services Inc. The major participants are GTI, Hatch Engineering, PSRI, Michigan Technological University, SynSel Energy, and Veolia Environmental Services Inc.



COMMENTS

- The project is about to finish, and GTI has performed very good work. It has developed a very promising process that is flexible and can use different feedstocks. The presenter has provided TEA data and LCA. CapEx for the demonstration unit is substantial. The cost of production using digestor biogas is $6.2/GGE. GTI should do further analysis to try to reduce this cost of production.

- GTI has conducted a good project and has successfully demonstrated the Cool GTL and its unique catalysts for reforming and FTS. The wax cracking is indicated as being in an “integrated trailing reactor.” This seems to indicate that the Fischer-Tropsch wax does not need to be separated for the wax cracking step, which simplifies the process.

  Has catalyst regeneration been conducted? What are the main lessons learned on this project that inform the next scale-up? Biogas sources tend to be smaller, distributed systems. What is the minimum scale at which the Cool GTL process is economically feasible?

- Fischer-Tropsch technology has been around for decades, and generally it is considered a high-capital-cost route to liquid fuels, so economy of scale is critical. A new reactor concept that can effectively operate at a smaller scale and lower temperatures and still crack wax formed during synthesis would be of high interest, provided the right catalyst and conditions can be proven. Key criteria for adoption in a biomass-to-fuels process are the feedstock cost and suitability for the gasification step, and whether the syngas produced can be effectively converted to liquids and at a low capital cost. This conceptual reactor uses an “ebullated” catalyst bed, so the demonstration should include catalyst physical integrity along with catalytic performance, coking, and life. A TEA and IRR will help determine the benefits, if any, to conventional Fischer-Tropsch.

- It will be helpful to understand how this project’s approach to electric reformer technology differs, if any, from that of WBS 3.5.2.701, which also employs this technology. The preliminary LCA data provided are encouraging. Can the proposed Fischer-Tropsch slurry reactor technology be modularized for commercial plant scales? At small scales, do Fischer-Tropsch reactors operate as economically and robustly as commercial-scale Fischer-Tropsch reactors? To gain a more comprehensive understanding of GTI’s diverse range of projects, it would be useful to have illustrations that highlight similarities and differences between them. Additionally, it would be beneficial to learn about how project team members from various backgrounds collaborate during the execution phase and share knowledge from different projects.

- The project demonstrates the production of jet fuel from biogas using a novel electric reformer to produce syngas followed by Fischer-Tropsch using novel catalysts to produce syncrude. Wax cracking takes place within the Fischer-Tropsch reactor to maximize the jet fraction. Further work is required to achieve the freeze point requirement for the jet fraction. If a novel bifunctional catalyst is used, it may not comply with ASTM D7566 Annex 1, and this should be investigated. From the analysis, there is still 1.1% oxygen in the diesel, indicating that further hydrotreatment will be needed. What is the strategy for upgrading? Because the jet fraction is only approximately 50%, will distillation and fractionation be part of the demonstration unit? Slide 26 shows only separation of the liquid and gas fractions. From slide 23, it seems that the break-even price is $6.2/gallon without the RINs for digestor biogas, whereas it is $3.2/gallon for IH^2 biogas. Presumably, the claims made for the production of jet at less than $3.5/gallon are therefore based on using IH^2 biogas. The integration between the two processes was not shown. The IH^2 biogas will not deliver the same emission reductions achievable with digestor biogas, and the difference between the two sources must be shown.

PI RESPONSE TO REVIEWER COMMENTS

- So far, our Cool GTL Fischer-Tropsch and trailing reactor have not really deactivated enough for regeneration. In Budget Period 3, we will see if regeneration is necessary. We have a procedure developed for this if it becomes necessary. The smallest scale at which Cool GTL is economically viable will significantly depend on RIN credits; however, with the current renewable fuels credits, we believe it can be economically attractive at small biogas scales. Fractionation would be part of any demonstration unit. We do believe we will be able to make drop-in fuels requiring no further upgrading, and that is our goal in the Budget Period 3 testing. We also believe we can reduce costs for the biogas size unit by incorporating the electric reforming in the economics. This was not done in the initial Budget Period 2 economics, but the electric reformer will be included in the Budget Period 3 economics. An electric reformer provides the most cost savings for small-size equipment.

ULTRA-LOW-SULFUR WINTERIZED DIESEL

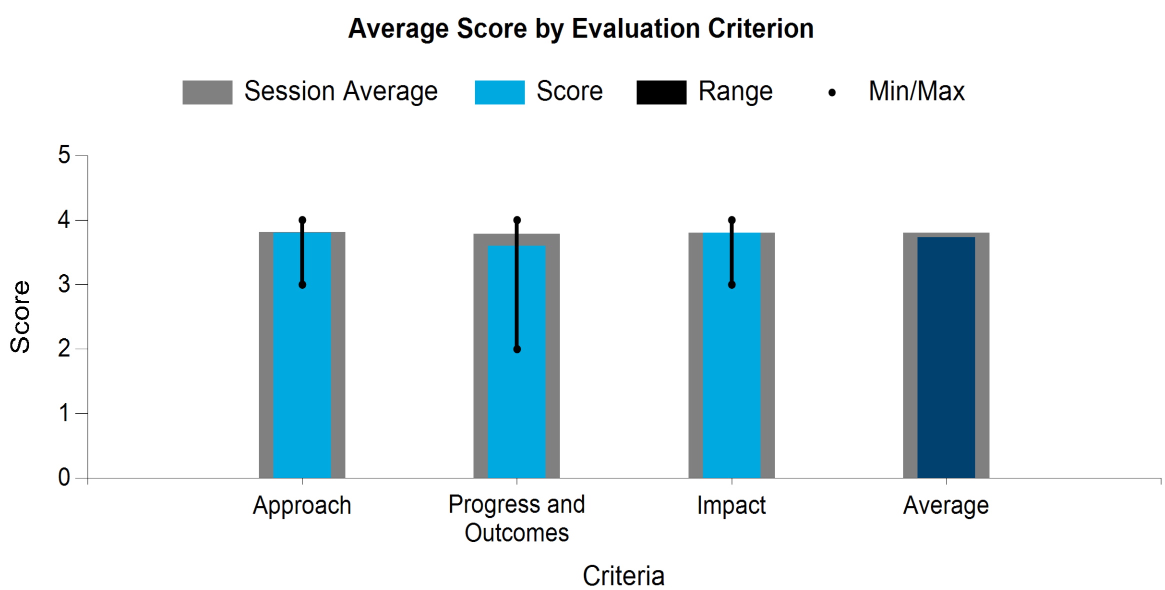
LanzaTech Inc.

PROJECT DESCRIPTION

WBS:	3.5.1.406
Presenter(s):	Rick Rosin
Project Start Date:	10/01/2018
Planned Project End Date:	03/31/2023
Total Funding:	$3,130,327

LanzaTech and PNNL are collaborating to develop and validate a robust, flexible alcohol-to-diesel (ATD) process for producing drop-in renewable diesel fuel with superior low-temperature performance from biomass-derived ethanol. PNNL is conducting R&D to understand the relationships among catalyst/process parameters and diesel product characteristics to enable diesel properties to be tuned to match the specifications for each diesel application. The technology will be validated through the production of hundreds of gallons of synthetic paraffinic diesel and engine testing.

By using an ethanol intermediate, the ATD process will enable renewable diesel to be produced from any ethanol that meets customer and application requirements. This feedstock flexibility will allow a commercial ATD refinery to minimize the cost of production by selecting the lowest-cost ethanol source that satisfies the needs of each market. Synthetic paraffinic diesel (SPD) from the ATD process will be a drop-in diesel fuel, fully compatible with existing fueling infrastructure and engines, suitable for use in each target market at any blend level. The SPD will have low sulfur content and superior low-temperature performance. The life cycle GHG reductions of the SPD fuel are expected to be 60% or higher, depending on the source of ethanol feedstock.



COMMENTS

- In the previous project presentation, LanzaTech indicated that they could change the process conditions to vary to the percentage of SAF or diesel in the final product. This project elaborates more on that possibility, but LanzaTech does not explain how they plan to do it. It seems they are using the same process and catalyst and are only slightly changing the oligomerizing reactor process conditions.

Currently, the ATJ process can produce 75% diesel without losing overall product yield. With this project, LanzaTech wants to achieve 90% diesel yield. The oligomerization will start with bottled ethylene, not produced upstream. This will not consider potential contaminants from the ethanol-to-ethylene process. LanzaTech includes a slide with unreadable information, which prevents me from properly evaluating the results. Despite its simplicity, the project is quite delayed. Very little has been accomplished during the 2 years the project has been running. LanzaTech has not provided any data regarding technical performance, TEA, or LCA, and it is using bottled petrochemical ethylene for its testing.

- The project aims to adapt the ATJ process to increase renewable diesel production and to produce a renewable diesel that has a sufficiently low cloud point to meet winter diesel specs. Winterizing the diesel is important to make it widely applicable across seasons and geographic regions and to expand the market. The project seems to be taking the thorough steps needed to ensure proper process development for commercial deployment and to ensure a consistent product that meets specs; however, the presentation does not provide details on the changes required to adapt the ATJ process to the ATD process.

  Activities in Budget Period 3 include building an ATD production unit. Is the design of the ATD production unit different from an ATJ production unit? Waste gas ethanol does not qualify for RINs. If sugarcane ethanol is to be used, what is the GHG reduction of the resulting SAF? Is sugarcane ethanol an economically feasible feedstock for renewable diesel at the commercial scale?

- This project builds on the ethanol-to-SAF approach under a separate project, and it seeks to optimize the catalyst used in the oligomerization and hydrogenation steps to increase diesel output to 90% versus jet fuel. If these unit operations can be proven to be robust in feedstock-to-ethanol production (i.e., not sensitive to variations in composition or quality), then it would allow any source of ethanol to be used to make diesel. The product will be validated as suitable for diesel engines, which should include cylinder sleeve wear, a critical step for commercialization. If the TEA and IRR prove sustainable, the impact would be large. A major concern is the mass loss because oxygen is eliminated from the ethanol during reduction.

- Slide 5 mentions “jet range hydrocarbons” even though the project’s current focus is on producing diesel from alcohol. This is confusing because the range of carbon numbers for diesel (C11–C23) is higher than that of jet fuel (C8–C18). This ATD project is similar to the ATJ project except the final product contains a higher proportion of diesel. Can you discuss the major challenges and differences that are expected to be encountered in this project compared to the already developed ATJ project? It is not clear how the production process will change from ATJ to ATD. Will two separate catalysts beds (one specific for jet fuel and the other specific for diesel) be used, or will the process be modified in some other way? Can you provide more information about the changes in the production process? Economic information (similar to WBS 3.5.2.403) was not available. The project aims to produce diesel, but it is not clear to which market this diesel will be targeted. Given that heavy-duty vehicles are moving toward compressed natural gas, what market is being addressed for this diesel? There is a mass loss associated with the dehydration of ethanol, which may affect the viability of the process. Can you discuss the economic feasibility of producing diesel from ethanol accounting for the mass loss associated with the process?

- This project uses ethanol as the starting material to produce diesel. It is the same technology pathway as for SAF production, but the product slate is shifted toward diesel production. Although the ATJ process includes a diesel fraction, this project proposes to optimize catalyst and operating conditions for diesel production. The approach is sound, and progress has been made that aligns with the project timeline. As the ATJ process is near commercialization, the technical challenges are limited and achievable; however, producing diesel using this process rather than maximum SAF is, in my opinion, not the most beneficial use of ethanol feedstocks. The biggest strength of the LanzaTech's ATJ technology is the high SAF fraction that can be achieved. No information is provided to support the stated claims for production cost.

PI RESPONSE TO REVIEWER COMMENTS

- *Subject to disclaimers on the associated presentation*

How is the ATJ process being changed? LanzaTech and PNNL optimized the structure-function properties, process design, and operational parameters to achieve 90% selectivity to diesel. Although major unit operations are the same, particular aspects of equipment have been optimized for the ATD process. The performance will be reviewed by DOE's independent engineer at the next verification. The details, including the data and the engineering design of the ATD production unit, are confidential and not available outside of DOE and the independent engineer.

Source of ethylene: All variations among ethanol sources, including contaminants, are removed before or during the ethanol dehydration (ethanol-to-ethylene) step, and the resulting ethylene is of very high purity, comparable to commercial ethylene. The ethanol-to-ethylene process has been demonstrated to be equivalent across a wide range of ethanol sources in prior projects and during the initial validation of the ATJ process on WBS 3.5.2.403; therefore, there was no need to include ethanol-to-ethylene here.

Impact of mass loss during ethanol to ethylene: The most important factor in feedstock utilization is high carbon yield to products, which is not affected by water elimination in the ethanol-to-ethylene step. Under energy-based incentive programs, such as the Renewable Fuel Standard, the increase in energy density of the resulting renewable diesel and SAF relative to the ethanol feed mean that essentially no economic value is lost due to dehydration.

Why diesel, not SAF? The intent of this project was to maximize product flexibility to provide optionality to producers. Although SAF is clearly an important market, diesel will continue to play a significant role in the fuel pool, even as some transport applications shift to compressed natural gas. Relevant factors include the longevity of vehicles in legacy and near-term fleets, even as production and sales of compressed-natural-gas vehicles increase as well as the logistics of compressed natural gas distribution on the necessary scale and to all locations. Diesel is also used outside of transport, and there is demand for renewable diesel in applications such as data centers' backup power generation, as evidenced by recent announcements from Kohler (biomassmagazine.com/articles/19120/kohler-approves-use-of-renewable-diesel-in-its-diesel-generators) and Cummins (www.biobased-diesel.com/amp/cummins-high-horsepower-diesel-generator-sets-approved-for-use-with-hvo).

TEA/LCA: Initial TEA and LCA were provided in the proposal and are to be updated later with the final results from Budget Period 2. The GHG reduction (and cost) of renewable diesel is comparable to that of the SAF product. The GHG footprint of the products is largely determined by the ethanol source. LCA results for SAF were presented during the last peer review of WBS 3.5.2.403 for five different ethanol sources. The EPA has approved the ATJ pathway for the generation of D4 RINs (biomass-based diesel) with at least 50% GHG reductions when using sugarcane ethanol feedstock (www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel). The cost of production is not impacted by the ratio of renewable diesel to SAF. We agree with the reviewer that waste-based ethanol is the preferred feedstock as cost and availability allow.

Reference to "jet range hydrocarbons" (slide 5): The reviewer is correct that this should have been changed to diesel.

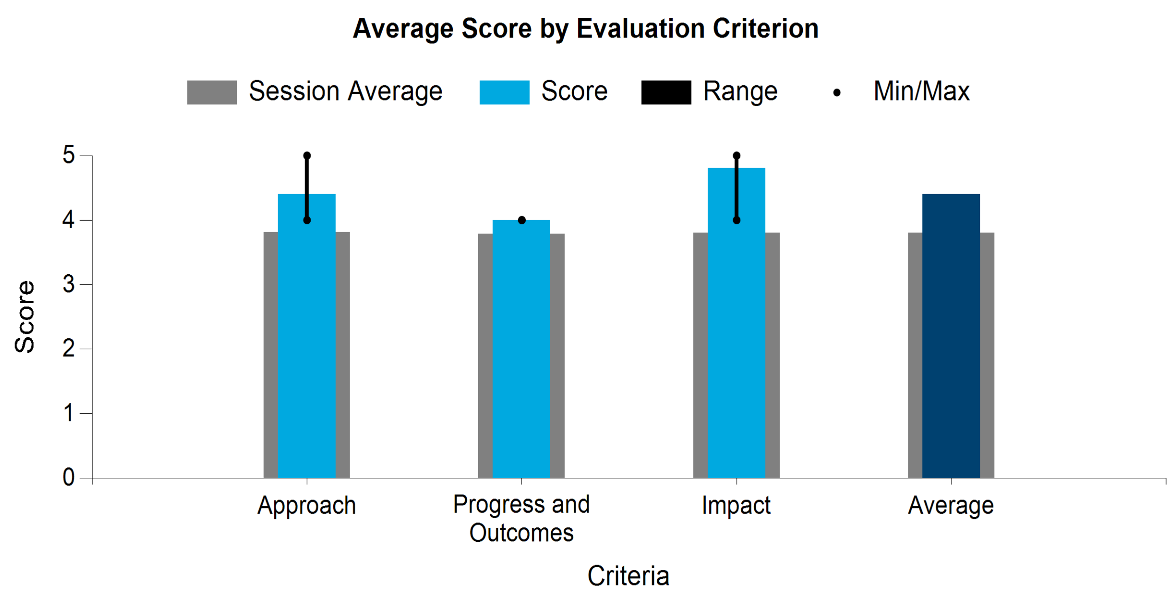
PILOT-SCALE BIOCHEMICAL AND HYDROTHERMAL INTEGRATED BIOREFINERY (IBR) FOR COST-EFFECTIVE PRODUCTION OF FUELS AND VALUE-ADDED PRODUCTS

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:	01/14/2023
Total Funding:	$2,317,995

The main objective of this project is to demonstrate the production of selected high-value products from the unhydrolyzed solids (UHS) recovered after biochemical processing of corn stover at a pilot-scale level with a throughput of 1 TPD. An additional goal is to understand the revenue stream that can be generated from high-value products and the GHG emissions. An integrated technology approach was developed to convert UHS into selected high-value products, such as biocarbon (graphitic carbon) and carbon nanofibers, via HTL processing followed by graphitization and electrospinning, respectively. The key activities included were: (1) preprocessing of corn stover at a pilot scale, (2) UHS processing and optimization, (3) HTL plant design and fabrication, and (4) graphitization of hydrochar and analysis. The carbon materials were found to be suitable for battery and supercapacitor energy storage applications. Their specific surface area, porosity, and specific capacitance exceeded the target metrics.



COMMENTS

- The South Dakota School of Mines and Technology (SDSMT) has developed an HTL process to convert UHS into biochar. HTL can handle a liquid stream with up to 20% in solids, whereas the PNNL process cannot go beyond 8%. This is a great advantage, coupled with a much simpler process design. In addition, the SDSMT team has been able to produce biochar that actually works as an energy storage material and as a capacitor. Why is the SDSMT working with UHS rather than raw preprocessed biomass? It seems that this also may work and will simplify the process. Overall, the SDSMT has done an excellent job as the team has developed a new HTL process and produced good-quality biochar.

- The team has successfully designed, fabricated, and tested a pilot-scale HTL plant that produced high-value biocarbon and carbon nanofibers, thus valorizing the unhydrolyzed waste from the biochemical processing of corn stover. The team seems to have investigated the entire process—from feedstock preprocessing in collaboration with INL, to biocarbon and carbon nanofiber characterization, to commercialization and partnerships. The TEA and LCA will be useful in determining the economic and GHG reduction impacts of the project and in determining the size of a commercial project.

  The HTL process can handle wet feedstock streams with up to 20% solids, which is higher than the 8% solids that PNNL's HTL PDU can handle. What range of solids content can the process handle? What other feedstock streams will work? Are there any process waste streams that are toxic or hazardous that pose a challenge for disposal?

- It is not clear if this approach (HTL) to processing post-hydrolysis solids will apply to all types of feedstocks and to other types of pretreatment. For the alkaline pretreatment of corn stover, it seems to offer a way to add significant value as coproduct streams. The supply-versus-demand balance for graphitic carbon may affect the value of that stream as this technology is implemented commercially, but it appears to be a growth market. The installed capacity of electrospinning equipment is small, so the TEA should determine if there are reinvestment economics for carbon nanofibers as well. The performance of those fibers appears promising based on early results. The properties and value of heavy bio-oil are not discussed, but they should be compared to No. 6 bunker oil as a start. Overall, extracting high-value products from leftover lignin solids is certainly helpful to the economics of an integrated biorefinery (IBR).

- It is encouraging to learn that the 2021 Project Peer Review has led to a more focused approach with two high-value products: biocarbon (Product 1) and carbon nanofibers (Product 2). These products can significantly enhance the economics of a biorefinery. We are curious to know why the team at South Dakota chose to develop a new HTL system instead of using PNNL's HTL equipment. It would be valuable to understand the decision-making process and the differences between the two systems. Further, it would be beneficial to learn about the lessons learned and how the team overcame any challenges during the project. As the project approaches its end, it would be useful to have a table outlining the final economic figures as well as the LCA and GHG reductions achieved. Additionally, we would like to inquire about the possibility of collaborating with PNNL in synergistic activities.

- The project's main objective is to explore the production of high-value products from the UHS after pretreatment and enzymatic hydrolysis of corn stover. The solids are processed through HTL, and the biochar is used to make biocarbon and carbon fiber mats. The project has substantial merit and could have significant commercial impact for the valorization of UHS (lignin) during cellulosic ethanol production. This fraction has generally been burned for energy generation, but upgrading to high-value products could improve the financial viability of cellulosic ethanol facilities. As illustrated on slide 9, the process shows alkaline pretreatment of corn stover, enzymatic hydrolysis with Cellic CTec2, pH adjustment with sodium citrate, and separation of the UHS. Based on this process, the solids are expected to still contain cellulose and hemicellulose because the alkaline pretreatment alone is insufficient to achieve high sugar yields. The Cellic CTec2 enzyme preparation is not as effective as the Cellic CTec3, and residual cellulose and hemicellulose will remain in the solids. The extent of cellulose/hemicellulose remaining in the solids could impact the chemistry of the biochar, and this must be considered. It might be beneficial to obtain UHS from a more realistic, near-commercial cellulosic ethanol process (e.g., DMR with CTec2 hydrolysis) because the two processes could have significant commercialization potential when used together. Because this project is close to completion, it might not be realistic to make changes at this stage, but further progression to a larger scale may consider these suggestions and potential collaboration with a cellulosic ethanol commercialization process for the valorization of the lignin fraction. Obtaining a realistic assessment of the techno-economics of the HTL will also need valorization of the bio-oil, and potential future collaboration could investigate the characteristics of the bio-oil and potential upgrading.

PI RESPONSE TO REVIEWER COMMENTS

- Comments: The SDSMT has developed an HTL process to convert UHS into biochar. HTL can handle a liquid stream with up to 20% in solids, whereas the PNNL process cannot go beyond 8%. This is a great advantage, coupled with a much simpler process design. In addition, the SDSMT team has been able to produce biochar that actually works as an energy storage material and as a capacitor. Why is the SDSMT working with UHS rather than raw preprocessed biomass? It seems that this also may work and will simplify the process. Overall, the SDSMT has done an excellent job as the team has developed a new HTL process and produced good-quality biochar. Response: Originally, this proposal was funded for the valorization of UHS from bioethanol/biochemical processing of corn stover, and therefore we focused on UHS; however, the HTL process is also applicable to corn stover (both low ash and high material). Experiments performed with corn stover indicated that the biochar is equally well suited for the energy storage application—supercapacitors and batteries.

  Comments: The team has successfully designed, fabricated, and tested a pilot-scale HTL plant that produced high-value biocarbon and carbon nanofibers, thus valorizing the unhydrolyzed waste from the biochemical processing of corn stover. The team seems to have investigated the entire process—from feedstock preprocessing in collaboration with INL, to biocarbon and carbon nanofiber characterization, to commercialization and partnerships. The TEA and LCA will be useful in determining the economic and GHG reduction impacts of the project and in determining the size of a commercial project. The HTL process can handle wet feedstock streams with up to 20% solids, which is higher than the 8% solids that PNNL's HTL PDU can handle. What range of solids content can the process handle? What other feedstock streams will work? Are there any process waste streams that are toxic or hazardous that pose a challenge for disposal? Response: SDSMT and INL are currently pursing TEA/LCA with specific system boundaries. Initial TEA estimates suggest that the scale of 880 TPD of corn stover processing produces the fuel at a cost of approximately $2/GGE with an approximately $50 million grassroot cost for the plant with recovery of 20%–30% oil and approximately 25%–40% biochar products. The process can handle up to 25 wt % solids in water. We successfully tested the process with this slurry concentration. Also, the system is capable of processing corn stover powder and pellets, pinewood, switchgrass, cardboard, paper waste, and food waste. As such, the gas stream is only 4%–5%, whereas the aqueous waste stream generally contains oxygenated hydrocarbons. We recycle the aqueous waste multiple times after the recovery of valuable products, such as phenols and substituted phenols and lactic acid. Alternatively, the carbon in the aqueous waste stream can be oxidized to meet the discharge standards. Solid hydrochar (approximately 40%) can be processed into energy storage material. So, we do not anticipate any disposal challenge.

  Comments: It is not clear if this approach (HTL) to processing post-hydrolysis solids will apply to all types of feedstocks and to other types of pretreatment. For the alkaline pretreatment of corn stover, it seems to offer a way to add significant value as coproduct streams. The supply-versus-demand balance for graphitic carbon may affect the value of that stream as this technology is implemented commercially, but it appears to be a growth market. The installed capacity of electrospinning equipment is small, so the TEA should determine if there are reinvestment economics for carbon nanofibers as well. The performance of those fibers appears promising based on early results. The properties and value of heavy bio-oil are not discussed, but they should be compared to No. 6 bunker oil as a start. Overall, extracting high-value products from leftover lignin solids is certainly helpful to the economics of an IBR. Response: We fully agree. The alkaline pretreatment adds value in terms of the coproducts, such as phenols/substituted phenols and carboxylic acids (e.g., lactic acid). For the commercial UHS and lab UHS, the hydrochar yield was 29.4 wt %, and 29.8 wt %, respectively, which suggests that the approach of HTL is applicable. The graphitic carbon market is continuously growing because of continuous demand for sustainable carbon electrode materials for reducing the carbon intensity. We fully understand that the electrospun carbon nanofibers were made on a small scale; therefore, we will determine reinvestment economics for carbon nanofibers through TEA. On average, we generate 20% viscous oil with higher heating values of 35 MJ/kg with sulfur content less than 0.1%

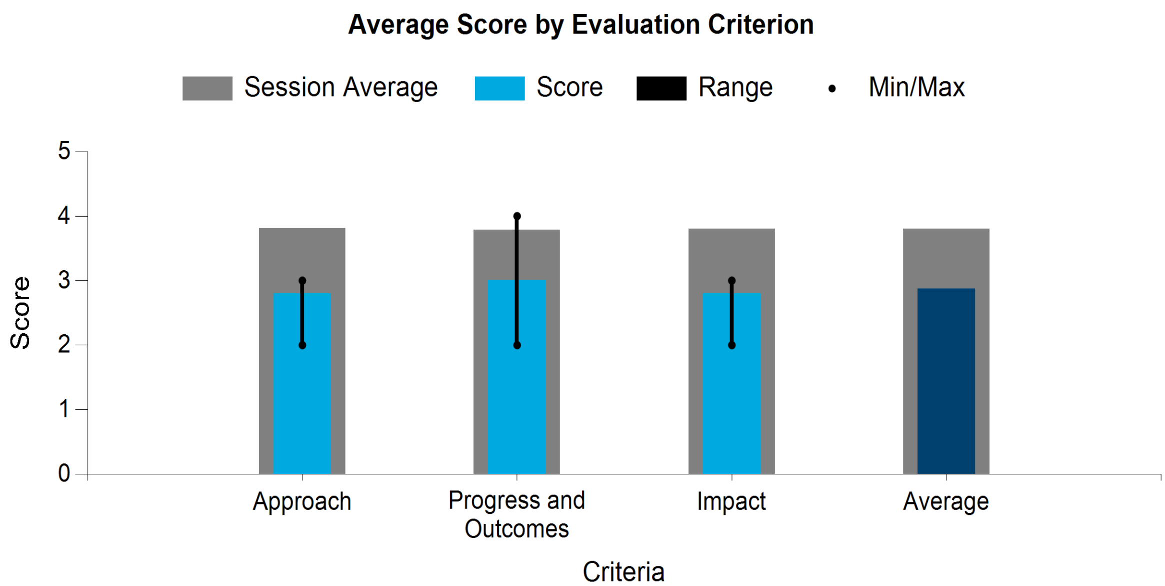
Comments: It is encouraging to learn that the 2021 Project Peer Review has led to a more focused approach with two high-value products: biocarbon (Product 1) and carbon nanofibers (Product 2). These products can significantly enhance the economics of a biorefinery. We are curious to know why the team at South Dakota chose to develop a new HTL system instead of using PNNL's HTL equipment. It would be valuable to understand the decision-making process and the differences between the two systems. Further, it would be beneficial to learn about the lessons learned and how the team overcame any challenges during the project. As the project approaches its end, it would be useful to have a table outlining the final economic figures as well as the LCA and GHG reductions achieved. Additionally, we would like to inquire about the possibility of collaborating with PNNL in synergistic activities. Response: There are two specific reasons that prompted us to design and build a new HTL system: (1) No pump characteristics are available in the literature, especially for slurries with higher solids loading; and (2) continuous pumping of slurries with higher solids loading has maintenance issues. Technical challenges were addressed by the inclusion of a digestor tank before the main HTL reactor and operating in a semicontinuous/batch mode. The SDSMT and INL are working on the TEA/LCA, and we will include all numbers, including GHG reductions. The SDSMT and the team will be extremely delighted to collaborate with PNNL on synergistic activities.

Comments: The project's main objective is to explore the production of high-value products from the UHS after pretreatment and enzymatic hydrolysis of corn stover. The solids are processed through HTL, and the biochar is used to make biocarbon and carbon fiber mats. The project has substantial merit and could have significant commercial impact for the valorization of UHS (lignin) during cellulosic ethanol production. This fraction has generally been burned for energy generation, but upgrading to high-value products could improve the financial viability of cellulosic ethanol facilities. As illustrated on slide 9, the process shows alkaline pretreatment of corn stover, enzymatic hydrolysis with Cellic CTec2, pH adjustment with sodium citrate, and separation of the UHS. Based on this process, the solids are expected to still contain cellulose and hemicellulose because the alkaline pretreatment alone is insufficient to achieve high sugar yields. The Cellic CTec2 enzyme preparation is not as effective as the Cellic CTec3, and residual cellulose and hemicellulose will remain in the solids. The extent of cellulose/hemicellulose remaining in the solids could impact the chemistry of the biochar, and this must be considered. It might be beneficial to obtain UHS from a more realistic, near-commercial cellulosic ethanol process (e.g., DMR with CTec3 hydrolysis) because the two processes could have significant commercialization potential when used together. As this project is close to completion, it might not be realistic to make changes at this stage, but further progression to a larger scale may consider these suggestions and potential collaboration with a cellulosic ethanol commercialization process for valorization of the lignin fraction. Obtaining a realistic assessment of the techno-economics of the HTL will also need valorization of the bio-oil, and potential future collaboration could investigate the characteristics of the bio-oil and potential upgrading. Response: We fully agree with the reviewer that instead of burning biochar for energy generation, valorization of UHS into biocarbon as well as carbon nanofibers will have more financial viability for cellulosic ethanol production. Commercially, this approach would be more impactful. We also believe that the Cellic CTec3 processing would be more effective than Cellic CTec2 and that the extent of the cellulose/hemicellulose remaining in the solids could impact the chemistry of the biochar. We have tested untreated corn stover for biochar production, and still we could achieve a highly porous biocarbon, which was found to be suitable for energy storage application. The HTL process was originally developed for the UHS solids that were commercially available from Glydia Biotech, Georgia, and later it was employed to the UHS derived from corn stover using Cellic CTec2. Although the hydrochar yield was almost similar (29.4% for commercial UHS and 29.8% for Cellic CTec2-derived UHS), we did observe difference in oil yields; therefore, we also believe that the use of UHS produced at a near-commercial cellulosic ethanol facility for biocarbon and carbon nanofibers will be commercially more significant. The SDSMT team will be happy and willing to join collaborative efforts with commercial cellulosic ethanol producers for valorization. At the laboratory scale, we have started valorization/upgradation of bio-oil to develop some understanding; however, this was not the focus of the currently proposed efforts. We are interested in collaborating on bio-oil upgradation. Currently, the SDSMT and INL are working on TEA/LCA, and we will include all numbers with GHG reduction in our reports.

PILOT-SCALE ALGAL OIL PRODUCTION

Global Algae Innovations

WBS:	3.5.2.201
Presenter(s):	David Hazlebeck
Project Start Date:	01/15/2017
Planned Project End Date:	06/30/2022
Total Funding:	$4,471,580



COMMENTS

- The presenter has not provided many details regarding the FEL-3 package. We do not know if this work has been done, and it is unclear whether the company has executed any pilot-plant construction yet. I question whether the company will execute the 160-acre plant or if it will be reduced to just two ponds. The 160-acre cost estimate is $73.9 million, and the production per acre is estimated at 22 tons of algae. The plant will use fresh water. The presenter did not provide the water consumption data, which represents a big concern, especially in areas like central California, where water is scarce. An industrial-scale facility will need 5,000 acres and an investment between $500 million–$1 billion. The economics of oil production are tight; water consumption in the ponds is a big environmental challenge.

- The presentation was confusing in regard to the scope of the funded project and the path to the commercial scale (slide 17). How many acres is the raceway for this pilot project? Slide 20 shows that the next scale-up for the raceways is 6 acres, then 18 acres. What is the anticipated acreage for each raceway in a commercial-scale farm targeted for design and construction in 2026–2027?

- The addition of nutraceuticals to enhance the return on investment seems useful but was not elaborated. Different conditions and sources for CO_2 and nutrients to enhance performance were also not fully explained, nor was contamination control. These seem to be critical to the overall cost and operability performance, as well as the higher percentage of lipids and protein, which were mentioned. Two-times productivity improvement, 10-times lower energy demand, and two-times higher product value are significant, but we need to understand how much that advances the technology versus other biomass-to-advanced fuels options. It would be helpful to put the statistics for the fertilizer and kilowatt-hours per metric ton of oil and meal into context relative to the other technologies and versus targets for this approach. In addition, it would be helpful to know how the estimated capital per pond acre per metric ton measures up to the national goals to understand what the land and water use impacts are to meet the goal $/GGE and GHG reduction.

- The influence of weather effects, such as wind velocity and hurricane impact, on the site selection and design considerations for algal cultivation has not been clearly understood. Further research is needed to determine their influence. There are concerns about the potential indirect land usage change resulting from commercial-scale algal projects. It is important to carefully evaluate the potential environmental impacts of these projects, including their effects on land use. The claim that a 100% increase in biomass value can be achieved for a product spectrum commensurate with 7 billion gallons of algal biofuel per year is ambitious and requires further investigation to determine its feasibility. Algal cultivation presents several challenges related to water use, water recycling after separation, and land use. These challenges need to be addressed to ensure that the industry is sustainable and does not negatively impact other sectors, such as agriculture. To better understand the various projects from Global Algae Innovations, it would be helpful to have a clear illustration of the similarities and differences between the projects. Additionally, understanding how the project team members collaborate, particularly during the execution phase, can provide valuable insights into the success of these projects.

- Does only the Nitzschia strain produce oils? If spirulina production is targeted for 75% of the time, lipid production will be negligible. Please provide an analysis of the lipids produced (chain length, etc.). What is the breakdown of the saturated, monounsaturated, and polyunsaturated lipids? What is the expected production of saturated lipids for biofuel applications (in volume per acre)? It is indicated that offtake agreements are in place for all the products—is there a specific offtake for lipids for biofuels production? Based on the information presented, the production of lipids for biofuels does not seem financially viable, although the project may be viable for other products.

PI RESPONSE TO REVIEWER COMMENTS

- This design project was for a 160-acre pilot plant based on being large enough that the revenue from the oil and protein products would cover the operational cost, so if the capital were paid by moving to Phase 2 of the award, the operations would be self-sustaining. The project was not started until after the downselection to Phase 2, so moving to Phase 2 to cover the capital was not an option. The size was fixed by the original proposal, so based on the business assessment, the design was based on operating part-time for nutraceuticals to provide a return on investment and part-time for oil and protein to prove out the technology for moving on to the commercial scale for these products. One hundred sixty acres are not needed to prove the technology and obtain offtakes for the commercial scale, so the likely path to commercialization for biofuel is to build out the initial 18 acre of the design, including a 12.5-acre individual raceway. This leaves an 8- to 16-times scale-up remaining to reach a full commercial-scale farm that includes 100- to 200-acre individual raceways. Global Algae currently has three other awards related to scale-up. This first is to build out the initial 2-acre cultivation and harvest, including a 1.3-acre individual raceway. The second is to add a 4-acre raceway and harvest system expansion with an option for a 12-acre raceway and harvest system expansion. The third is to scale up a novel drying and extraction system to approximately the 4-acre scale.

  For the Nitzschia strain, approximately 50% of the ash-free dry weight is lipid. The lipid is approximately 5% 14:0, 40% 16:0, 40% 16:1, and 15% omega-3 (primarily EPA0). The oil production is approximately 3,200 gallons per acre per year. The planned product spectrum is 1,600 gallons/acre of saturated oil fraction for biofuel feedstock, 1,300 gallons/acre of monounsaturated oil fraction for polymer feedstock, and approximately 300 gallons/acre of omega-3 fraction as an ingredient for feed. The oil is upgraded through the hydroprocessed esters and fatty acids (HEFA) process to SAF and renewable diesel. This product spectrum results in approximately $1.60/kg of oil on average, which is projected to provide a good return on investment at the commercial scale. The markets for these three products could support approximately 7 billion gallons/year of algal biofuel. Because of supply constraints relative to demand in the United States, the current price for oil for HEFA upgrading is approximately $1.6/kg, so all 3,200 gallons/year could go to biofuel with a good return on investment at the current pricing. We currently do not have offtakes for the commercial scale. Our plan is to operate at the pilot scale to validate the products so that offtakes can be obtained to enable financing the first commercial-scale farm.

Similar to any other food or biofuel crop, algal water use depends on the location. The evaporation of water per acre from algal raceways is similar to the loss of water from evapotranspiration per acre in land crops; however, algae produce approximately 24 times more protein than the most productive land plant at the same time that it is producing approximately 3,200 gallons/acre of oil. During the oil production, the algal farm reduces the total water use for protein production for feed by approximately 90%; thus, algal biofuel will reduce the water use for agriculture by 100 to 500 gallons of water per gallon of biofuel. The actual amount of water added from surface waters, underground water, or reduced water recharge through the use of rainwater is dependent on the location, just as with conventional agriculture. Global Algae's harvest system removes all biological components, so the water from harvesting is fully recycled without any issues. Compared to other biomass-to-advanced fuel options, the metrics are: land use: cellulosic ethanol approximately 600 gallons/acre versus algal oil approximately 3,200 gallons/acre; water use: cellulosic ethanol approximately 600 to 1,200 gallons of water use/gallon of fuel versus algal oil, which saves 100 to 500 gallons of water/gallon of fuel; GHG: cellulosic ethanol—at least 60% GHG reduction; algal oil 60% reduction with conventional drying and extraction or 90% with advanced drying and extraction. For all options, the key is economic biofuels production. For algal oil, the combined oil price needs to be approximately $1.60/kg for the composite price with the current technology for a high return on investment. Our current plan is to sell 50% of the oil at approximately $0.80/kg for biofuel, 40% of the oil at $2/kg for the polymer feedstock, and 10% of the oil at $4/kg as an omega-3 feed ingredient. After the first approximately $5 billion gallons/year of biofuel, additional technical and operational advances will need to be achieved to reduce the cost so that all the oil can go into biofuel and consumer markets to replace palm oil at less than $1/kg.

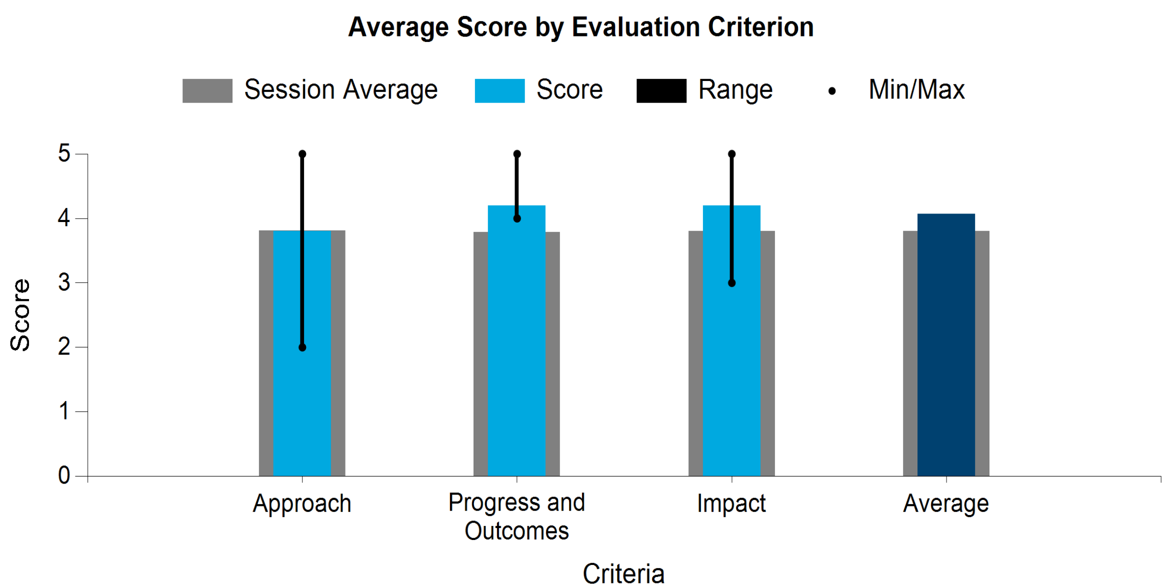
LOW-CARBON HYDROCARBON FUELS FROM INDUSTRIAL OFF-GAS

LanzaTech Inc.

PROJECT DESCRIPTION

WBS:	3.5.2.403
Presenter(s):	Laurel Harmon
Project Start Date:	01/15/2017
Planned Project End Date:	09/30/2023
Total Funding:	$37,317,103

LanzaTech and its partners are implementing a 10-million-gallon/year facility to demonstrate the production of low-carbon jet and diesel fuels from ethanol using the ATJ that originated at PNNL and was scaled by LanzaTech. The technology will be demonstrated using ethanol from steel mill off-gas and other sources. The ATJ facility, Freedom Pines Fuels, is a project entity owned and operated at LanzaTech's Freedom Pines Biorefinery by LanzaJet, a company formed by LanzaTech to commercialize 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. National Environmental Policy Act approval was secured for the project. All technology and engineering, procurement, and construction partners have been selected. Now in Phase 2, the project is in construction, with mechanical completion expected in Q4 of 2023.



COMMENTS

- The project seems to be on track, with much preliminary work already performed. What is unclear to me is whether this technology has been proven at the pilot/demonstration scale and what have been the results. The presenter has not provided any technical or performance data to allow me to evaluate their results. LanzaTech changed the project's scope, eliminating the integration of ethanol produced by gas fermentation with SAF production because they say that the ethanol production had already been demonstrated; however, it is unclear if the integration of both processes may have an impact or how synergetic it can be. Now it is not clear what ethanol they are going to use and whether they can achieve the goals of GHG reduction and the cost of production. They did not share any information about the cost of the plant, operational cost, or carbon footprint. LanzaTech claimed that all this information was confidential and had been shared with DOE. I cannot make any project review, or assessment, or provide an opinion on the project.

- The project has taken a sound approach to scaling and seems to be achieving the target progress and outcomes at a high level. Technical details and results are not presented. What challenges have been solved and proven by the demonstration project? Waste gas ethanol does not qualify for RINs. If sugarcane ethanol is to be used, what is the GHG reduction of the resulting SAF? Is sugarcane ethanol an economically feasible feedstock for a commercial plant?
- This project assumes that gas fermentation of mainly CO_2 off-gas from industrial sources to ethanol is an economic reality. Otherwise, this facility would need to use existing ethanol sources that may or may not be acceptable under the current guidelines for feedstocks. It focuses on dehydrating that ethanol to ethylene, then oligomerization and hydrogenation to paraffins as advanced biofuels—mainly SAF. The participants in this project have good expertise and experience with these unit operations, thus increasing the chance of success. One concern is that the initial feedstock is an off-gas of undisclosed composition, and it is not clear how broadly applicable the process will be for other off-gas feedstocks. Another question is how this approach compares to other syngas-to-SAF approaches, such as the Honeywell UOP technology. A TEA and IRR would be useful to understand the economics. Assuming those concerns are mitigated, this approach has strong merit for scale-up.
- It is not obvious how the project plans to source the ethanol feedstock. Could you provide more information on the intended source of the feedstock? The project's end-of-milestone goal is to demonstrate that its products meet the Renewable Fuel Standard 2 requirements for advanced or cellulosic biofuels. Given that the project's scope has changed, could you explain how the project plans to achieve this goal? Although specific cost numbers and economic analyses were not provided, it would be useful to have at least a range of the project's estimated costs. This information can help in determining the financial viability of the project. It would be helpful to know about any lessons learned during the project's execution and how the project has addressed any unanticipated changes that have occurred. This information can be used to improve the project's efficiency and effectiveness and to inform future projects.
- The aviation sector faces significant challenges to achieving net zero by 2050, and SAF is considered the most important solution to contribute approximately 60% of emissions reductions; however, delays in the commercialization of additional pathways (other than HEFA) are one of the challenges that must be addressed because waste lipid feedstock volumes are limited. The ATJ pathway is one of the most promising technologies because it can use multiple sources of ethanol to produce SAF. The Freedom Pines facility will pave the way for this technology to become fully commercial and deliver significant volumes of SAF through multiple facilities worldwide. Completion of this pioneer facility is an important and exciting milestone, and this project will have a significant impact on the SAF sector.

PI RESPONSE TO REVIEWER COMMENTS

- *Subject to disclaimers on the associated presentation*

  Data and results from prior-scale work: Technical and performance data were generated in previous efforts with both DOE and private funding. The data are confidential and were provided to DOE during the application for this project and to the DOE independent engineer during validation. The purpose of the current project is to finalize the design and construct the facility; new data will be generated during initial operation.

Integration of ethanol production and ATJ: The project was designed from the outset to use multiple sources of ethanol (a hub-and-spoke model); therefore, potential synergies between gas fermentation and ATJ are out of scope here but are being assessed in other projects.

Ethanol source and GHG reductions: The GHG footprint of the products is largely determined by the ethanol source. LCA results were presented at the last Project Peer Review for five different ethanol sources. The EPA has approved the ATJ pathway for the generation of D4 RINs (biomass-based diesel) with at least 50% GHG reductions when using sugarcane ethanol feedstock (www.epa.gov/renewable-fuel-standard-program/approved-pathways-renewable-fuel). The facility will initially use sugarcane ethanol feedstock while working to build a supply of waste-based ethanol from gas fermentation and other technologies.

Waste gas feedstocks—feasibility and applicability: Three commercial gas fermentation plants are operating now, a fourth is in commissioning, and two more are in construction—all with differing feed gas compositions. Many millions of gallons of waste gas-based ethanol have been produced from these plants (www.biofuelsdigest.com/bdigest/2021/01/31/commercial-ccu-plant-using-lanzatech-tech-receives-rsb-advanced-products-certification/, www.forbes.com/sites/erikkobayashisolomon/2021/09/21/lanzatechs-paradigm-shifting-plan-to-create-carbon-negative-industrial-chemicals/?sh=2e7a9e573bdf); therefore, the feasibility of producing ethanol from waste gas has been well-established. The ethanol produced is independent of the waste gas source, so gas composition does not affect the ATJ process. Although not part of this project, gas fermentation can also produce ethanol from the syngas generated by gasifying biomass or municipal waste. A reviewer asked about the comparison to “other syngas-to-SAF approaches, like the Honeywell UOP technology.” We note that Honeywell UOP does not have a commercialized syngas-to-SAF process but has commercialized HEFA technology using lipid feedstocks to produce SAF. Fischer-Tropsch is the primary alternative process for producing SAF from syngas. Limitations of Fischer-Tropsch were included in the presentation; they include lower overall yield to high-value products (SAF, diesel) and less selectivity to SAF. As noted by one reviewer, fuels from waste gas do not yet qualify for RINs.

Costs (CapEx, OpEx): Details of the facility cost have been shared with DOE and the DOE independent engineer, including regular updates during the project development. Responding to one specific question, the cost of production from sugarcane is economically attractive for a commercial plant.

TEA/LCA: As noted, LCA results were presented at the last Project Peer Review and were recently approved by the EPA for sugarcane ethanol feedstock. Both TEAs and LCAs specific to individual regions and feedstocks are continuously updated in confidential discussions related to new projects and project finance.

Challenges and lessons learned: One key challenge was the need to raise capital for a first-of-a-kind plant, which was exacerbated by the pandemic. This was addressed in part by developing multiple creative financing mechanisms, including the involvement of strategic investors with commitments to implementing follow-on plants. In addition, both the pandemic and the war in Ukraine created significant supply chain challenges. Although such events cannot be anticipated or part of the planning process, that experience highlights the importance of maintaining supply chain flexibility to mitigate unforeseen gaps. These challenges can be mitigated in large part by good partnering, close attention to details, and the continuous consideration of alternative sources of supply.

ADVANCED BIOFUELS AND BIOPRODUCTS WITH AVAP

AVAPCO

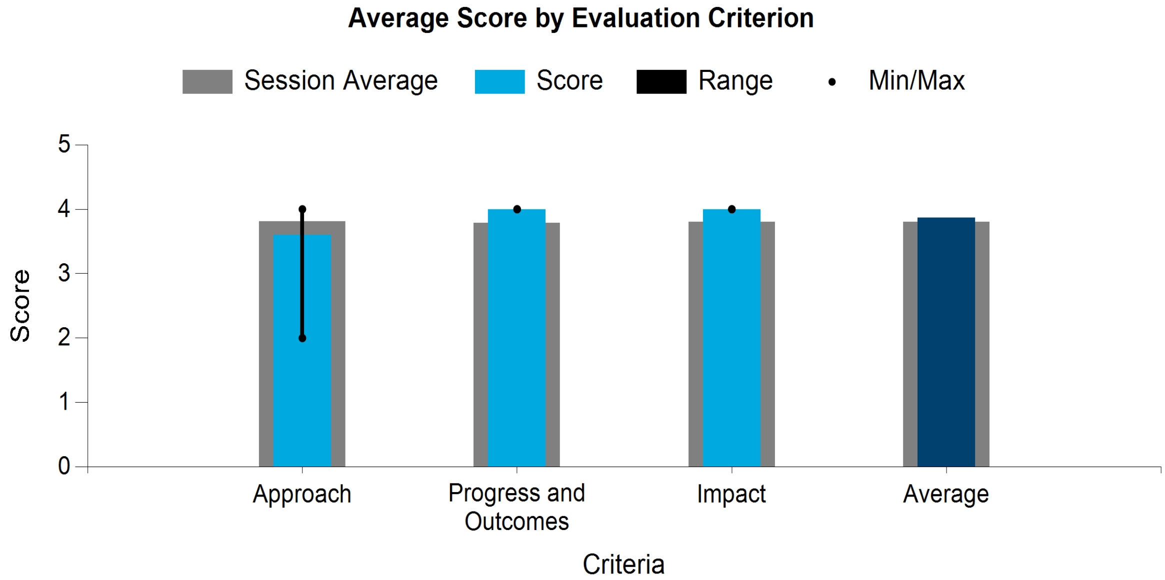
PROJECT DESCRIPTION

WBS:	3.5.2.405
Presenter(s):	Ryan Zebroski
Project Start Date:	01/15/2017
Planned Project End Date:	02/01/2023
Total Funding:	$9,341,328

The Advanced Biofuels and Bioproducts With American Value-Added Pulping (AVAP) project 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 AVAPCO's existing biorefinery site in Thomaston, Georgia. The targeted scale is 100 dry TPD of woody biomass from neighboring sawmill residues and harvesting operations and 1.2 million gallons/year SAF and renewable diesel. The coproducts include the Nanocellulose Dispersion Composite (NDC) rubber masterbatch for commercial sale to the tire industry and cellulosic sugars for conversion to a biochemical by a confidential global chemical industry partner.

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, and they are 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, followed by the NDC rubber masterbatch. The rest of the cellulose is enzymatically saccharified at a low enzyme dose for hydrolysis to C6 sugars for off-site conversion.

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 first converted to ethylene by Petron Scientech and then converted to full-replacement liquid hydrocarbons using a catalytic synthesis process that produces petroleum distillate equivalents with overall LCA reduction greater than 90% at the commercial scale. 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 4 companies of 90 under the Federal Aviation Administration's Continuous Lower Energy, Emissions, and Noise (CLEEN) program, where rigorous engine testing was performed by Rolls Royce that demonstrated Byogy's fuel characteristics provide a premium full-replacement renewable aviation fuel.



COMMENTS

- I do not see a clear business case in the presentation. It is a combination of multiple components without a clear strategy. I do not see any economics or studies to show the competitiveness of the solution. No yields either. It seems that nanocellulose composite is the main product, and SAF is a byproduct, when it should be all the way around. It is unclear why the company does not maximize ethanol production, as an SAF precursor, fermenting both cellulose and hemicellulose. The pretreatment uses SO_2; has the company studied the effect of sulfur in fermentation and ethanol-to-ethylene conversion? It is very common to see sulfur as an irreversible poisoning agent of the catalysts. I cannot determine whether the company has produced any SAF yet in the previous stages of the project. The company is seeking $80 million in grants from DOE. That means that the project cost will be at least $160 million for 1.2 million gallons/year of SAF. It seems to be very intensive in capital needs for such a small output.

- AVAPCO and its partners seem to have taken a sound approach to trialing, optimizing, and piloting its process and is now scaling up to the demonstration scale. High-value bio-based coproducts enable the production of low-value commodity liquid fuels. What are the technical scale-up challenges for the demonstration plant? For the next scale-up plant? The presentation indicated the usage of 340,000 dry TPD of biomass for a 100-million-gallon/year SAF plant. Is the roundwood required to obtain this amount of feedstock within an economic draw radius?

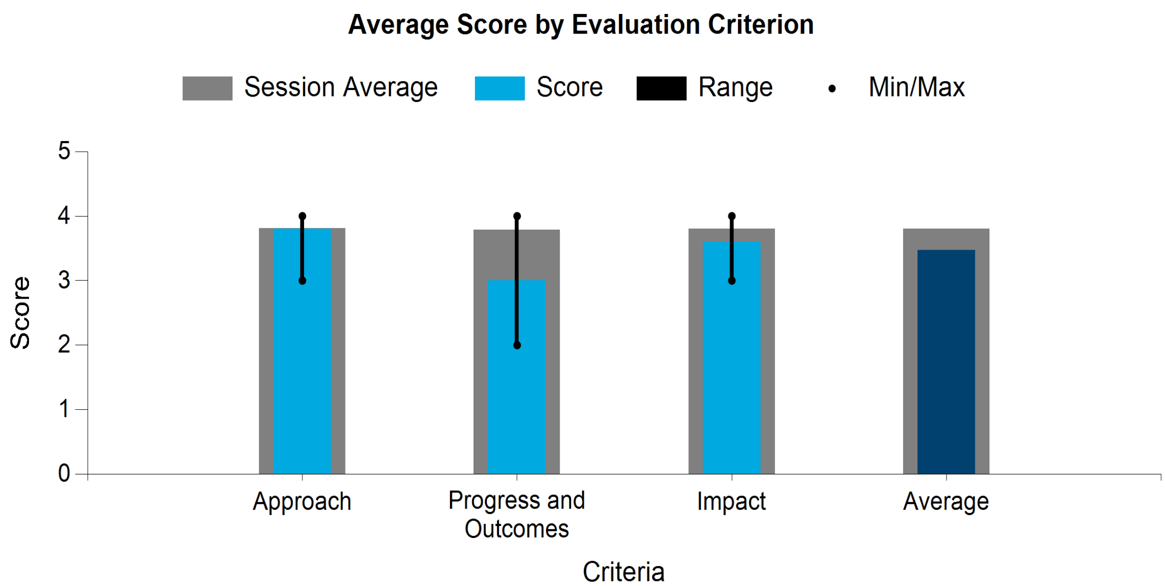
- This project uses the well-proven pretreatment process for wood used in making pulp for paper, with the noncellulosic portion normally being diverted to black liquor and burned for fuel value. The separation and fractionation of cellulosic feedstocks into component streams that are clean enough to use as intended may be the biggest challenge for this project. Handling diverse and variable feedstock compositions and producing consistent quality intermediates has been a difficult challenge in past integrated biorefineries. Making clean nanocellulose is critical to the overall economics of this process, along with large-scale demand. Similarly, making cellulosic glucose with the same fermentability (lack of inhibitors) as dextrose seems challenging if the intent is to use GMOs, especially at near-neutral pH, to make high-value products other than ethanol. Once the path to ethanol is demonstrated, ethanol-to-olefins and advanced biofuels seems straightforward. Need to see the TEAs and IRRs of the integrated process to understand if the impact suggested is likely.

- It is critical to ensure that this project meets the requirement of converting at least 50% of biogenic carbon to fuels as the cellulose portion of the feedstock is being converted to C6 sugars and NDC; therefore, it is crucial to establish a mechanism for monitoring this conversion rate. Regarding the replication and scaling of the current design, the team needs to develop a clear plan that outlines the necessary steps for upgrading the current model from the demonstration scale. As the project approaches its end, it would be beneficial to present a comprehensive table outlining the final cost, environmental impact, and reduction of GHG achieved. Additionally, I recommend including a section that details the lessons learned and how unanticipated changes were effectively addressed during the project's execution. Finally, a risk register should be integrated into the project deliverables to ensure that all completed projects include an assessment of potential risks that might adversely affect the project's goals and objectives.
- The project approach seems to align with the BETO Multi-Year Program Plan for the production of fuels and high-value coproducts; however, the production of the coproducts seems to be the main target, whereas SAF and renewable diesel production seems to be a very minor component. It would also be useful to clarify whether the further scale-up is expected to integrate the ethanol-to-ethylene and the SAF production components with the AVAPCO component (even though it is not part of this project). It is not clear whether the hemicellulose and cellulose fractions, produced after digestion, contain significant contaminants and inhibitors that may impact the fermentation and other downstream processes, and this should be clarified because it could have a significant impact on ethanol production and yield. No specific strategy or approach indicates how this will be addressed. Information should be provided on the proposed source of enzymes for the hydrolysis of the cellulose, and information should be provided on the fermentation organism. According to the presentation, SimaPro was used to calculate the LCA, but GREET is the model used specifically for fuel production, and it should be assessed. For purposes of the Inflation Reduction Act, the CORSIA model must be used for SAF, and this could have a significant impact on the outcome because energy allocation is used. In the case of nonfuel coproducts, energy allocation will likely change the carbon intensity of the SAF fraction.

RIALTO ADVANCED PYROLYSIS INTEGRATED BIOREFINERY

Rialto

WBS:	3.5.2.601
Presenter(s):	Andrew Dale
Project Start Date:	04/01/2017
Planned Project End Date:	12/31/2023
Total Funding:	$6,391,391



COMMENTS

- The project has completely changed its initial objective of producing pyrolysis oils from biosolids to enhance biogas production in an anaerobic digestor to destroy PFAS in biochar to allow land application. The new PFAS regulations that the EPA published in 2021 prevented the use of Anaergia pyrolysis oils in biogas production because they contained PFAS exceeding the allowed limits. Now the company has focused on ways to remove PFAS from biochar and obtain a permit for its land application. Although PFAS have been almost entirely removed by thermal oxidation at 650°C, the presence of concentrated metals in the biochar may restrict its applicability as a fertilizer. The company has tried to get the best results, but there is still a big question mark regarding the usefulness of this technology for biochar treatment. It is certainly not a project focused on biofuels.

- As part of its commercialization plan, the team has taken the appropriate steps to investigate the potential to convert the biosolid waste stream into valuable products, which helps solve the biosolids disposal issue and increases the supply of low-carbon fuels. The project found that the condensable oils cannot be used for fuel production due to the PFAS content. Although the project could not achieve its original objectives, it is useful to elucidate where PFAS ends up in the pyrolysis process. In response to the new EPA rules regarding PFAS, the project shifted the objectives to PFAS removal from the biochar product for land application uses and PFAS destruction. The team was able remove the PFAS from the biochar and make the biochar usable for land application. This seems like a very reasonable pivot. The biochar market is still a nascent market, and the economic feasibility would need to be shown by a TEA.

- High-temperature pyrolysis of municipal waste sludge to eliminate PFAS, then granulating with fertilizer to produce a safe and valuable product seems like a reasonable plan, provided there are low enough levels of heavy metals in the biochar to not cause problems with absorption by plants. That risk needs to be addressed as part of the plan. Halogens from PFAS destruction will be captured by scrubbing gases with caustic. Heat integration will be critical, along with good TEA and IRR results. The project will need to show that the material and energy balances are economic and sustainable in terms of safety and GHG impact (farm to farm).
- Please provide information on the starting and ending TRLs for this project? Have there been any studies conducted on the market acceptance of biochar produced from this project? In addition, we are curious about how the metal content in biochar is being managed for land application. Are there any measures in place to prevent metals from being absorbed by plants? To make a proper assessment, it would be beneficial to have access to additional information, such as specific operating data, LCA, GHG, and economic analyses.
- This project was initially intended to produce pyrolysis bio-oil to be added to the anaerobic digester operated by the company to increase yields of RNG from the facility. The bio-oil was found to contain PFAS, and the project was changed to achieve the destruction of the PFAS through thermal oxidation of the volatilized compounds. Temperatures of 650°C were required to remove the PFAS from the biochar, allowing the biochar to be used as a fertilizer. The additional equipment and conditions for the thermal oxidation and the subsequent fate of the fluorides were not presented and should be added. The application of the blended biochar as a fertilizer is undergoing field trials, and initial studies show promising results, although trial experimental design was not clear. Why is nutrient uptake in the leaves tested as opposed to different metrics, such as fruit production, etc.? Was the biochar blended product fully formulated as equivalent to other types of fertilizers? Analytical results should be added. How does the cost of the biochar fertilizer compare with commercial fertilizers? Has a TEA been carried out? How does the biochar product compare with other biochars available on the market (cost and composition)?

NOVEL ELECTRIC REFORMER FOR DROP-IN FUELS FROM BIOGAS OR WASTE CO_2

Gas Technology Institute

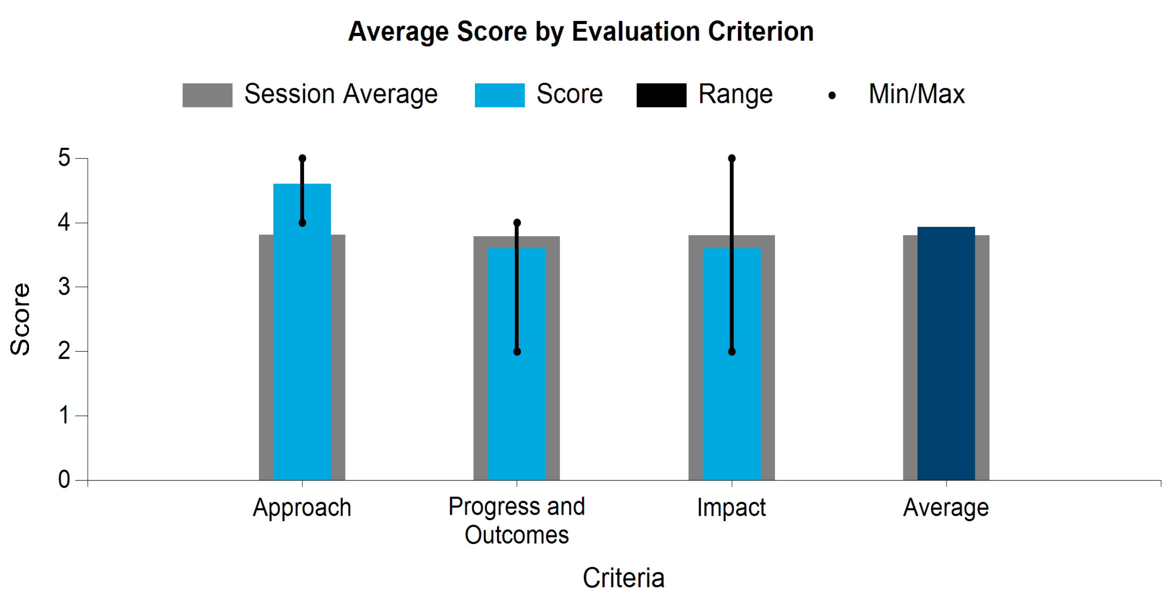
PROJECT DESCRIPTION

WBS:	3.5.2.701
Presenter(s):	Terry Marker
Project Start Date:	10/01/2021
Planned Project End Date:	03/31/2024
Total Funding:	$5,008,195

The goal of this project is to significantly reduce biogas-to-liquid costs by scaling up an electric reformer/reverse water gas shift reactor for the conversion of waste carbon dioxide from ethanol plants or biogas from digestors to synthesis gas. The synthesis gas from the reformer will be used to make drop-in fuels using the Cool GTL technology or will be used in other GTL processes. The ultimate objective is to produce biofuels from biogas or waste CO_2 from bioprocesses for less than $2.75/GGE with greater than 70% reduction in GHG emissions. In this project, the electric reformer/reverse water gas shift reactor will be modeled, designed, constructed, and tested for more than 500 continuous hours for two cases covering biogas conversion to liquids (Case 1) and waste CO_2 utilization (Case 2). This project will scale up GTI's electric reformer design, which has been tested at a smaller scale, as the first stage of the Cool GTL process (this produces 1–2 gallons/day) to a larger scale.

A key goal is to ensure that the model correctly predicts the internal heat transfer and that the reactors ultimately produce the desired synthesis gas composition of 2.2–2.5/1 H_2 to CO at expected temperatures. To achieve this, the project includes extensive mechanical, structural, and electrical design, reactor performance parametric studies based on an anchored model, and the preparation of engineering design drawings and procurement specifications for a commercial electric reformer. Also, this study will accurately determine the capital cost, techno-economics, and life cycle advantages of a large commercial electric reformer as the basis of renewable fuels production.

The major benefit is to greatly reduce the reformer or reverse water gas shift reactor's capital cost, size, and waste carbon dioxide production.



COMMENTS

- The electrical reformer is an interesting concept for CO_2 or biogas conversion to syngas in relatively small applications where an industrial-size reformer is unsuitable. In other words, this concept could apply to distributed production; however, the design of electrically heated equipment has limitations that must be addressed when working with hydrogen. According to ATEX regulations, the maximum superficial temperature for hydrogen is 450°C. This means that the heating element in the presence of hydrogen cannot surpass that temperature if there is a risk of having oxygen in contact with hydrogen because it autoignites at 550°C. Electrical heating of hydrogen is very cumbersome, and I strongly recommend that GTI thoroughly investigate safety issues and ATEX limitations immediately. I also have big concerns about the maximum size of this type of equipment. Heating elements with large power demand are not in the market today. Although GTI is working with Siemens, this issue should not be disregarded. GTI has not presented any TEA to allow me to check their $2.75/GGE cost of production. This is the first of a set of projects on the Cool GTL technology.

- This project takes a sound technical approach to developing an electric reformer that provides the advantages of a smaller footprint, reduced cost, and eliminates air emissions impacts. Clean renewable electricity is used in place of natural gas. With a smaller footprint and lower cost, the electric reformer has the potential to make smaller, distributed biorefineries economically feasible as well as larger refineries. The preliminary TEA projects a jet fuel production cost of $2.75/GGE. What size plant was this TEA performed for? It would be interesting to see the range of scales for which the electric reformer would be economically feasible.

- Conceptually, substituting new large-scale reformers with smaller electric reformers could allow for the use of that unit operation in smaller and more decentralized applications as well as significantly increase the feedstock-to-fuels yields. Critical to prove out is the robustness of the reformer design and performance in producing syngas with the right composition, especially with scale-up. The project would benefit from more of a market analysis to determine the size and number of units that ultimately might be deployed, if the design and materials of construction prove to be economic. A comparison to current reformer technology should include both energy utilization and CapEx. To a great extent, this project assumes that renewable energy from solar and wind will be available, so that question should be addressed in the implementation plan. Siemens seems like a good partner for this development.

- This project is interesting because it employs a technically robust approach. I'm very curious about the scale of the experimental electrical reformer system in the lab and how the mathematical model accounts for wall and end effects and their influence on scale-up. It is very critical to ensure that the operability and robustness of the electrical reformer are ascertained for the actual feedstock as opposed to mock components and compositions mimicking the actual feedstock. Economic comparisons for the proposed electrical reformer should be with the current reformer system before embarking on the path of electrical reformer technology. It is crucial to adhere to safety standards (see slide 14) with proper personal protection equipment for all personnel involved in this project. To gain a better understanding of GTI's various projects, it would be helpful to have illustrations that highlight similarities and differences between them. Additionally, it would be beneficial to learn about how project team members from different projects collaborate during the execution phase and share learnings from various projects.

- This project has significant potential for developing small GTL technology based on biogas and steam or CO_2 and hydrogen. The Cool electric reformer is novel and has a much smaller footprint than a traditional natural gas reformer. The TEA and LCA to be carried out will be important to assess the viability of this technology. The carbon intensity of fuels will be impacted by the source of the electricity, and perhaps different electricity sources can be compared in the LCA. Although the FTS is not part of this project, it would be advisable to check whether the catalyst formulation in the Fischer-Tropsch reactor will comply with ASTM D7566 Annex 1.

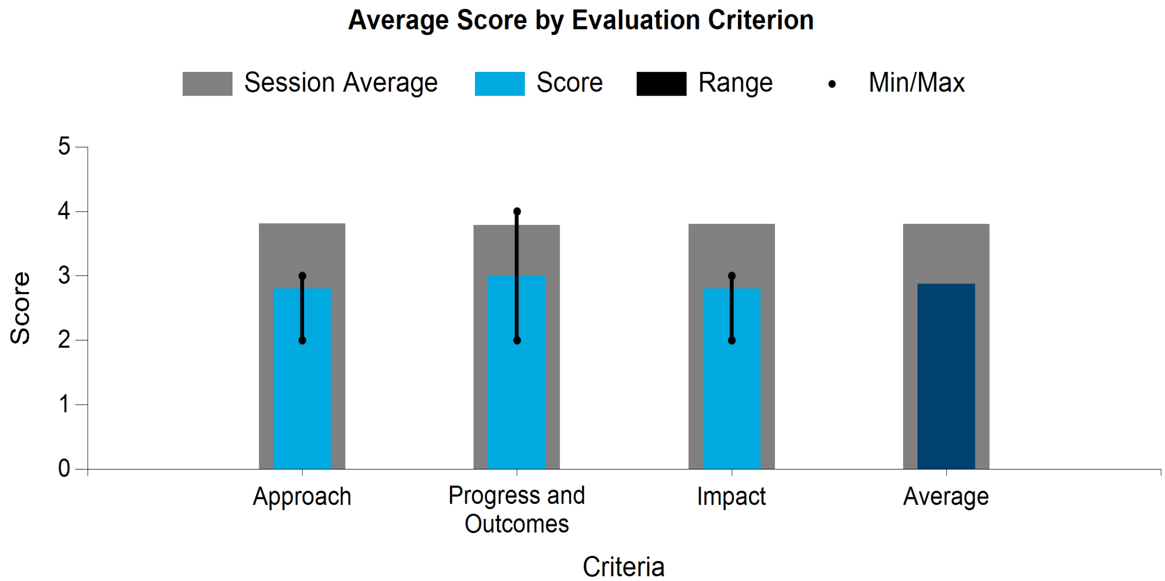
PI RESPONSE TO REVIEWER COMMENTS

- Most hydrogen and synthesis gas is produced from steam methane reforming of natural gas. This reaction is done at 850°C–900°C, well above 450°C, which is the autoignition temperature of hydrogen. The ATEX regulation the reviewers mention do not really apply to the temperature of hydrogen inside a steam methane reforming reactor. In general, there is little or no oxygen present in a steam methane reformer. GTI is aware of all the safety regulations around the use and production of hydrogen and does indeed carefully review all designs to ensure they are safe.

DIRECT AIR CAPTURE ALGAE CULTIVATION

Global Algae Innovations

WBS:	3.5.2.702
Presenter(s):	David Hazlebeck
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2023
Total Funding:	$5,000,000



COMMENTS

- The presenter has not described any work done regarding the direct air capture of CO_2. The company seems to have been doing preliminary work for the pilot plant in California but nothing related to CO_2 capture. I cannot find if the scope of work is to build a pilot plant or is something different, especially considering that the company has another project to construct the pilot plant. The company needs to clarify the scope of work of the three awarded projects and the final outcome of this DOE investment.

- The presentation did not provide any description on the direct air capture technology and the capital cost; thus, and evaluation is not possible. For this funding opportunity, Global Algae Innovations is planning to scale up the project to 2 acres of raceways. What is the scale-up factor from the pilot plant in Kaui? The California project will incorporate many newly developed technologies. This may pose a challenge to integrate and deploy many new technologies at the same time.

- The project has proceeded with the selected strains in locations where piloting facilities were established. It is not yet clear where future commercial scale-up will occur, and the algal productivity of 15 gm/m^2/day was not translated into number of ponds needed for a specific oil and coproducts production target. The approach to avoid contamination in open ponds was not fully disclosed, nor how that approach compared to closed systems fed by concentrated CO_2 sources in terms of productivity and capital use. Water use also was not fully addressed. The TEA of this technology would be more helpful if it looked at the relative performance of this approach versus other biomass-to-fuels pathways.

- Evaluating the use of direct air capture for algal cultivation involves several factors, including the current concentration of CO2 in the air, which stands at around 410 ppm. Although direct air capture technology holds great potential for reducing CO_2 levels in the long term, current efforts are still in the research phase. In the near term, concentrated sources of CO_2 may prove more economically viable for the development of processes to produce biofuels and bioproducts from algae; however, the cost of producing biofuels from algal biorefineries remains prohibitively high, which hinders their widespread adoption and impact. To gain a better understanding of the various projects undertaken by Global Algae Innovations, it would be helpful to have an illustration that highlights their similarities and differences. Moreover, it is important to understand how team members from different projects collaborate during project execution to ensure their success. By improving transparency and communication, stakeholders can better assess the potential impact of these initiatives.
- According to the presentation, the facility in Hawaii was supplied with CO_2 via slipstream from an adjacent power plant stack. In this project, the source of CO_2 is direct air capture; however, there are no details on what “direct air capture” means, and this needs to be clarified for project evaluation. Is CO_2 concentrated from air similar to carbon capture technologies (which is very expensive)? How does this compare with the economics and life cycle of using CO_2 from a power stack? How is the CO_2 supplied to the algal ponds? Algal cultivation for biofuels production has not been successful in the past, and companies shifted to the production of higher-value coproducts rather than extracting lipids for biofuels production. Although biofuel is a target of this project, shifting all the lipids to other high-value products will likely improve financial viability. The location of the facility in a water-scarce area is problematic and may impact sustainability certification. Water consumption compared with various crops should be shown (not just alfalfa). The cost per GGE is given for cultivation at a 5,000-acre scale. What is the cost per GGE for the proposed 160-acre scale?

R-GAS ADVANCED GASIFICATION PRE-PILOT DEMONSTRATION FOR BIOFUELS (BIOR-GAS)

Gas Technology Institute

PROJECT DESCRIPTION

WBS:	3.5.3.101
Presenter(s):	Zach El Zahab
Project Start Date:	10/01/2021
Planned Project End Date:	03/31/2024
Total Funding:	$4,999,898

Objectives: The R-GAS Advanced Gasification Pre-Pilot Demonstration for Biofuels (BioR-GAS) project will demonstrate that aviation fuel, diesel, or marine fuel can be produced at the commercial scale from biomass and sorted MSW for less than $2.75/GGE and with a reduction in GHG emissions of greater than 70% over the petroleum-derived equivalent. The proposed pathway is R-GAS entrained flow gasification followed by FTS of fuels from the resulting syngas. The project will demonstrate the feed and gasification units of this entrained flow gasification pathway at a scale of 6 TPD.

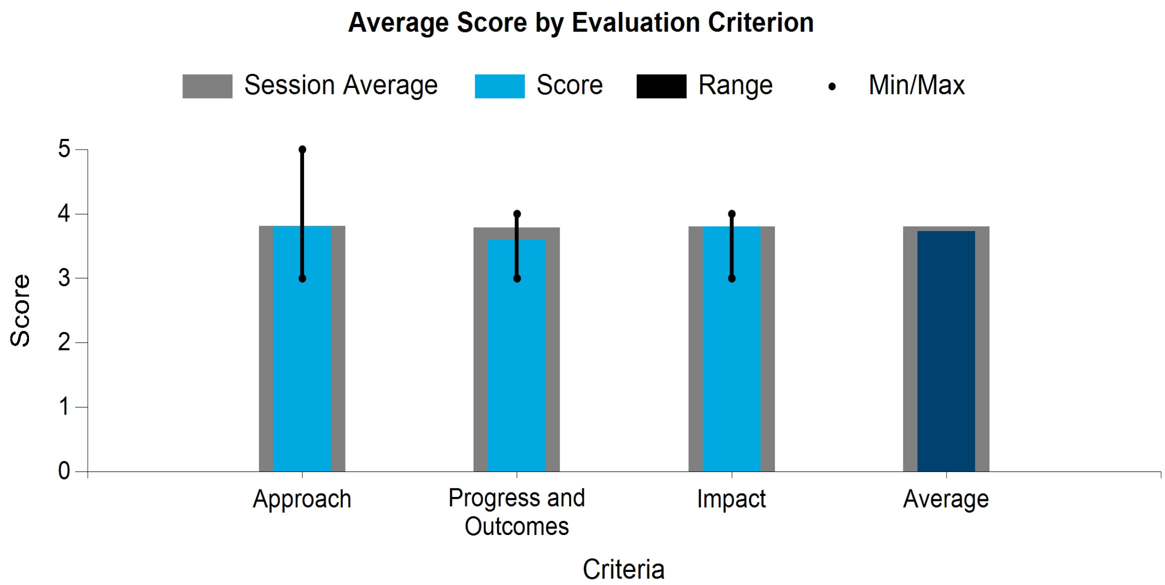
The objective of Budget Period 1 is to independently verify the proposed technical and programmatic baseline plans to successfully meet the topic area metrics. The objective of Budget Period 2 is to select a maximum of three types of biomass and/or sorted MSW, with associated preprocessing, for integrated feed system/gasification demonstration testing in Budget Period 3, from up to eight candidate feedstock/preprocessing combinations and evaluation in our flow system. The final Budget Period 3 objective is to complete a cumulative total of at least 500 hours of gasifier operation, with at least one 100-hour continuous run, and satisfy the overall project objectives by completing a commercial-scale TEA and LCA.

Methods to be employed: GTI has selected a low-risk work plan that involves an informed decision process on the economic and viable feedstock selection and preparation technologies. GTI has in-house tools, including economic models, Aspen Plus process modeling with capital cost estimation, and internal capital cost databases and GREET LCA software to perform the analysis required to make these decisions. The biomass and sorted MSW processing methods to be evaluated are torrefaction, steam explosion, and nonthermal drying and pulverization.

GTI has pilot-scale, ultra-dense phase pneumatic conveying equipment, gasification hardware, and all necessary utilities and auxiliary equipment to process and dispose of the syngas that will be leveraged for the proposed flow evaluation and gasification testing. Data acquired during these tests will be used for scale-up modeling and a detailed TEA and LCA on a commercial plant.

Benefits and outcomes: The primary benefit is the development of technology that will enable low-cost sustainable and low-environmental-impact biofuels production. Our plant cost-benefits include reduction in equipment sizing, eliminating the refractory lining, and eliminating the requirement for tar reformers because the high reactor temperatures do not allow tar formation. Our diversity and inclusion plan has identified the benefits of the program to include developing technology that will be developed and deployed in rural areas with high poverty rates, bringing well-paying jobs and clean technology to these underrepresented communities.

Major participants (collaborative projects): GTI, Ekamore, and INL.



COMMENTS

- The project has partially accomplished the objectives of Budget Period 2, which is the testing of corn stover preprocessing using three different methods: torrefaction, steam explosion, and nonthermal drying. The company still needs to characterize MSW and conduct the same testing. The company has selected torrefaction as its preferred pretreatment process for corn stover, with an energy requirement of 128 kWh/ton-out. Most of the energy (76%) goes to pelletization before torrefaction. And the pellet is ground using an additional 9.5 kWh/ton-out. My question is, why is it necessary to pelletize the corn stover? Could it just be torrefied once deconstructed? The nonthermal drying also presents a good opportunity, posing the same question again. Why is it necessary to pelletize? I hope GTI continues the research of nonthermal drying, the most promising alternative in terms of cost, and concludes the same research for MSW.

- This project has taken a sound approach to developing the R-GAS gasifier for commercial deployment by giving due attention to feedstock preprocessing, flowability, and feeding into a pressurized reactor, which has often been overlooked in past projects but is critical for ensuring reliable and consistent operations at the commercial scale. Additionally, techno-economic data were collected to inform the selection of the feedstock preparation method; however, corn stover collection, handling, contaminant removal, and storage have been not addressed. The project overview on slide 3 indicates woody biomass as a feedstock of interest, but the presentation provided information only on corn stover. Will woody biomass also be investigated? Has the team been able to modify the system/design to solve the plugging issues in the ultra-dense phase line? Because the project goal is to demonstrate the technical and economic feasibility of the R-GAS gasifier for biofuels production, TEA and LCA will be key activities for the remaining project work.

- This project is a feedstock preparation method competition for corn stover input to a flow gasification step, which generates syngas for downstream processing. The main criteria are energy input, suitability for conveying to gasification, and capital cost. A significant future criteria should also be the overall cost of producing advanced biofuels from syngas. TEA and IRR will follow in future work. The project should also consider the composition and quality of corn stover as well as other feedstocks to feed to a gasifier. Concerns about feedstock stability and variability also need to be assessed.

- This project builds on the insights gained from a previous endeavor that focused on the torrefaction of woody biomass feedstock. It is not obvious whether the current focus in this project will be woody biomass feedstock (see slide 3) or also involves corn stover (see slide 4) in addition to sorted MSW. Further, we are interested in understanding how the handling of solids, which posed a challenge in the previous project, has been addressed in this one. On slide 13, the carbon utilization is reported as approximately 37%—what does this mean? Is it the total carbon in the biomass or the carbon fraction in the biomass after torrefaction? A mass balance diagram would be useful to understand the reported utilization value. To gain a more comprehensive understanding of GTI's diverse range of projects, it would be useful to have illustrations that highlight similarities and differences between them. Additionally, it would be beneficial to learn about how project team members from various backgrounds collaborate during the execution phase and share knowledge from different projects.

- Gasification technology will play an important role in the production of biofuels from feedstocks such as MSW and lignocellulosic biomass. One critical challenge for the gasification of biomass is the production of tars and the subsequent syngas cleanup and the cost of cleanup. Using an entrained flow gasifier can overcome some challenges, but it requires very small and low-moisture particles to be effective. This project examined three methods for size reduction, measured particle size and energy requirements, and identified torrefaction and nonthermal drying as promising feedstock preparation methods. Whether these methods will scale up to a commercial level and provide similar performance will be a challenge. In real-life situations where feedstock moisture content may vary, the nonthermal drying method may not be effective. Testing in the gasification reactor will be critical in the next stage to determine if the particle size obtained is adequate. The subsequent TEA and LCA will also inform the financial viability of this project and its commercialization potential.

PI RESPONSE TO REVIEWER COMMENTS

- Response to Comment 1: Palletization is necessary because it will enable the pulverization process to result in improved particle size distribution. The nonthermal drying corn stover feeding tests to the gasifier were not reliable compared to the feeding of the torrefied corn stover. When analyzing the powder rheology results, it was found that the cohesive coefficient of the nonthermal drying corn stover is notably higher than the cohesive coefficient of the torrefied corn stover. Response to Comment 2: Within the context of the presentation, corn stover is meant to be a category of woody biomass. Yes, the team was able to implement a larger ultra-dense phase line, which resolved the feedstock plugging issues. Response to Comment 3: Within the context of the current project, the project team plans to assess the flowability of torrefied MSW in addition to torrefied corn stover. Response to Comment 4: Within the context of the presentation, corn stover is meant to be a category of woody biomass. Feeding torrefied sorted MSW will be part of this project. The 37% represents the utilization of the biomass carbon in the final biofuel product. Response to Comment 5: Agreed.

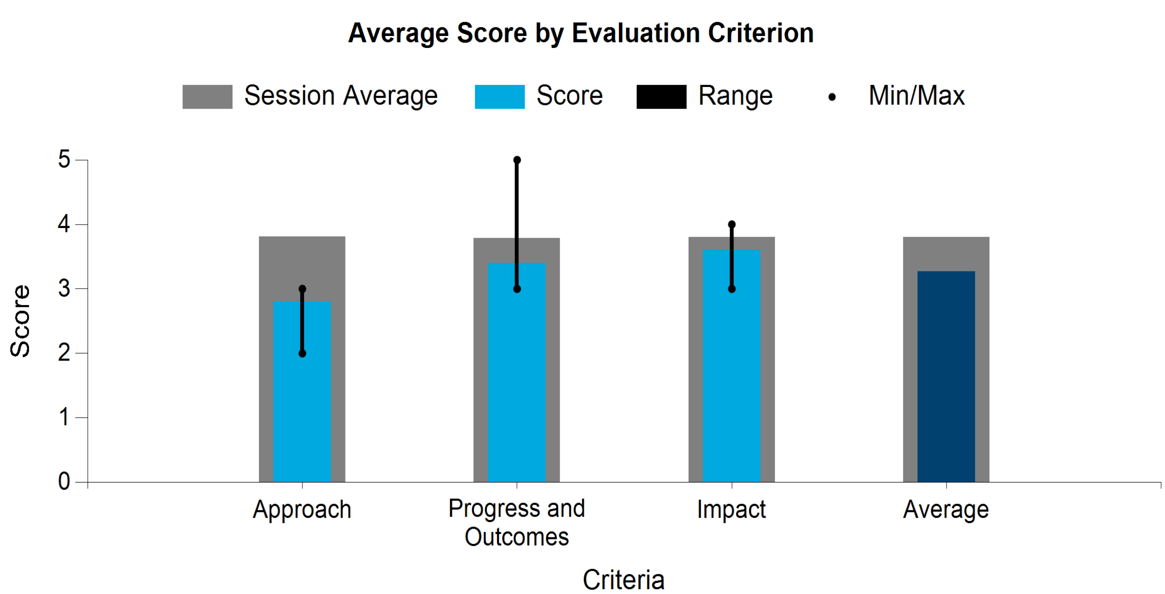
PRODUCTION OF SUSTAINABLE AVIATION FUELS FROM CORN STOVER VIA NREL'S DEACETYLATION AND MECHANICAL REFINING TECHNOLOGY (SAFFIRE)

D3MAX LLC

PROJECT DESCRIPTION

WBS:	3.5.3.103
Presenter(s):	Mark Yancey
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2022
Total Funding:	$999,976

Project SAFFiRE will demonstrate the reliable, low-GHG production of ethanol from corn stover in a fully integrated, 10-TPD pilot facility; the ethanol will be upgraded to SAF by LanzaJet at their commercial ATJ facility in Soperton, Georgia. The global aviation industry seeks to achieve net-zero GHG emissions by 2050. This will require 35 billion gallons/year of low-carbon SAF in the United States and 200 billion gallons/year globally. Multiple sources of SAF will be required to meet the U.S. and global demand for SAF. If successful, project SAFFiRE will: (1) significantly reduce the cost of SAF, allowing for wider use of SAF; (2) enable the production of billions of gallons of SAF from cellulosic ethanol; and (3) help the airline industry to decarbonize by producing SAF with >70% GHG reduction compared to Jet A. Our primary challenge is to design a pilot plant that will operate reliably, at the design rate of corn stover use, and obtain the design yield of ethanol from the stover. We are currently in Phase 1 of this two-phase project. We have completed Task 1: Verification of Application Data; passed the CD-1: Review Verification Outcome (Approve Budget Period 2); and completed Milestone M2.1.1: Design Basis Documents Complete and Milestone M2.1.2: Process Flow Diagrams Complete. We plan to complete Phase 1, Budget Period 2 by Aug. 31, 2023.



COMMENTS

- The project seems to have significant delays. No test has been done that will back up the PI's claims. Although the fermentation time is pretty good, the cellulosic ethanol cost of production required to get to $2.76/gallon seems to be a real stretch. No quantitative data, only qualitative. The project is based on

NREL's DMR technology. The presenter has not indicated if DMR has been proven at scale and has not commented on any plan for changing it from batch to continuous. The pretreatment does not produce sugars, just separates the three portions of biomass. How the company plans to prepare the corn stover for DMR treatment is unclear. How will the company handle dirt and ashes that have always been a problem? The presenter said it had been solved, but no information was given on this very important topic. I see big risks in the project. The presenter has not addressed them (bale handling, corn stover cleaning and shredding, DMR from batch to continuous, stream separations, inhibitors handling in fermentation, and impurities management).

- The project team is taking the right approach to ensure successful scale-up by piloting the conversion of a proven batch process to a continuous process; however, details on the strategies for conversion from a batch to a continuous process would be helpful to the reviewers. The integration of processes from one step to the next has often been the key challenge and risk to scaling up a project. What are the main integration challenges to be investigated for this project?

  The project team has taken lessons learned from past projects and appropriately identified reliable corn stover handling and processing as a key risk; however, the presentation did not provide a list of feedstock challenges to be investigated in this project. For example, will the project investigate the main contaminants of concern and determine how these contaminants will be detected and removed? What about long-term storage and degradation of corn stover?

  For the pilot plant, the team's mitigation strategy for wet corn stover is to identify dry sources of corn stover and arrange for the use of a bale dryer only if needed. What is the strategy for ensuring dry corn stover for a commercial plant? Will the TEA be performed for the commercial plant scenario or for the pilot plant?

- This project appears to depend on the utilization of excess infrastructure and ethanol refining capability at Generation 1 facilities to produce more ethanol, otherwise it would seem to be a substitute of corn grain feedstock for cellulosic feedstock. The opportunity to expand overall ethanol production is otherwise not elucidated. It also requires proving out at scale a biomass-to-sugar process suitable for fermentation, which so far does not appear to have been successful at a large scale. Both issues need to be addressed to ensure the economic expansion of bioethanol so that utilization by ethanol to advanced biofuels is achievable. Key learnings from unsuccessful corn stover demonstration plants to date need to be clearly incorporated into the design, and demonstration plans for piloting the front end of this process should consider those past learnings. Of particular concern is the ability to safely store biomass for long periods of time and the stability of the biomass during storage.

- Is there evidence to support the claim that the failure of past commercial cellulosic ethanol plants was largely due to their scale-ups exceeding 100:1? Although this may have been a factor, it is important to note that much of the failure was mainly attributed to issues with feedstock handling and processing as well as the degradation of feedstock that had been stored for extended periods of time. As such, any risks and mitigation approach taken by this project should include potential long-term storage risks of corn stover, such as decomposition and decay. Have appropriate measures been identified to mitigate these risks? This project aims to expand production without overburdening regional feedstock supplies and intends to use wheat straw and switchgrass as alternate feedstocks. It is vital that a comprehensive characterization be conducted to assess similarities and differences between these feedstocks and ensure their suitability for large-scale production. Additionally, it remains unclear what plans are considered for this project to move from batch operations to continuous operations of DMR as well as the integration of DMR with the D3MAX technology. Finally, the successful execution of this project will require the implementation of a variety of strategies to achieve commercial volumes of SAF, which would greatly impact and improve the industry.

- Meeting the goals of the SAF Grand Challenge will require the development of commercial cellulosic ethanol for conversion into low-carbon-intensity SAF. The lack of success of the previous commercialization of cellulosic ethanol has spurred the development of the new DMR approach by NREL (to be used in this project as a first demonstration of the integrated process). The DMR process has significant potential, and demonstration of the integrated process will be critical for future scale-up to the commercial level; however, one of the most important causes of the failure of previous cellulosic ethanol facilities is not adequately addressed here—namely, the feedstock supply and logistics. The DMR process has been demonstrated with clean feedstock of consistent quality, but this ideal situation will not be encountered in this project. It is well documented that feedstock harvesting, storage, handling, high contaminants, and inconsistent quality caused some of the most important challenges to commercialization. This project should include a clear strategy and approach to address this, particularly with a view to future scale-up where these problems will be amplified. A further aspect of this project is the lignin valorization and the potential value of this lignin ($350/ton shown in the presentation). Lignin recovery and its valorization into high-value applications have not been resolved, and it is not a foregone conclusion that this will be achieved. The specific strategy for lignin valorization is not addressed.

PI RESPONSE TO REVIEWER COMMENTS

- The SAFFiRE team thanks the reviewers for their time and thoughtful comments. Two things before we address specific reviewer comments: The DOE Project Peer Review is a public event, and our presentation, and this response to the reviewer comments, do not contain any confidential information, per DOE instructions. Many of the comments were directed at the lack of quantitative data and detailed information about our pilot project. The design of our pilot plant is confidential, including how we intend to process bales of stover and convert DMR to a continuous process. The second issue is that DOE specifically instructed us to address Phase 1 of our pilot project in our presentation, not commercial SAFFiRE plant issues. Many of the comments related to commercial operation are dead on, but, in general, we did not address commercial issues in our presentation. We will address many of those issues in this response.

  The reviewers correctly identified corn stover with high levels of sand, dirt, and ash as a key issue for our project. We plan to use a two-pass corn stover harvesting method, so we will have sand and dirt associated with the stover (external ash) as well as internal or structural ash. When we process the corn stover bales in the pilot, we will have a dirt/grit removal step as well as rock and debris removal. We have designs for both a wet and dry dirt/grit removal process. We have engaged experts at INL to assist in the design and equipment selection for our bale processing system, including the removal of external ash. Our goal is to remove 80% of the external ash to prevent excessive equipment wear. We also have a proprietary method to remove the remaining external and internal ash in the corn stover pretreatment process. This ash ends up in the DMR lignin coproduct stream. Our bale processing and pretreatment process will produce a relatively ash-free biomass for conversion to ethanol. We will harvest about 800 bales of corn stover this fall (2023) so that we can measure corn stover internal and external ash and evaluate stover degradation with various storage and bale tarping and storage methods. This stover will be stored for more than a year. Corn stover degradation in storage is caused by high moisture in the stover bales. High moisture (above 20%) and warm temperatures cause microbial growth in the stover and loss of carbohydrates. This leads to lower ethanol yields per ton of stover. The problem is that dry stover bales can absorb moisture unless the bales are stored in a covered enclosure, which currently is too expensive. Tarps can cause condensation under the tarp, and if exposed to rain, the sides of stover stacks can get wet. In Phase 2, we will conduct a cost-benefit analysis of storage costs versus stover degradation. Some degradation is inevitable. We will adjust our feedstock supply plan as necessary based on the results of our initial stover harvest and storage study. We will also explore the impacts of processing wet stover (moisture >20%) when we operate the pilot plant.

We are laser focused on feedstock supply and stover bale processing at both the pilot and commercial scales. Our project includes a subcontract with the stover supply consultant that designed the successful, but short-lived, feedstock supply system for the DuPont cellulosic ethanol plant in Nevada, Iowa. This plant was shut down by DuPont during startup when DuPont exited the cellulosic ethanol business. More than 50,000 tons of stover were collected for the DuPont project. We have also extensively studied the final technical report for POET-DSM's Project Liberty in Emmetsburg, Iowa (www.osti.gov/servlets/purl/1866610). In 2014, Project Liberty collected nearly 200,000 bone dry tons (BDT) of corn stover bales prior to the start of operations. Corn stover collection was one of Project Liberty's success stories: "Despite a concern for feasibility of biomass collection, POET-DSM proved that the large-scale commercial corn stover collection is possible and farmers are willing to participate in the process. The IBR in association with POET Bioprocessing - Emmetsburg enjoyed strong relations with surrounding corn growers. The trust and positive relations, together with new ideas for biomass collection such as POET EZ Bale and the right choice of baling equipment, contributed to the development of an efficient supply chain" (*Project Liberty Final Technical Report*, page 93) With the experience gained from DuPont's cellulosic ethanol project and Project Liberty, we are confident that we can design and implement a successful corn stover supply chain for both the SAFFiRE pilot plant (10 TPD) and planned commercial plants. Key concepts that we will implement include:

- We will capitalize on the relationships Generation 1 ethanol plants have with local corn producers to help develop our relationships with these producers that will provide corn stover for our pilot project and future commercial plants.
- We will fully compensate every party in the feedstock supply chain, including compensating corn growers for their stover. This includes nutrient replacement and profit in addition to harvesting and baling costs.
- We will provide options for corn growers: Corn growers can harvest the stover themselves or SAFFiRE will provide a custom harvester to harvest the stover.
- We will work with growers and the U.S. Department of Agriculture to establish sustainable stover harvest levels by developing guidelines to prevent wind- and water-induced soil erosion, maintain proper soil organic carbon, and sustain or improve chemical and physical properties associated with "soil growth."

Feedstock logistics for our pilot project are actually low risk because we will only process one corn stover bale per hour. If we ran the pilot 24/7 for one year, we would need only 8,000 bales of stover. A SAFFiRE plant that produces 20 million gallons/year of ethanol would require half a million bales/year. Our pilot project will demonstrate how we will harvest and transport corn stover to the pilot plant while mitigating stover degradation while in storage. Moreover, our feedstock supply chain must be scalable to very large SAFFiRE plants (i.e., to at least 20 million gallons/year of ethanol production or approximately 750 BDT/day of stover).

The major risks related to the use of corn stover to produce ethanol and our mitigation plans are summarized here:

- Corn stover moisture: High moisture in bales can lead to degradation in storage and yield loss. We will optimize storage costs to prevent high moisture versus yield loss. High-moisture bales can also cause plugging and reduced throughput in the bale processing system. We will develop storage techniques that minimize moisture migration into stored bales.
- Corn stover ash: Internal and external ash (dirt) is abrasive and can cause excessive equipment wear. We will remove external ash during bale processing. Additional external ash and internal ash

will be removed by our modifications to the DMR process. Our ash removal designs are confidential.

- Through our pilot design and pilot testing, we will develop a reliable bale processing system. Our commercial plants, however, will have redundant bale processing trains to increase plant reliability. This cost is in our CapEx estimate for commercial plants.
- Alkaline DMR pretreatment solves the issues created by dilute acid pretreatment. This issue was addressed in slide 4 of our presentation. Our Phase 1 verification test demonstrated that DMR produces a clean sugar stream with no significant fermentation inhibition. NREL has published several peer-reviewed papers on DMR that demonstrate greater than 90% sugar yield from corn stover with very low enzyme loading (approximately 10 mg of enzyme formulation per gram of biomass glucan content). These papers are based on pilot-scale DMR tests conducted by NREL and Andritz (for disc refining of the deacetylated corn stover). Our DMR, saccharification, and fermentation designs are confidential. Our Phase 1 designs will result in several patent applications, so protection of confidential information is very important until nonprovisional patent applications are filed.
- Lignin valorization: We agree with the reviewer who asked about our lignin valorization plans. We recognize that this is a risk for commercial SAFFiRE plants. We are exploring multiple near-term and potentially large markets for the SAFFiRE lignin coproduct. These plans are confidential and could not be presented at the Project Peer Review. There are small markets for lignin today, with prices significantly higher than our $350/ton in our financial proforma. We expect to have multiple letters of intent to test our lignin streams in industrial formulations by the end of Phase 1.

One reviewer commented, "This project appears to depend on the utilization of excess infrastructure and ethanol refining capability at Generation 1 facilities to produce more ethanol, otherwise it would seem to be a substitute of corn grain feedstock for cellulosic feedstock." On the contrary, we believe that both Generation 1 and Generation 2 ethanol (along with many other sources of SAF) will be required to meet the projected U.S. demand for SAF of 35 billion gallons by 2050. We do not see Generation 2 ethanol replacing Generation 1 ethanol. Our colocation strategy takes advantage of a developed ethanol production site to reduce CapEx and OpEx costs for the Generation 2 ethanol. Expanding the utilities, if necessary, for an existing site is much cheaper than building a greenfield Generation 2 project. Staffing a Generation 2 ethanol plant at an existing ethanol plant also results in significantly fewer new employees than a greenfield project. For example, a 100 million gallons/year Generation 1 ethanol plant will have approximately 60 employees. Adding a 20-million gallons/year Generation 2 plant at that site will require approximately 20 new employees versus 80 employees for a greenfield Generation 2 plant.

There are no special integration steps required for the DMR sugars to be processed by the D3MAX technology for saccharification, fermentation, and distillation. D3MAX has commercialized these process steps at the commercial D3MAX plant at Ace Ethanol in Stanley, Wisconsin, which produces cellulosic ethanol from corn fiber. If I implied or stated that scale-ups exceeding 100:1 are largely responsible for past Generation 2 failures, I misspoke. Large scale-up ratios for past Generation 2 projects strained the ability to efficiently collect, transport, and store corn stover. All the reviewers stated this was an issue for past Generation 2 projects and an issue for our project. The past Generation 2 projects went from no or very little stover collection experience to 750 TPD or more. I think it is obvious that this is not a good strategy and did contribute to some project failures. POET-DSM's Project Liberty seems to be the exception, with the equivalent of approximately 550 TPD of stover collected in 2014 when the Project Liberty plant began startup. POET began conducting stover harvesting trials in 2008, and this certainly contributed to their success in stover collection in 2014. SAFFiRE will begin stover collection trials in 2023. With our first commercial plant scheduled to be operational in 2028, this gives us 5 years to perfect our feedstock supply chain, just as POET did. In addition to low D3 RIN prices, Project Liberty's downfall was primarily due to the dilute acid pretreatment system. Even after a complete replacement, the pretreatment system did not operate reliably. Our TEA for Phase 1 will be done for commercial SAFFiRE plants; most likely our 200-BDT/day demonstration plant (5.6 million gallons/year of ethanol) and our target scaled plant of 750 BDT/day (20 million gallons/year of ethanol). The TEA in our proposal was done by NREL and demonstrated the potential to achieve the $2.75/GGE MFSP target for SAF based on valorizing lignin at $300/dry ton. Our project experienced a significant delay when our original cost-share partner left the project. We replaced that partner with Southwest Airlines, but finding the right partner and negotiations with Southwest resulted in a five-month delay in the project. Since the lifting of the conditional status of our award on July 21, 2022, allowing us to proceed with Budget Period 1, we are on schedule to complete Phase 1 by Aug. 31, 2023.

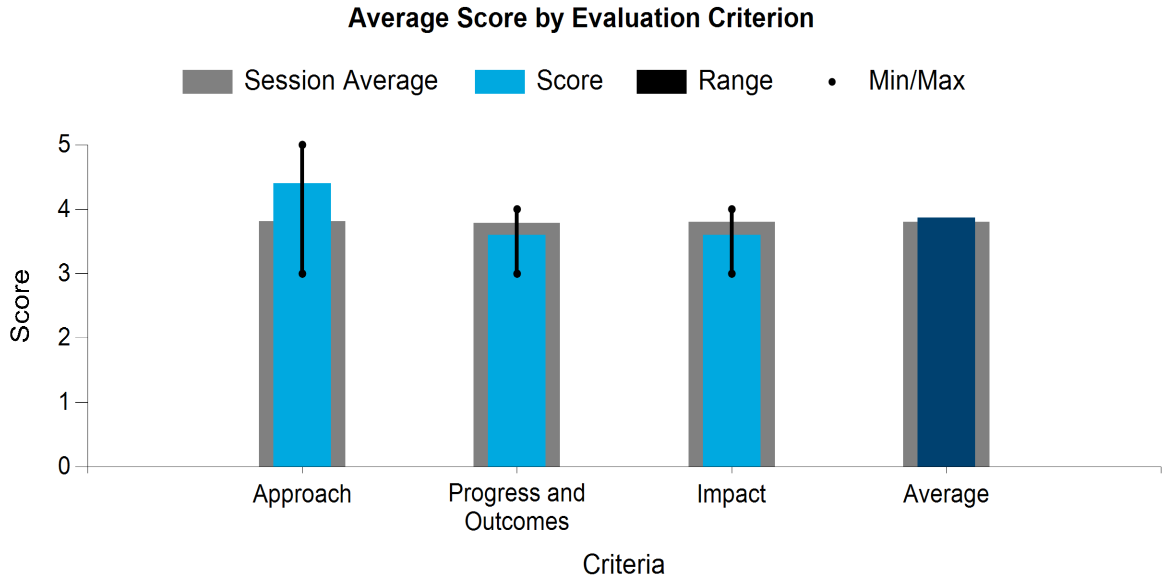
DEMONSTRATION SCALE-UP: TRIFTS BIOGAS TO RENEWABLE FUEL

T2C-Energy LLC

PROJECT DESCRIPTION

WBS:	3.5.3.105
Presenter(s):	Devin Walker
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2026
Total Funding:	$1,067,238

T2C-Energy developed and patented a proprietary process, we have trademarked TRIFTS, by which to convert biogas (or landfill gas) to liquid transportation fuels. This project seeks to scale the TRIFTS technology to enable the design and construction of a demonstration plant achieving a TRL of 7 by the end of the project. The TRIFTS process has been thoroughly tested at the pilot scale (during the past 2 years) processing a 9–24-scfm slipstream of raw biogas into drop-in renewable transport fuel. The process is capable of using both the carbon dioxide (CO_2) and methane portions of biogas and incorporates the biogenic carbon from them into the hydrocarbon backbone of the final fuel product of the process. In doing so, the technology essentially uses 100% of the biogas as a feedstock. The use of carbon dioxide is a critical cost reduction step because it represents 40%–50% of the total makeup of biogas, effectively doubling the utilizable carbon compared to technologies that remove CO_2 using expensive pretreatment processes. T2C-Energy and its project partners will implement a 1,400-scfm biogas capacity plant and produce more than 1,000,000 gallons/year of renewable cellulosic diesel. This renewable source of diesel resembles its petroleum counterpart both physically and chemically, passing ASTM D975 specifications, and it can be used in current-day engines with no engine modifications. The demonstration plant final fuel product is tunable with the ability to produce renewable fuels for the heavy trucking, aviation, and marine industries by varying process conditions within the FTS reactor with no equipment modifications required. By avoiding wax formation, we eliminate the necessity for expensive hydrotreatment, hydrocracking, and high-temperature distillation post-treatments of the FTS product. Proven performance at the demonstration scale makes future projects more financeable because technology risk is removed. Many of the inherent restrictions of waste-to-energy facilities in the United States will be solved by this project, including high capital costs, subsidy reliance, additional infrastructure costs, vehicle modifications, carbon capture, substandard financial performance, limited or specific feedstock, low fuel output, and scalability.



COMMENTS

- Same comments as in the previous project. This is a good presentation. There is a lot of good data. It has credible information and is a good business concept. It can survive with no subsidies. Well done. I have concerns about the catalyst life. The presenter said it would last at least 6 months, but no proof was provided. There is very little information about the type of catalyst, cost, and regeneration procedures. It is not clear how the company is going to deploy the technology. Will it be in large biomass-producing sites, building large facilities, or installing mobile units and running campaigns?

- Same comments as the other T2C-Energy project: This project presents an investigation of a new catalytic process that removes five unit processes and thereby simplifies the GTL process platform while also using the CO_2 to maximize production. The capture and use of waste heat and FTS water helps to create a self-sufficient process, is a best practice for sustainability, and may be key in making this process economically feasible at the commercial scale. The project seems to replicate actual commercial operation conditions by using raw biogas as a feedstock and using the FTS water in the process (with results showing a lack of impact on the process and products).

  Slide 8 shows that the TRIFTS system produces the jet fraction. A distillation system, which is a well-proven technology, would be needed. The project team has chosen to produce only renewable diesel to minimize the number of unit processes and associated costs and to keep the number of products down to one.

  The presentation indicated an independent engineer-validated MFSP of $2.91/GGE without subsidies or credits, which is commendable. At what scale was the MFSP of $2.91/GGE calculated? It would be helpful to see at what scale this process is economically feasible, given that FTS is generally economic at large scales.

  Can the catalysts (for tri-reforming and FTS) be regenerated, and if so, how many times? How long does it take to regenerate? Would the catalyst be regenerated in place, or would it be removed from the reactors and regenerated off-site? What does the waste industry scale translate to in terms of range of production volumes of the renewable diesel (in gallons or barrels)?

Additional questions for this project: Does the process water contain any toxic or hazardous components that are a concern for disposal? What treatment, if any, is required for proper disposal? What integration and scale-up challenges will the project team focus on for the demonstration project?

- In addition to the concerns previously stated about the availability and aggregation of biogas, this process depends on reformer performance, including mitigating any sensitivity to contaminants, proving catalyst life, and understanding the impact of corrosion on capital cost for installations. The Fischer-Tropsch reactor also has to perform well, and it may not be too capital intensive. The TEA is promising, but the project needs to look at the net present cost of the fuels produced, which would include the capital cost impact and comparison to other routes to advanced biofuels. Reliance on capturing RINs and other incentives may not be sustainable for the long term.
- To enhance the understanding of the project's progress, providing information on the project's execution would greatly benefit the reviewers. It would enable them to understand the various milestones achieved, the challenges encountered, and the overall progress made toward achieving the project's goals. On slide 20 displaying the impact, it is evident that the numbers used are from another project (WBS 3.5.1.201). To ensure accuracy, it is suggested to update the figures to align with the current information and performance of the project. Additionally, slide 17 depicts operators without safety glasses, hard hats, or cut-resistant gloves, which is not meeting the safety requirements. Providing safety training and mandating the use of safety gear should be implemented to avoid such instances in future. These comments are in addition to the ones provided for another project (WBS 3.5.1.201).
- This is an exciting project, and the approach is comprehensive with substantial merit. It has a clear management plan, and risks have been identified with appropriate strategies in place. The long-term impact of the technology and the project approach can be significant, but they will depend on the scale-up potential. The technology was demonstrated at a small scale and a modular approach, and it is not entirely clear how this will translate into larger-scale production. This demonstration project is therefore important, but it would be good to have a clear idea of the future potential for scale-up and the potential capacity of facilities using this technology. The future impact of the technology will rely on achieving large-scale production of renewable fuel. Although extensive industry engagement has taken place in the development and demonstration of the technology, commercialization and scale-up will need industry partners that can take it to the next level. Although the current focus is on renewable diesel, the potential production of SAF should be further explored for larger-scale facilities. It will be useful to separate and analyze the jet fraction against ASTM specifications. Note that a bifunctional catalyst will likely not meet current ASTM D7566 Annex 1 specifications for SAF.

PI RESPONSE TO REVIEWER COMMENTS

- Catalyst and process longevity studies were done during a seven-month continuous pilot study on-site at the Citrus County central landfill using the raw biogas produced at this MSW landfill. During this pilot demonstration, the plant consistently achieved methane conversions of 88%–92%, at times approaching the theoretical maximum conversions of 99%. CO_2 conversions were consistently between 30%–40%, at times reaching 50%–60% conversions. Conversion efficiencies during the long-term pilot demonstration aligned with bench-scale results as we proved the ability to maintain high conversions throughout the entirety of the demonstration. During the entirety of the demonstration, the reformer was able to produce the ideal syngas composition with an H_2:CO ratio of 1.7–2.2. This is one of the unique aspects of our tri-reforming capabilities to tune the syngas H_2:CO ratio as needed throughout the demonstration. During this pilot demonstration, the plant consistently achieved CO conversions of 50%–70%. During the pilot demonstration, we intentionally limited the CO conversion to 60%–70% because it is known that higher conversions can lead to high partial pressures of H_2O and deactivate the FTS catalyst; however, there were little to no signs of FTS catalyst deactivation throughout the entirety of the demonstration, and, in fact, we achieved our greatest conversions toward the last few weeks of the demonstration.

Typical industrial gas to liquids have lifetimes of approximately 4–5 years, based on the long-term pilot data at Citrus. We believe the catalyst used in this project would meet or exceed industrial catalyst lifetimes. The reformer and FTS catalyst used in this project were produced in-house using the T2C-Energy patented catalyst. Currently, T2C-Energy manufactures the reforming and FTS catalyst at $20.44/kg and $85.59/kg, respectively. Current manufacturing capabilities allow us to produce approximately 10 kg/hour of catalyst. During the pilot demonstration, regenerative studies were performed using two techniques. The first technique involved regenerating the reforming and FTS catalyst while remaining online (*in situ* regeneration). Higher steam flows are fed to the reformer to oxidize carbon deposits on the catalyst surface. This increases the H_2:CO ratio of the syngas product while also removing carbon in the form of methane. The elevated H_2:CO ratios feeding the FTS facilitate carbon removal and shift the FTS products to a lighter boiling point fraction, allowing for continuous operations as the FTS catalyst bed is regenerated. This regeneration cycle typically takes approximately 2–4 hours to complete and return to steady-state conditions. The second regeneration technique requires the feed to both reactors to be removed and replaced with a steam/air feed, effectively oxidizing coke deposits on the catalyst surface. This is done over a 1-hour period, followed by a reduction gas mix of hydrogen and nitrogen to reduce the active metal of the catalysts. This second regeneration cycle takes approximately 24–30 hours to complete and return to steady state. The second regeneration technique is more rigorous and done approximately every 2,000 hours of run time or if the catalyst activity drops 10% below the desired conversion efficiencies. Both regeneration methods are performed within the respective reactors for reforming and FTS. Spent catalyst are disposed of according to EPA solid waste regulations (K171). This includes utilization to produce new catalysts and other useful materials, recycling through recovery of metals, and treatment of the spent catalyst for safe landfill disposal.

The full-scale TRIFTS modular system is designed to accommodate biogas production facilities generating 123–1,750 scfm. This is T2C-Energy's short-term serviceable available market because most commercial technologies struggle to remain profitable within this range. Larger centralized facilities with traditional construction methodologies will be deployed once confidence within the waste-to-energy sector is gained through proven full-scale operational data at the 123–1,750-scfm biogas range. The average biogas flow rates of an anaerobic digester facility and landfill in the United States are 210 scfm and 1,380 scfm, respectively. At these biogas flow rates, using the TRIFTS process, the average size anaerobic digester would produce 230,000 gallons of renewable fuel annually, and an average size landfill would produce 1,470,000 gallons of renewable diesel fuel annually. The independent engineer-validation MFSP of $2.91 was calculated based on a biogas feed rate of 1,500 scfm and excludes environmental attribute revenues. T2C-Energy has specifically targeted landfills producing >300 scfm of landfill gas, farm-based anaerobic digesters producing >123 scfm of biogas, and wastewater anaerobic digesters producing >275 scfm of biogas. Sites flaring the majority of their biogas and sites producing electricity from biogas with expiring electrical power purchase agreements meeting these biogas flow rate capacities are T2C-Energy's short-term market focus. "Stranded" facilities where the natural gas pipeline infrastructure does not exist are of particular interest for TRIFTS biogas-to-diesel projects. T2C-Energy has gained interest from these stranded facilities and also from developers wanting to avoid the costly gas connection/distribution fees of natural gas pipeline owners. Liquid fuel production simplifies logistics in that it can be stored and transported under ambient conditions; therefore, current freight and rail distribution channels are used, and project location becomes less relevant than RNG types of projects. TRIFTS landfill projects generate a carbon intensity score of -36 gCO_2e/MJ fuel, and, therefore, for the project to break even, the flow rate of landfill gas needed is 300 scfm. Whereas TRIFTS farm-based anaerobic digester projects have carbon intensity scores of less than -500 gCO_2e/MJ, and, therefore, for the project to break even, the flow rate of biogas needed is 123 scfm. Carbon intensity scores are based on the ANL GREET module that was completed under this project for the TRIFTS fuel production pathway.

The process water generated in the process contains 1% water soluble hydrocarbons, such as lower chain alcohols. Process water is recycled back to the process in the form of steam to the reformer, where the hydrocarbons are converted into the desired syngas product. Regarding water usage, approximately 10–30 gallons/minute of water are needed within the cooling tower unit due to evaporative losses.

Scale-up challenges addressed during this demonstration project are related to the integration of waste heat streams associated with the reformer furnace to produce green electricity, continuous quality control of diesel and jet fractions, unsteady-state startup conditions and regeneration cycles, proving an annual on-stream factor of >93%, reduction of OpEx costs, optimizing preventative maintenance cycles, long-term removal of contaminants, prevention of contaminant accumulation, producing long-term operational data at full scale, effective operational management at full scale, and proving the ability to produce more than 1 MM gallons/year of renewable diesel meeting an MFSP of <$2.50/GGE.

In general, the project execution strategy will follow this framework: DOE award notification; planning and mobilization; formal kickoff meeting with DOE, engineering contractor, and applicable third parties; global document orientation and review; process optimization studies; update material and energy balance; long-lead identification/sizing/sourcing; hazard and operability study; basic engineering reviews; issue for design (completion of engineering); initial 3D modeling/isometrics/physical design; development model reviews; vendor identification and initial procurement activities; final 3D modeling/physical design (inside battery limits and outside battery limits); development model reviews; vendor data reviews; detailed engineering reviews; drawing production/physical plans; model freeze; preconstruction and commissioning reviews; issue for construction; fabrication and factory acceptance testing; installation and commissioning; and plant handover and operations.

T2C-Energy will review expectations, global documents, design criteria, budget, schedule status, limitations, design standards, templates, specifications, lessons learned, project history, deliverables, and specific responsibilities of the team members of each organization. At the outset of the project, the primary focus of the execution team will be full definition of all global documents for the demonstration project. These documents define the engineering decisions that will be reflected in the procured materials and physical design. Any changes to these documents later in the project will directly impact the quality, cost, and schedule of the overall effort. These documents include but are not limited to: design basis, process flow diagrams, general arrangements/plot plans, piping and instrumentation diagrams, one-line diagrams, and communication block diagrams/control architecture. Internal and external reviews will be conducted by T2C-Energy, the engineering contractor, and appropriate project stakeholders. Initial efforts are focused on ensuring that all engineering definitions, input, and decisions are properly captured and vetted up front with all project team members and stakeholders. This will ensure that the procurement and physical design can effectively proceed with the issued for design (IFD) milestone. Safety reviews, the hazard and operability study, and process hazard analyses will create action items that will be incorporated/addressed in updated designs. Additional reviews on global documents will include construction representatives of T2C-Energy, the engineering contractor, vendors, and other project stakeholders. The main objective of these additional reviews is to have all required personnel contribute to the design up front, such that decisions on paper at the IFD milestone represent a thorough, vetted, accurate consensus from the project team. This will minimize and effectively manage the impact of design changes downstream, during procurement and physical design. The global documents will undergo a complete yellow-line check prior to IFD. Although not expected to be true construction quality at the IFD milestone, these deliverables are expected to contain all required information for procurement and physical design to proceed through project completion without any further development. Any gaps found on the global documents that would prevent procurement or the physical design from proceeding will be addressed or approved to be placed on hold due to circumstances outside the direct control of the project team. A master document register will be generated capturing all tasks, documents, drawings, and activities associated with the statement of project objectives. The master document register will be used to support the earned value productivity tracking at the deliverable level throughout the life of the project. The work breakdown structure is the basis for the schedule and is used to link the task timelines and key milestones to ensure that the target delivery dates are achieved with the allocated resources. The Gannt chart will assist in planning the resource allocation and tracking the work progress. The project schedule is managed via conventional critical path method. Project reviews are scheduled to ensure efficient execution of the project deliverables. Internal and external stakeholder reviews will ensure that all input is captured and a set of frozen IFD deliverables are released. The IFD documents serve as the basis for the specification and procurement of components and the physical design. Internal and external reviews conducted on 3D models, isometrics, and structures ensure that all input necessary to obtain a static, stable design is in hand prior to the issue for construction deliverables. All drawings and models are reviewed to ensure regulatory compliance and to meet expectations defined in the initial project reviews prior to the release of a construction-quality bid package.

T2C-Energy's management philosophy is to provide an experienced, quality team with management procedures and systems emphasizing an efficient team concept. The establishment of strong, internal coordination of efforts is key to success. Generally, this coordination is accomplished through clear project organization, where responsibilities are defined and understood. Direction is provided through internal meetings and control lists, with action items assigned with due dates, defined procedures/criteria for engineering and drafting reviews, performance assessment systems, checklist verifications, and project audits. This type of personnel management highlights potential problems before they occur, ensures adequate interaction between disciplines, and provides the key personnel with a basic knowledge of all facets of the project. T2C-Energy involves all levels of project personnel in work discussions to establish specific actions, set delivery dates, and challenge/motivate people to do a quality job, which instills a positive team spirit. T2C-Energy will initially staff this project with current employees and obtain third-party contract support for engineering. T2C-Energy has highly skilled engineers; project control specialists; environment, health, and safety specialists; operations and maintenance staff; and administrative personnel ready to mobilize for this effort. Work performed by the assigned resources is coordinated by the project manager and project engineer, with additional supervision of resources by their respective supervisors. The overall management of a project is the direct responsibility of the project manager (PI). The project manager is ultimately responsible for the successful coordination and execution of the overall project. To help ensure that the project manager has all the necessary support from the organization to achieve this goal, T2C-Energy will assemble the following project leadership team to assist the project manager throughout the duration of the project effort. The project leadership team functionally reports to the project manager. The project engineer; process engineering lead; environment, health, and safety lead; project controller; operations manager, and additional support personnel and specialists will be added to the team as required through the life of the project. The project manager is responsible for the following: overall coordination and project work scope; overall management of engineering, procurement, and construction and third-party contractors; management of stakeholder relationships; on-schedule submission of deliverables; regulatory compliance; design compliance; technical accuracy and standards compliance; compliance with T2C-Energy standards and procedures; overall project quality; resource planning; project execution plans; change management (supported by project leads); status reports; interface management; project reviews and audits; recordkeeping of all documents and drawings (support from projects); day-to-day coordination (inter- and intra-discipline checks); and quality control. The project engineer and engineering lead is responsible for: discipline-specific scope, budget, and schedule; compliance, technical design criteria, and internal standards; defining work scope interfaces across inside battery limits and outside battery limits; coordination with engineering contractor and project stakeholders; deliverable production; quality control checks and signoffs; interface management with other disciplines; technical accuracy and standard compliance on deliverables; inter- and intra-discipline checks; resource forecasting and planning; vendor management and data collection; scheduling internal model reviews; drawing reviews, checks, and signoffs; and compliance with design criteria. The environment, health, and safety lead is responsible for: environmental compliance; federal, state, and local regulatory compliance; construction and operation permit approval and compliance; compliance with internal and external environment, health, and safety policies; safe execution of the project; LCA reviews and development; and renewable fuel regulatory compliance. The project controller is responsible for: recordkeeping of all documents and drawings; project budgeting and accounting; resource allocation; quality control; coordination with the engineering contractor and project stakeholders; and administrative management. The operations manager is responsible for: day-to-day operations; supervision of all operations and maintenance staff; coordination with contractors; participating in project reviews; plant layout development; supervising the T2C-Energy commissioning team; vendor coordination; maintenance planning and scheduling; and meeting plant performance metrics. T2C-Energy uses project planning and control systems to assist in planning, monitoring, and managing all execution activities. Focus is placed on defining the cost and time frame for completion of the statement of objectives. The deliverables listed in the statement of project objectives detail all the documents, drawings, tasks, activities, etc., required to complete the work scope. Earned value productivity is established by developing a master document register and standard rules of credit during the initial efforts. Man-hours and costs are established at the deliverable level. Standard rules of credit provide objective, quantifiable means of measuring completion status per deliverable as the project progresses. Using project management software, the entire project is planned and tracked. Critical path analysis, planned versus earned graphs, cost curves, schedule performance index, cost performance index, variance reports, completion forecasts, and resource-leveled schedules are provided as required to effectively monitor and manage the work being performed.

LANDFILL OFF-GAS TO ULTRA-LOW-CARBON-INTENSITY SAF (LOTUS)

SkyNRG Americas Inc.

PROJECT DESCRIPTION

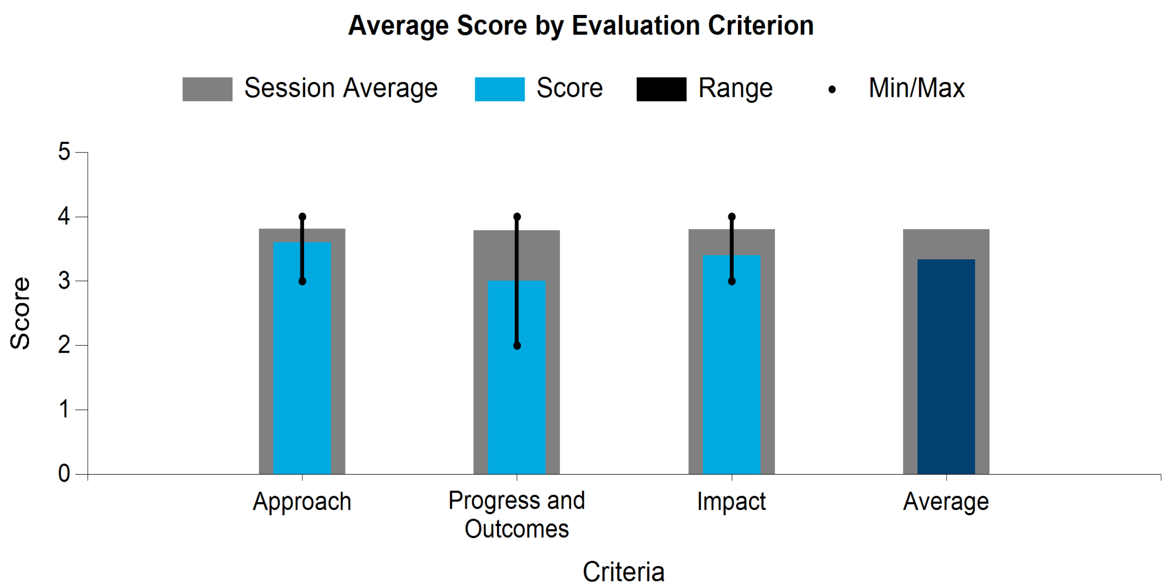
WBS:	3.5.3.107
Presenter(s):	Brian James
Project Start Date:	10/01/2021
Planned Project End Date:	03/31/2023
Total Funding:	$2,000,000

Major partners: SkyNRG Americas, LanzaTech, Linde, LanzaJet, Energy Vision, PNNL, and ANL.

Project objectives: Construction and operation of the first RNG-to-SAF commercial demonstration facility.

Project description: SkyNRG Americas, the project developer, and its commercialization partner, LanzaTech, will design, engineer, build, and operate a unique demonstration-scale facility that will convert RNG into SAF. In Phase 1, the team will verify the TRL and complete a −15/+30 cost estimate. In Phase 2, the team will continue engineering and site construction, leading to a 5-million-gallon/year nameplate capacity demonstration site for RNG to SAF.

Project impacts: The aviation sector is challenged by commitments to reduce GHG emissions in the face of continued dramatic growth. The goals can only be met by SAF. The United States uses 26 billion gallons of jet fuel but produces less than 4 million gallons of SAF. Project LOTUS will provide a new supply chain for producing SAF while reducing methane emissions and improving air quality that is applicable to the entire nation due to the wide distribution of RNG production facilities across the United States. The resultant fuel is high quality, low soot forming, and sustainably derived, reducing GHG emissions by up to 110%. DOE funding will accelerate the commercial rollout of SAF production from RNG by reducing the technical and financial risks for future integrated commercial plants.



COMMENTS

- The project sponsor was flexible in changing the feedstock to allow for better project economics. The technology components were independently tested before the project started. The project has demonstrated the production of ethanol, not SAF.

The economics of the project are based on heavy subsidies. I do not think that this is the right long-term business model. RNG is a very expensive feedstock. Although the presenter said that RNG would be cheaper in the future, he can get long-term purchase contracts at much lower prices than today. This is to be seen. It is very unlikely that the project will be economically feasible. The presenter says that the conversion of ethanol to SAF is not part of the project. I think that the project needs to prove that with the ethanol produced, it is possible to produce SAF. It is not enough to produce ethanol.

The cost of a first-of-a-kind plant producing 30 million gallons/year of SAF is estimated at $500–$700 million. This level of investment is very unlikely to be assumed by any private investor. I think it is difficult to justify a sustainable financial return on this project.

- Technically, the project presents a well-planned approach for the scale-up of the process technology platform and pathway from RNG to SAF and renewable diesel, with a high selectivity (90%) for SAF.

  The presentation indicates that the Linde hot oxygen burner partial oxidation reformer can “easily tolerate variation in feedstock composition and flow rate.” Can the hot oxygen burner respond in real time to variations to feedstock composition?

  The economics seems challenging using RNG as a feedstock. Currently, RNG enjoys high incentives when sold as a transportation fuel. As such, procurement of RNG as a feedstock for SAF would be expensive and currently seems uneconomic. SkyNRG indicates that RNG will become more affordable as incentives decline and more RNG production facilities come online. What is SkyNRG’s forecast for when RNG will become an economic feedstock for the LOTUS ATJ process platform?

  Will the results of the BETO scale-up project provide sufficient demonstration to reduce the technical risk for landfill owners? If not, what else is needed for landfill owners to accept the LOTUS process platform?

- This project depends on a number of critical factors for large-scale impact, two of which are the availability of RNG at large enough centralized locations to reach economy of scale and continuing RINs to offset costs. The overall project also depends on multiple not yet fully proven steps, so an assessment of the variability of the RNG amount and composition and that effect on each subsequent step to liquid fuel production would be advisable to understand the potential for large-scale impact and economic success. In addition, it might be useful to compare the value creation with this approach to the alternative uses of RNG in the current routes to market. The value of RINs long term seems uncertain, and, in addition, understanding the costs as they relate to project location (oxygen availability, for example) and the energy integration opportunity is critical. CapEx and OpEx for a fully integrated facility at scale are a concern, and their effect on IRR should be evaluated. Overall, the concept appears worthy of development—at least to the point of prove out at a semicommercial scale.

- To ensure the success of this project, it is imperative to include an assessment of the availability of the required quantities of RNG. Additionally, the impact of using RNG in the form of compressed natural gas for heavy-duty vehicles must be carefully evaluated. When selecting feedstock sources, it is essential to consider the physical and chemical characteristics of RNG from various sources as well as the requirements for purification. Further, the potential for competing uses of RNG, such as replacing natural gas for electricity generation, must be considered when estimating the costs of RNG within the TEA. Ultimately, the successful outcome of this project will greatly contribute to the increased commercial availability of SAF, and thus it is vital to carefully consider these key factors throughout the process.

- This project proposes to produce SAF through multiple steps using RNG to make syngas to be fermented into ethanol using LanzaTech’s technology, after which the ethanol will be used to produce SAF through the ATJ process. The production of syngas through partial oxidation is fully commercial, whereas the syngas fermentation technology has been operating at a commercial scale but using industrial off-gases. The scope of the project was changed from using biogas to using RNG because the production of fuels using CO_2 is not currently EPA-approved, and therefore RINs could not be generated. This seems to be an inefficient approach because biogas must first be upgraded into RNG, with carbon lost in the process. RNG has multiple other efficient applications, and competition with these applications may impact the availability and price of RNG. The syngas fermentation step and yields of ethanol should be provided. The solubility of CO and H_2 and gas transfer limitations will impact yield in this step and will impact the overall commercial viability of the process. TEA and LCA will be carried out in the next phase, and results will be critical.