FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

TECHNOLOGY AREA

CONTENTS

INTRODUCTION 781

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM REVIEW PANEL 781

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM REVIEW PANEL SUMMARY REPORT 782

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM PROGRAMMATIC RESPONSE 786

FOREST CONCEPTS DFO 789

MOISTURE MANAGEMENT AND OPTIMIZATION IN MUNICIPAL SOLID WASTE FEEDSTOCK THROUGH MECHANICAL PROCESSING 793

WONDERFUL COMPANY DFO 796

SMART TRANSFER CHUTES WITH IN-LINE ACOUSTIC SENSORS FOR BULK-SOLIDS HANDLING SOLUTIONS 800

TASK 1—MATERIALS OF CONSTRUCTION 805

TASK 2—FEEDSTOCK VARIABILITY 809

TASK 3—MATERIAL HANDLING 813

TASK 4—DATA MANAGEMENT 818

TASK 5—PREPROCESSING 822

TASK 6—HIGH-TEMPERATURE CONVERSION 827

TASK 7—LOW-TEMPERATURE CONVERSION 831

TASK 8—TEA/LCA 835

TASK X—PRINCIPAL INVESTIGATOR/PROJECT MANAGER 841

INTRODUCTION

The Feedstock-Conversion Interface Consortium (FCIC) Technology Area is one of 12 technology areas that were reviewed during the 2021 Bioenergy Technologies Office (BETO) Project Peer Review, which took place virtually March 8–12, 15–16, and 22–26, 2021. A total of 14 presentations were reviewed in the FCIC session by five external experts from industry. For information about the structure, strategy, and implementation of the Technology Area and its relation to BETO's overall mission, please refer the corresponding Program and Technology Area Overview presentation slide decks, which can be accessed at: https://www.energy.gov/eere/bioenergy/2021-project-peer-review-feedstock-conversion-interface-consortium and https://www.energy.gov/sites/default/files/2021-04/beto-01-peer-review-2021-fcic-wolfrum.pdf.

This review addressed a total U.S. Department of Energy (DOE) investment value of $29.8 million, which represents approximately 4.5% of the BETO portfolio reviewed during the 2021 Peer Review. During the Project Peer Review meeting, the presenter for each project was given 25 to 35 minutes to deliver a presentation and respond to questions from the Review Panel.

Projects were evaluated and scored for their project management, approach, impact, 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 Review, including scoring information for each project, comments from each reviewer, and the response provided by the project team.

BETO designated Liz Moore as the FCIC Technology Area Review Lead, with contractor support from Alexander Jansen (Boston Government Services). In this capacity, Liz Moore was responsible for all aspects of review planning and implementation.

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM REVIEW PANEL

Name	Affiliation
Mark Penshorn*	Penshorn Analysis
Kim Nelson	GranBio
Paul Paxson	E3 Consulting
Michael Tupy	Cargill
Phil Weathers	Weathers & Associates Consulting

* Lead Reviewer

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM REVIEW PANEL SUMMARY REPORT

Prepared by the Feedstock-Conversion Interface Consortium Review Panel

INTRODUCTION

The Feedstock-Conversion Interface Consortium (FCIC) provided 14 presentations to the public on March 15 and 16, 2021. These presentations covered the progress of the national labs and their academic and industrial partners. These projects are geared toward providing data and solutions to the challenges of identifying the correct feedstock for a given process as well as moving that feedstock from the front gate of a facility into the reactor. These challenges are often overlooked because of the age and ubiquity of other biomass handling facilities in the nation, such as pulp and paper, pellet mills, corn syrup, and corn ethanol facilities. The notion is that the technology already exists, and one must simply select the most cost-effective solution. Actual experience in the industry has proven otherwise. Countless months and dollars have been expended attempting to move the raw biomass. When it has found its way into to the main process equipment, unexpected problems have arisen because of the nature of the biomass itself.

Biofuel and biochemical start-ups have limited understanding of feedstock variability and related impacts. These companies, reasonably, focus their initial resources on the heart of their intellectual property, such as their organism, reactor, or catalyst. That intellectual property is what will earn them corporate value and continued patience from investors. Bench-scale research is often done using bottled gases or pristine feedstocks. These companies understand that they cannot address or even know about feedstock risks that may exist at larger scales and technology readiness levels and accept risk during development. FCIC is attempting to help these companies by providing guidance to their research, tools to monitor for those risks, and design best practices that fall outside of the heart of their technology.

In 2019, FCIC updated their intent from a focus on operational uptime and reliability to a "first principles"/"quality by design" (QbD) approach. First principles are the core building blocks of process models and designs. The first principles approach is a root cause analysis on many of the failures BETO that have been witnessed. QbD is the practice of providing controls to correct for and address the causes of failure in these processes learned through the first principles approach. Hand in hand, they can work effectively provided the right roadmap.

STRATEGY

Does the technology area have a defined strategy in terms of a clear mission, goals, and/or set of technical targets?

The philosophy of FCIC has evolved since 2018 into a more sophisticated and valuable mission to uncover the root causes of many failures seen in the biofuels and biochemicals industry to date. Given that the plan is very recent, it is reasonable that not all parts of the overall mission are defined at this time. What we believe is still missing is a roadmap that will provide a vision for how this overall process can be achieved in a timely and efficient manner.

What was clear to the reviewers during the presentations is that the full breadth of the biofuels industry is not part of the current work of the FCIC member teams. This left gaping holes during our review, questioning whether such things as high-temperature gasification, other non-deacetylation and mechanical refining (DMR) pretreatment processes, or feedstocks beyond corn stover and wood are a part of a future plan or whether these have been pushed to the side. The reviewers note that while high-temperature gasification is not a part of the FCIC current work plan, two of the three demonstration-scale plants funded by the Department of Defense and supported by the Department of Energy utilize high-temperature gasification.

The goal of working from first principles across so many different technology types, feedstocks, products, and pathways is an immense challenge. It would be impractical and detrimental to expect that BETO and FCIC attack these different paths all at once. FCIC and BETO have had to choose, and they have chosen. The concern is that the choice is a silent one. A roadmap with measurable SMART metrics is needed that encompasses the known technology pathways. In time, BETO should plan to incorporate new complexities and options as the science, industry, and progress dictate.

To date, the reviewers believe that at a task level, FCIC has done an excellent job of accepting the new work approach and providing meaningful results. The implementation of the QbD and first principles approach in FCIC is noticeable and should be applauded. In the past, some projects have fixated on improving the performance of a particular piece of equipment, which may or may not have further utilization by others. The current slate of projects within FCIC are clearly addressing more general fundamentals and applying those learnings toward specific units of operation. Therefore, in the future, units of operation that rely on common operational principles can leverage past research in its design and application.

Integrating a summary of a relevant techno-economic analysis (TEA) case study into each task's presentation would help the audience better understand the impact and industrial relevancy of the work being performed. The science is impressive, but for several tasks its significance for solving industrial problems is not entirely clear.

Is the technology area considering appropriate industry and stakeholder input in developing program strategy, FOA topics, and laboratory calls?

DOE and BETO put every effort into involving industry through outreach programs, funding opportunity announcements (FOAs), and other contracting opportunities. In recent years, BETO has listened to industry feedback and incorporated more biochemicals into its development, has begun to look more closely into marine and aviation fuels and other arenas that will be more challenging to electrify, and has pushed more fluid catalytic cracking integration into the platform. Although not reflected in its current set of industry partnerships, FCIC has set up a structure and strategy to address challenges from that same variety of projects and processes. The problems being addressed by FCIC are appropriate and impactful to industry. However, without many new large-scale demonstration or commercial projects, DOE has had to rely on the lessons learned from the nearly 10-year-old American Recovery and Reinvestment Act projects and few commercial projects that are in construction.

Industry partnerships with DOE have of late come from a very consistent group of stakeholders. DOE is missing significant involvement from the pulp and paper industry, a wider group of feedstock/landowners, venture and/or other capital firms, aviation, and pellet producing companies. More varied voices are needed within DOE to sow excitement and capital into the industry. Industry input from the conversion industry was lacking particularly in the area of sustainable aviation fuels. The recently announced multi-topic FOA (2396) once again emphasizes biofuels, especially sustainable aviation fuels and marine.

Awareness of the BETO and FCIC program may not be the primary issue. The cost of managing federal funding remains a hurdle many businesses are not willing to jump over. If FCIC can help streamline this management, it may aid in attracting additional businesses to conduct additional work with the government.

Are there any gaps in the technologies or approaches the technology area is funding which are necessary to achieving strategic outcomes?

Certain industrial partnership projects were either started prior to the new QbD approach or have otherwise not been incorporated. It appears that additional project communication inside and outside of FCIC could benefit the overall BETO program to minimize replication and improve collaboration. One FCIC principal investigator (PI) noted during the Peer Review that they were unaware of the work going on within FCIC that could influence their own project.

The critical material attribute (CMA)/critical quality attribute (CQA) approach that FCIC and BETO are taking appear to be working well. However, for several projects, the relationship between CMAs, critical process parameters (CPPs), and CQAs was not clear. Furthermore, in several cases it was difficult to trace back the CMA for a given unit operation to the original feedstock CMA. Overall, the reviewers believe that the QbD approach is in its infancy with substantial opportunity for its use both experimentally and in the first-principle modeling. The projects have made good progress on known issues within industry and are building a system that can more efficiently extrapolate upon their current work. The expectation is that in a few years' time FCIC will be able to identify the best practice of conveying feedstock into a number of pieces of equipment with a science-backed specification. Examples of our observations are as follows:

1. The Materials of Construction team did not describe the impact of any CMAs on the wear of the knives.
2. The Feedstock Variability team developed new CMAs for corn stover and pine, but the new CMAs were not used in any of the other tasks or first-principle modeling.
3. The Material Handling team did a good job of showing the relationship of CMA, CPP, and CQAs. They also used the values in some of their modeling.
4. The Preprocessing team discussed the number of CMAs, CPPs, and CQAs they had identified but did not show the relationships except in air classification. Air classification was a good example of tying the properties together with some modeling.
5. The High Temperature Conversion team utilized CMAs in their first-principle models and used one CPP (reactor temp). The fiscal year (FY) 2021 case study is an opportunity to look at additional CPPs and correlate the CMA/CPP both experimentally and through their kinetic model using two different materials (13-year and 23-year whole tree).
6. The Low Temperature Conversion team looked at CMAs and compared the results using artificial intelligence (AI) modeling. There is no mention of CPPs, which reflects an opportunity for future work.

STRATEGY IMPLEMENTATION AND PROGRESS

Is the technology area funding a range of projects closely tied to the program or technology's strategic direction? Which projects are particularly relevant to achieving these goals?

The projects currently in development have been appropriately selected to achieve the goals of FCIC for both the 2018 mission of increased reliability and then the modified 2019 mission for increased reliability through an understanding of first principles and a QbD process. There was a concern when moving toward the QbD approach that validation and piloting would be hindered by a lack of complete knowledge. However, the projects are being executed in a sound manner.

Of particular importance, the reviewers noted the adoption of a common depository for data (Task 8). This task ties all of the other efforts together and, in the future, may be able to provide the ability for projects to be consistently planned and executed. The final user experience that is implemented will be critical to ensure that scientists are drawn to the platform and want to use it. If the data architecture does not result in a system that allows users to quickly and easily find the data that they are after, or if users flood the database with data not collected or defined in a consistent manner, then there will be no tool to inspire and ensure the collaboration necessary to achieve the QbD approach.

The efforts of Task 3 were notable for its progress as well as the effort to make the tools accessible to parties who do not have access to a high-performance computer. The team did an excellent job demonstrating how the increase in modeling complexity impacted the results that were generated. This is the type of work that can not only provide meaningful accurate conclusions but also provide people the ability to make reasonable assumptions and engineering estimates in the future based on experimental data.

Is the technology area funding projects that are on the leading edge of work within this field? Which projects are particularly impactful?

BETO and the national labs showed an impressive number of new features and experiments that have real-world potential in the short term. The reviewers consistently agreed that the work being done by Forest Concepts to develop a new shear-based feedstock processing unit was very important for both the short- and long-term development of biorefining facilities. The project demonstrated the ability to collaborate with other groups within DOE to obtain and refine project knowledge, to focus on an important failure mode and determine the first principles cause, and to provide multiple options to address an otherwise fatal flaw.

Is the technology area likely to meet stated near-term/mid-term goals and/or targets based on the current portfolio of projects?

Materials of Construction (Task 1) appears to be closest to identifying a final recommendation for improvement to certain pieces of feedstock handling equipment. Two different options exist with a validation test planned in the near term. The team is also demonstrating how they have been able to transfer the knowledge and models built in Task 1 into other projects such as the Forest Concepts Crumbler. The reviewers believe that following the validation work, the team should move on to the study of other materials in industry. In particular:

1. Soft materials such as seals in wood and corn stover applications to further remove risk and increase uptime. Understanding the failure mechanism of soft seals in lock hoppers could expand the availability of solutions to the industry.

2. In high-temperature applications, a large amount of work is needed on developing new refractory materials for highly alkaline, high-temperature, abrasive applications. No such product exists today that meets the requirements of biomass gasification. In addition, rotating seals are a constant source of failure in these applications and could be studied to provide a more durable solution.

3. Materials to improve the wear of feed augers. Other tasks looked at the measurement of wear, but existing projects did not appear to be looking at different materials to improve auger wear.

Is the technology area team actively managing projects to ensure beneficial outcomes for the performer and the government?

Notably, it appears that every project is meeting or exceeding their targets for this Peer Review. That in and of itself is a project management success.

The reviewers noted an increase in cross collaboration between groups and projects from past Peer Reviews. With some exceptions, the teams appear to be aware of the work occurring in other parts of FCIC and team members were actively working on multiple related projects. Additional collaboration is needed between FCIC and other BETO groups, as non-FCIC projects are performing tasks that appear to be similar.

As stated elsewhere in this review, measurable metrics are needed to understand overall progress. If, for example, a model is presented, the presentations did not make clear how far along they were in the development process. Is validation done at 75% complete or 95%? Are both long-term and short-term validation tests being considered in the overall scope of work? The task scope does not appear to be laid out in the plan.

RECOMMENDATIONS

Recommendation #1: Establish SMART Metrics and an FCIC Roadmap.

Industry typically has a 5-year plan for its projects, which DOE mirrors in the Multi-Year Program Plan. The roadmap for FCIC, however, is unclear. The current projects are limited by the utilization of DMR, feedstock size and type, and duration of reliability testing. Additional details of when other technologies and feedstocks are to be tested have not been defined. The development of such a roadmap would allow the public to understand how far along DOE is in developing the industry.

The projects all appear to have achieved their tasks within the allowable schedule. But how close are we to having completed the goal? What is the goal? How do you measure progress on an open-ended task? The reviewers do not pretend to know how to address these questions. However, BETO is building a house, and we don't know how many floors there are. The program needs some guideposts to calibrate against.

Recommendation #2: Manage the Rise of Product Development Within BETO.

DOE and BETO need to be careful when process development veers toward product development (e.g., industrial instrumentation or customer-facing databases). Additional expertise is needed to manage product development aspects. When projects have user interfaces, or if an original equipment manufacturer (OEM) may seek to develop a BETO-funded product, or even more generally, a software engineer is needed, BETO is doing product development.

Project managers need to be aware of methods, costs, and expected durations of tasks typically used in product development, especially what is referred to as the fuzzy front end. Examples include a user interface wireframe, journey maps, and contextual interviews. Several projects either did not plan to do user research or planned to do them after the design was complete. This is a clear misunderstanding of how and when user research is utilized in product development. User research not only determines the appearance, it determines the feature set required by design. It is not clear that those skill sets are being utilized on all projects.

Recommendation #3: More Meaningful and Diverse Industry Engagement.

In most cases, the tasks cited industry collaboration. However, that collaboration was limited to the dissemination of papers, participation in conferences, etc. The panel is interested in seeing innovative methodologies to directly engage industry. Post-project symposiums or a proactive approach in utilizing the BETO website might be one possible approach in engaging industry. Other methods may include podcasts, a programmatic use of social media (LinkedIn, etc.), and/or other internet-based approaches. By reaching out in new ways, BETO can pursue new collaborations with a broader audience and find more interested parties within industry organizations.

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM PROGRAMMATIC RESPONSE

INTRODUCTION

BETO would like to thank the reviewers for their detailed comments and review of the projects involved in the FCIC.

In the strategy subsection above, reviewers noted that some feedstocks and processing technologies were not included in the FY19 re-scope. At that time, BETO Technology and Program Managers as well as the Office Director set the overall goal to broaden the understanding of how biomass feedstock properties (especially chemical, physical, and mechanical properties) impact system performance. Programmatically, BETO provided guidance to the consortium to focus on corn stover and pine residues as feedstock and to focus on select conversion processes therein. There was concern that including other feedstocks (e.g., energy crops, municipal solid waste) as well as additional downstream conversion processes (e.g., hydrothermal liquefaction, gasification) might spread the funds for this research too thin. Steering Committee feedback in FY19 was that BETO should "get processes across the finish line." Given that corn stover and pine were the feedstocks with which BETO had the most experience, this decision was also a reflection of trying to create some successes around those feedstocks. BETO acknowledges that there are additional important conversion properties and feedstocks for this consortium to explore and this will be a key component of a strategy or roadmap document going forward.

BETO has included many of these recommendations in its guidance and requirements as part of the FY22–FY24 merit review process. These include the need to partner with industrial entities, disseminate knowledge in ways outside of peer-reviewed journals, and include other feedstocks and conversion processes for consideration.

Recommendation 1: Establish SMART Metrics and an FCIC Roadmap.

BETO concurs with this recommendation and believes that it is appropriate to build upon the findings in the first triennium of the consortia and establish SMART metrics and outcomes. BETO has issued very explicit guidance that tasks and subtasks for FY22–FY24 must be clear on their 1-year and 3-year outcomes. These outcomes are expected to vary by task, but the consortium is being encouraged to develop design guidelines or heuristics that a vendor or engineering firm could apply to their own practices. This could represent a very tangible result of some of the experiments and models developed for problematic unit operations like augers, hoppers, and other feeding equipment.

At this point, BETO has not developed a formal roadmap for FCIC; rather, the consortium is enabling the office priorities as a whole. These include two notable areas: sustainable aviation fuels and the use of wastes as feedstocks. Across the office, research at scales from bench-scale to demonstration-scale are being targeted for producing aviation fuel-range molecules. Accordingly, the FCIC will be exploring feedstock/processing combinations that are supportive of this goal as well as tackling research challenges that are complementary of pilot- and demonstration-scale plants. For example, both the Research Triangle Institute and Gas Technology Institute efforts are working with Idaho National Laboratory (INL) on the same feedstock to understand the sensitivity of the respective processes to a feedstock that was harvested, stored, and preprocessed in the same way.

Waste feedstocks, including municipal solid waste (MSW) fractions, play an important part of this office strategy. The Conversion R&D program has funded research on these processes for several years, and the Feedstocks Technologies program is executing a multi-year FOA strategy aimed toward MSW as a feedstock. MSW is clearly more heterogeneous than corn stover or pine residues and it is anticipated that many, but not all, of the CMAs identified will be starting points for these additional feedstocks. MSW has been included as an area of interest for the FY22–FY24 lab call.

Ultimately, a consortium roadmap and objective are critical and will be developed by the end of Q1 FY22. The research roadmap will encompass several facets of the biomass handling supply chain, including:

- Plans for particular feedstock and conversion processes
- Providing recommendations/processing parameters for improved feedstock handling equipment
- Delivering publicly available and readily usable feedstock variability data, including its performance in select conversion unit operations

- Providing open-source models that can determine key operating regions of interest such as flowability, particle size control, etc.
- Plans for disseminating results, models, and information to equipment manufacturers and vendors to establish performance guarantees.

Recommendation 2: Manage the Rise of Product Development Within BETO.

BETO agrees that the FCIC should not pursue product development, and the FCIC does not target product development. Instead, the consortium is developing tools and knowledge that enable decision-making by industry. These contributions by the consortium include design heuristics for hopper designs, recommendations for materials of construction to avoid particularly abrasive constituents in feedstocks, and flow diagrams that inform ranges where plugging will happen. The consortium is also publishing distributions of material attributes through publicly facing databases. All of these efforts are encouraged to include industrial partnerships and engagement to ensure relevance to ultimate adopters. However, the consortium is not looking to develop complete software packages, sensors, or other systems that would require user interface/user experience work.

Recommendation 3: More Meaningful and Diverse Industry Engagement.

BETO strongly concurs with this recommendation. The partnerships to-date on the directed funding opportunities (DFOs) have been high-quality collaborations and afforded opportunities for the consortium to apply the knowledge generated to-date. A follow-on DFO, as well as other ways of partnering with industrial partners, may be worth considering. However, as the review panel notes, there has been minimal industrial engagement beyond these DFO projects, and there is limited diversity in which industrial/external entities have been partnering. Industrial engagement is one of four key priorities for the consortium in FY22–FY24. The consortium will be encouraged to employ some of the strategies recommended by the Review Panel and employed by other BETO-funded consortia such as post-project symposia or industrial listening days. The consortium also has to prepare dissemination materials beyond peer-reviewed journals, as these have a limited audience.

The reviewers also note that each task should include TEA in their presentations. The TEA and life cycle assessment (LCA) are funded to conduct case studies on the various processes being studied in the consortium. A key purpose of these case studies is to have the economic and sustainability information required that these researchers can make the work more relevant to external audiences. This will remain a priority into the future.

Ultimate success of the consortium is to disseminate results into industry that can de-risk the processes to the point that vendors and engineering firms can deliver performance-guaranteed processes and for investors to feel sufficiently confident in these processes to invest.

FOREST CONCEPTS DFO

Forest Concepts

PROJECT DESCRIPTION

WBS:	1.2.2.7101 1.2.2.7102
Presenter(s):	Jun Qu; Tim Theiss
Project Start Date:	10/01/2019
Planned Project End Date:	07/31/2021
Total DOE Funding:	$1,200,000

Forest Concepts has recently developed (with significant BETO support) a new biomass comminution system—the Crumbler® rotary shear with benefits of narrower particle size distribution, lower aspect ratio, lower fines, and more tolerance of high moisture variations. The rotary shear, however, experienced significant wear in processing dirty feedstocks (e.g., logging and agricultural residues and MSW). This DFO project—a cooperative research and development agreement among Oak Ridge National Laboratory, Argonne National Laboratory, and Forest Concepts—is to gain mechanistic insights for the wear issues of critical components, develop cost-effective wear-resistant tool materials, and improve tool designs. The goal is to advance the state-of-the-art biomass size reduction process by improving tool life and throughput as well as reducing downtime and power consumption. As of today, the team has learned from Forest Concepts for the baseline tool design and materials of the rotary shear, gained fundamental understanding of the wear mechanisms, and constructed finite element analysis models to help understand the cutter-feedstock interface. We currently are developing abrasive wear models, evaluating candidate wear-resistant alloys and coatings, and optimizing tool designs. In the second half of the project, the team plans to fabricate prototypes of critical components using improved design and/or advanced materials, test the prototypes on an actual rotary shear with various feedstocks to demonstrate improved tool life and cutting efficiency, and conduct TEA.

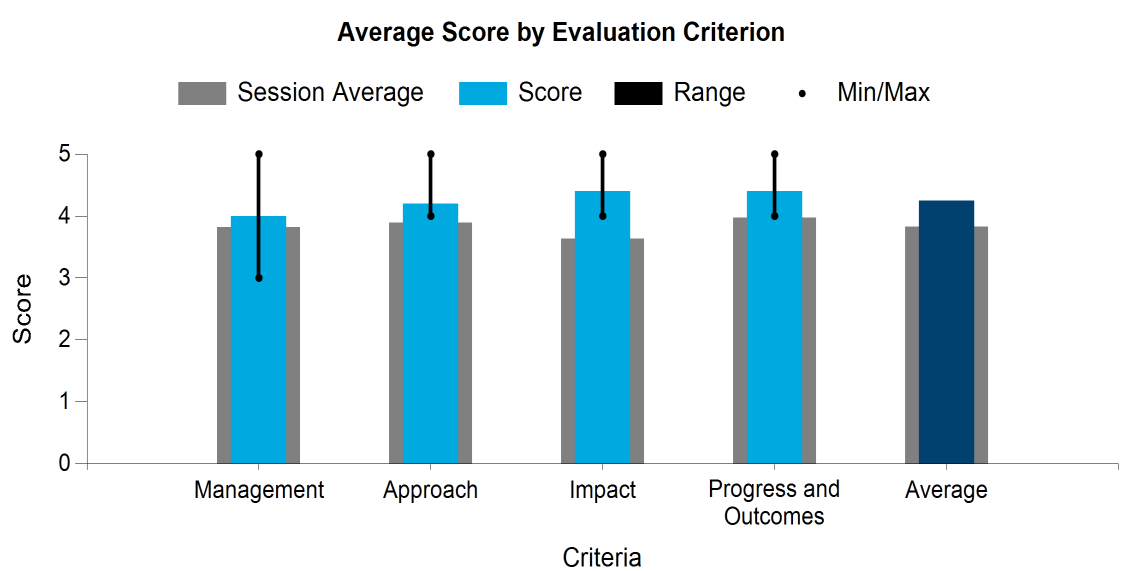


Photo courtesy of Forest Concepts

COMMENTS

- Prescreening of woodchips to remove dirt and abrasive material is common practice within pulp and paper. It would be interesting to know how efficient these screens are for preserving conventional chipping tool life and how their capital expenditures (CapEx) and operating expenditures (OpEx) compare with the wear solutions identified within this project.

- Project had a clear goal to improve the performance of their equipment to make it commercially attractive. Current limitations in operating hours and maintenance make the Crumbler (at 200 hours of operating time) impractical to consider. However, the machine has shown advantages in feedstock quality (lower variability) in other studies, making it worth the effort to modify and improve. This project involves the OEM directly, which allows project recommendations and insights to be driven right to the product in question. The project is a great extension of another FCIC task and requires utilizing the modeling efforts done on that project and expanding on those results. This is an efficient use of FCIC funding to build on top of projects to provide more value to each dollar spent. The project is making real and significant advancement in resolving the technical challenges of the project. Continued effort is needed to advance to a long-term validation test on multiple feedstock types. Extrinsic mineral types in other feedstocks need to be studied to be sure that the new material choices do not limit the Crumbler to wood feedstock only. It isn’t clear whether moisture content or temperature were factors in developing the model. Many producers of in-field chips provide them at a 2” spec, which is lower than the top end of the sizing spec described by the project (20x20x50mm). Project had a great comparison of risks when describing the difference between coating thickness risk on this project versus the knife mill. This is a great example of not only knowing the existence of a risk but the first principles behind that risk as well. Validation testing is expected next year, which is obviously critical to the overall progress and impact of the project.

- The Forest Concepts DFO identifies a clear goal of improving the number of operating hours for the Crumbler rotary shear mill, particularly in dirty systems. The team identifies the mechanisms of wear, proposes solutions, and demonstrated improved wear life. This project has a well-designed project approach and good execution. The results are summarized in terms of reduced wear and economic benefit to bring focus on the potential impact.

- The management approach doesn’t appear to assign responsibilities to groups or individuals as concisely as the other presentations. The metrics shown in the project’s approach mesh well with real-life industry experience and could be useful to stakeholders when measured. The details shown in the progress and outcome section of the project's presentation are exemplary and clearly identify wear resistance issues experienced by scaled-up biomass facilities currently operating. It's not clear to the reader if the new design of the clearing plate (the less sharp S-shape) has been implemented and tested. This was addressed during the Q&A following the presentation. Many of my comments noted in the Task 1 review could be mirrored here. This is an exciting approach to a real-world issue that could transfer to industry in the near term in a cost-effective manner. This is an exciting project and could serve industry and stakeholders well. This is one of the most exciting projects in this year's Peer Review. Well done and kudos.

- This project is a good application of the experimental work done in FCIC Task 1. The project made good use of finite element analysis and experimental work to improve the design of the cutter heads and study wear on a variety of wood types. The improvement in tool life demonstrates the economic advantage of the wear resistant coatings. It was not clear how the project was evaluating the impact of dirty wood chips (versus clean feedstock) on knife life as stated in the current limitations section of the project overview. One approach could be to compare precleaned feedstock with dirty chips to determine the impact on the economics as well as knife life. Forest Concepts being actively engaged in the project is key to project management.

PI RESPONSE TO REVIEWER COMMENTS

- We truly appreciate the overall positive and encouraging feedback from the reviewers. Critical comments are answered here.
- Reviewer 1: (1a) Q: It was not clear how the project was evaluating the impact of "dirty" wood chips (versus clean feedstock) on knife life as stated in the "Current Limitations" of the Project Overview. One approach could be to compare "precleaned" feedstock with "dirty chips" to determine the impact on the economics as well as knife life. A: We fully agree and have planned to run Crumbler tests on both "precleaned" and "dirty" woodchips to benchmark prototypes of cutters made of candidate alloys and coatings against the baseline cutters.
- Reviewer 2: (2a) Q: Continued effort is needed to advance to a long-term validation test on multiple feedstock types. A: We fully agree and would like to propose systematic long term (1,000+) validation tests using a variety of feedstocks in the follow-on project. (2b) Q: Extrinsic mineral types in other feedstocks need to be studied to be sure that the new material choices do not limit the Crumbler to wood feedstock only. A: The work scope of this project is focused on wood feedstock. We would like to propose to study the extrinsic minerals of other types of feedstocks including MSW in a follow-on project. (2c) Q: It isn't clear whether moisture content or temperature were factors in developing the model. A: The moisture content and temperature significantly affect the feedstock mechanical properties. Woodchips of different moisture contents are already being studied in the finite element analysis and temperature effect will be incorporated too. In terms of the abrasion model, moisture would affect the hardness and elastic modulus of the wood chips.
- Reviewer 3: (3a) Q: The management approach doesn't appear to assign responsibilities to groups or individuals as concisely as the other presentations. A: Oak Ridge National Laboratory leads efforts in tribosystem analysis including finite element analysis, mitigation development, bench tribo-testing, and materials characterization; Argonne National Laboratory is responsible for wear modeling and involved in mitigation development; and Forest Concepts provides the baseline design and worn components, participates in mitigation development, and fabricates and tests prototype components. (3b) Q: It's not clear to the reader if the new design of the clearing plate (the less sharp S-shape) has been implemented and tested. A: The new design is still being optimized.
- Reviewer 4: No critical comment.

- Reviewer 5: (5a) Q: Prescreening of woodchips to remove dirt and abrasive material is common practice within pulp and paper. It would be interesting to know how efficient these screens are for preserving conventional chipping tool life and how their CapEx and OpEx compare with the wear solutions identified within this project. A: We appreciate the suggestion and will run Crumbler tests using woodchips of as-received and prescreened to compare the CapEx and OpEx with the tool material and design solutions developed in this project.

MOISTURE MANAGEMENT AND OPTIMIZATION IN MUNICIPAL SOLID WASTE FEEDSTOCK THROUGH MECHANICAL PROCESSING

Fulcrum

PROJECT DESCRIPTION

WBS:	1.2.2.7301
Presenter(s):	Jaya Tumuluru; Mujinga Mwamufiya
Project Start Date:	10/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,018,000

Fulcrum BioEnergy (Fulcrum) developed an innovative and efficient process to convert municipal solid waste (MSW) into renewable transportation fuels. The higher moisture content and high processing cost of MSW present unique challenges. High moisture content in the MSW results in a reduced volume of syngas produced in the gasification system as energy is required to vaporize the additional water. Conventional drying systems, such as rotary dryers, require high temperature, which can result in material degradation, excess volatile organic compound emissions, and potential combustion issues.

In this project, INL and Fulcrum work collaboratively to assess the feasibility of densifying MSW using advanced preprocessing technologies developed by INL. The successful completion of the project relies on achieving pellet quality targets at 40% lower cost with the integrated demonstration of fractional milling, high-moisture pelleting process, and low-temperature drying. During the first year, the team successfully tested the high-moisture pelleting process and discovered that the produced MSW pellets met the density and durability targets of 480 kg/m^3 and >95%. MSW pelleted at 24% moisture content using the high-moisture pelleting process costs about 45.93% less to produce, whereas at 30% moisture content, it is about 39.65% less than the conventional pelleting process. Greenhouse gas emissions are about 45.76% less for the high-moisture pelleting process as compared to conventional pelleting. The team expects more cost savings when fractional milling is tested this year.

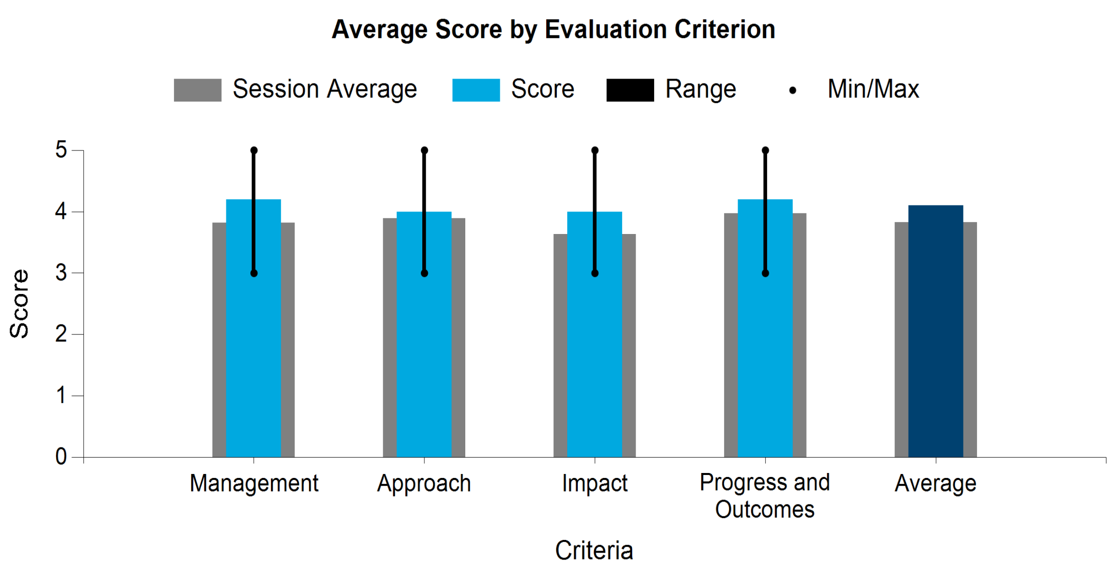


Photo courtesy of Fulcrum

COMMENTS

- The idea of pelleting a ground feedstock for increased bulk density into a conversion technology appears to be very specific to one process reactor. It is not obvious that MSW facilities would take on the responsibility for grinding and pelletizing the waste to realize any potential cost savings from that capital expense or whether there are numerous cases for realizing the cost savings of being above a certain mile radius from the MSW sorting site. The breakeven price for pelletizing versus trucking distance was not made clear. A study of the savings and physical characteristics of wood in this same process would be an interesting comparison for its impact to the wood pellet market as well. Overall, the project has done what it set out to do and has provided clear results from their work. A 13% moisture content sample was used for the ¼" screen, whereas other samples were nearly twice as high. The reason for this change and the impact of it on the testing results were not explained. Testing results shown had no material impact to durability from any setup. It isn't clear if the project understands the mechanism for impacting durability based on the experiments shown. It can be of benefit to demonstrate the ability to produce a product that does not meet the specifications required. This adds evidence that in-process drying from hammermills, pellet mills, etc., can be relied upon instead of conventional drying than a study on the performance of pelleting. Design without a dryer is of course, risky, if other equipment cannot dry the feedstock to the correct moisture. I'm not sure I've seen enough long-term test results to demonstrate that this equipment can be relied upon without external humidity controls or other equipment.

- The MSW feedstock processing DFO is a foray into a well-known constraint in the biofuels space of transporting disperse and low-density materials economically. The task approach is solid, the presentation gives well described results, and the interpreted in economic terms. The ballpark 40% reduction in pelleting/drying and the 50% reduction in transportation costs are significant. Does the result address a single decision for Fulcrum or can the results be leveraged more fully in the industry?

- The project team is commended for its strong, innovative project with clearly defined success metrics and achievements.

- The TEA/LCA of high-moisture pelleting versus conventional pelleting clearly demonstrates the advantage of the high-moisture route both for cost and energy usage. Using the high-moisture pathway advances the state of technology of pelletizing for MSW. Although the transportation costs of compacted MSW versus high-moisture pellets shows clear advantage to the high-moisture pellets as distance increases, it is unclear as to whether transportation will be a significant factor in the Fulcrum business model. If the biorefinery is located close to the MSW processing plant, transportation may not offset the cost of pelletizing. Reliability and time-on-stream for the pelletizer using MSW should also be a critical parameter for determining the economics of the process. In order to understand the TEA and reliability benefits of high moisture pelleting, a TEA comparison is needed for Fulcrum's current method of preprocessing.

- The use of open-source modeling tools is a positive attribute of this project. The project presentation doesn't mention what the market-ready products are as a result of the production of homogenous intermediates. As near as I can tell, the project's presentation doesn't follow the Management, Approach, Impact, and Progress and Outcomes format of the other presentations. The technical details of the project seems to be lacking from a technical perspective, leaving the reader wanting more. The project's presentation clearly identifies collaboration with industry but needs more details related to those prospective opportunities. Again, leaving the reader wanting more.

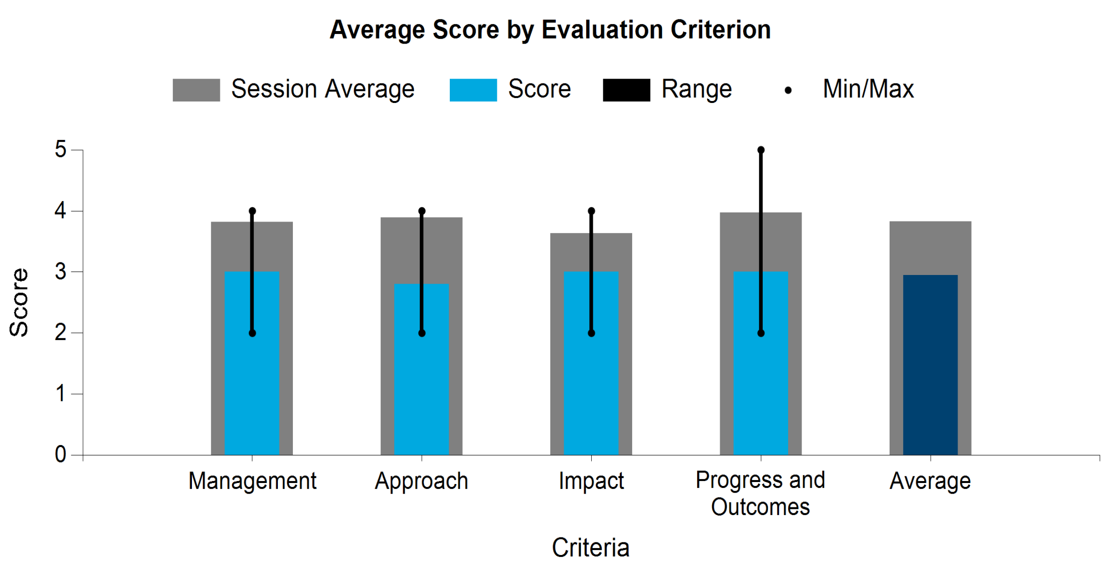
WONDERFUL COMPANY DFO

The Wonderful Company

PROJECT DESCRIPTION

WBS:	1.2.2.7501 1.2.2.7502
Presenter(s):	Daniel Carpenter
Project Start Date:	01/01/2019
Planned Project End Date:	12/31/2020
Total DOE Funding:	$840,000

Consistent and reliable preprocessing, conveyance, and reactor in-feed systems, particularly for low-cost waste feedstocks, remain a major technical challenge for the emerging bioeconomy. By identifying critical biomass attributes and connecting them to flow and conversion behavior, science-driven system designs can address these often-overlooked solids handling challenges. The Wonderful Company is the world's largest almond and pistachio grower, generating 250,000 dry tons/year of waste material including hulls, shells, and wood (>5 million tons/year industry-wide in the United States). This project seeks to turn this environmental and economic liability into a sustainable and profitable resource, targeting conversion via gasification to syngas for electricity and biochar, by addressing related material handling and feeding challenges. Based on optimized preprocessing strategies, bulk material flow, and thermal conversion properties, an overall system design will be developed. The methodology will be tested with FCIC's benchmark loblolly pine residues to demonstrate the robustness of the overall approach and provide insight and guidance for future systems. The project will culminate in extended field trials to demonstrate an improved continuous feeding system with a commercial biomass-to-electricity gasifier vendor, and an economic analysis demonstrating a reduction in electricity production costs by maximizing on-stream time while minimizing preprocessing and CapEx costs.



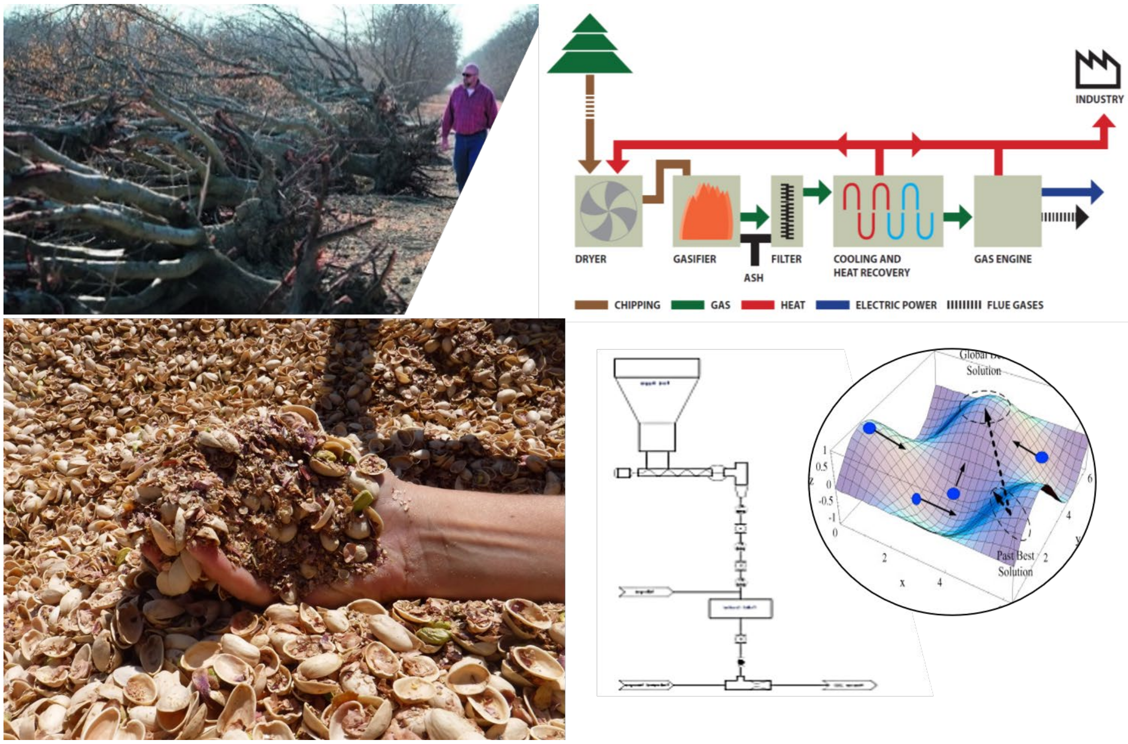


Photo courtesy of The Wonderful Company

COMMENTS

- It is not clear in the background section of the project presentation if there is a specific market target that is able to economically receive the biochar (e.g., pyrolysis oil or fertilizer). It is not clear in the management section of the presentation where The Wonderful Company is managing or collaborating on the project. The project presentation's approach section has a direct correlation to commercial uses with economic benefits. The graph of operational downtime in the impact section of the project presentation is particularly interesting, but it doesn't cite the data source. The project's approach to modeled costs and the pelletization of fines is of particular interest. Section 4 of the project presentation's progress and outcomes is particularly detailed from an economic perspective. The projects presentation doesn't cite the success or failure of the B-Grid gasifier skid, although it seems particularly interesting.

- Particular shells are a low-volume (250,000 tons per year = 1 to 2 plants max), regionally specific, dispersed, high ash feedstock. The motivation for this project must be a waste removal rather than the benefit of a gasification system. However, the social or monetary cost of shell disposal is not made clear. The tornado diagram has numerous assumptions that appeared very dubious—from the capital cost potential savings, to the number of employees, to the price of biochar. The values of these figures did not seem to have a sufficient or reasonable basis. The biggest driver of the TEA is personnel, and the reviewer does not know how 0.25 people is possible for a realistic figure. The price of biochar at 4x fertilizer is unfathomable. Uncertainty levels are very high even for an initial design. The process and business strategy of this technology was not made clear. The project participants do not appear to know what the future version of their gasifier should look like or even if it should remain "mobile and distributed" or else a small demonstration-scale facility. The Aspen model for this process was made after the process was built and operated. This is a major red flag that this process was not properly vetted or managed prior to this project. It isn't clear whether there is any innovation in the Jenike & Johanson feed system or whether there needed to be any innovative design work for this project. What is clear is that the Jenike & Johanson feed system presented does not meet the objective of a distributed gasification system. Based on the objectives, the reviewer was anticipating a new feed hopper that could remove overs or other unwanted materials in an integrated design. Minimal insights in this project to date—fines removal, classification, etc.—are essentially methods of getting the feedstock stream to meet a given gasifier spec that includes items such as fines percentage, mineral content, and an ultimate/proximate analysis requirement. Management of the project required wrangling the needs of a client with a specific problem, national labs, and a technology provider. The process has divided tasks up reasonably for managing the project. Validation testing does not have a long schedule and it isn't clear if there are units available for testing. The process appears to not know whether it will be utilizing a co-mingled stream or separate streams at different facilities. However, each design seems to require separations equipment, which begs the question of why would you not co-mingle everything and have one set of upstream separations equipment? The client is not willing to put the biochar on its own fields. This is as clear of a statement as anyone can make on the risks of producing biochar and trying to sell it.

- Risk mitigation strategies are needed to assess project management. Considerable amount of project work remains to be completed by the August 2021 end date. Agricultural residues will likely play a role in the large consumption of biomass anticipated for the bioeconomy, so the project concept is appreciated. However, it is not clear how this project's feedstock attributes affect preprocessing, handling, reactor feeding performance and down-time, or how the knowledge gained can be extended to other types of feedstocks.

- The project has met its initial goals of providing a design package for classification and conveyance of pistachio shells to the V-Grid gasifier. The extended run, incorporating the new preprocessing and material handling design into the V-Grid gasifier system, is a good approach to determine the improvement in operating efficiency. Future work should consider a scale-up strategy using multiple, linked V-Grid gasifiers to determine the overall effectiveness. A corresponding TEA is needed. A separate TEA should compare the process with and without pelletizing the fines. A business case including a marketing and distribution plan for both the biochar and electricity would be beneficial. Observation: The tornado diagram is based on a 50-kw V-Grid unit operating at 4,000 lb/hr. To process the 250,000 tons/year (assuming 50% shells), an array of 10 or more linked V-Grids may be needed depending on the operating assumptions.

- The Wonderful Company DFO scope addresses some key constraints in biofuels in processing materials that are variable, disperse, and low density. Additionally, the project looks at the important question of reliable, economic operation of a scaled-down process necessitated by the dispersed feedstock supply. The task delivered information quantifying the feedstock quality and variability and a feedstock conveyance design. What appears to be the key result and not yet addressed is demonstrating improved process performance. During the presentation we learned that making progress on-site is a challenge given some limitations put on the team. Perhaps the project team realigns deliverables and timelines to ensure the most valuable outcome can be realized.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for their insights, questions, and suggestions to improve this project. Regarding the reviewer's comment on how feedstock attributes impact the overall process and extending this knowledge to other materials: this may not have been clear from the presentation, but we have assessed how feedstock attributes impact some aspects of preprocessing (e.g., significant generation of fines with milling) and handling/flowability (e.g., clogging of storage silos). To date, we have much less information on reactor feeding and downtime, other than limited qualitative performance data shared by the gasifier vendor. The tests with V-Grid's gasifier system are ongoing and we are collecting performance data as part of this project, including the impact of feedstock attributes.

- Thank you for the comments on the project relevance and motivation. The total availability of nut waste industry wide is closer to 5 million tons/year, which is already aggregated at a few processing sites. For example, The Wonderful Company processes >95% of pistachios grown in the United States, so this supply is very concentrated. While a large motivation for the project is in fact waste removal (i.e., avoidance of landfilling material and environmental impacts of its decomposition), the reviewer is correct that the social and monetary costs were not made clear in the presentation. The comments regarding TEA and assumptions therein are noted. This was not detailed in the presentation due to time constraints and business sensitivity, but some clarifications are warranted. The purpose of the Aspen model was to establish a baseline electricity production cost for this gasifier system that could be compared to an end-of-project cost, showing a reduction due to improved uptime. For the preliminary TEA, several assumptions were made where information from the industry partner was incomplete or were otherwise needed for consistency with model requirements. All analysis methods, assumptions, and references are documented in project milestone reports, and are consistent with other BETO projects. The assumptions used here will be modified and updated as more operational data is collected during the extended trials.

- The assumption that one person can operate four modular units may be optimistic; this is based on a strategy where several co-located units can be automated and operated in parallel. In fact, this is the configuration being tested at the demonstration site. The overall effectiveness of this approach will be evaluated as part of this project.

- The comment on biochar prices and markets is noted. Understandably, The Wonderful Company has a rigorous process for testing or varying agricultural practices. Measuring the impacts of applying biochar on orchards would be a long-term proposition and outside the scope of this project. The comment on accounting for pelleting costs is also noted; the pelleting operation will be considered separately in the analysis. We agree that articulating the business case for electricity and biochar would be a good addition to the project outcomes. The potential scale mismatch is also noted and will be considered moving forward.

- Data for the cost versus operational downtime on Slide 9 was derived from the analysis in: "Process Design and Economics for the Conversion of Lignocellulosic Biomass to Hydrocarbons via Indirect Liquefaction: Thermochemical Research Pathway to High-Octane Gasoline Blendstock Through Methanol/Dimethyl Ether Intermediates" (https://www.nrel.gov/docs/fy15osti/62402.pdf). Regarding the technology choice and timing of the Aspen model development, there may have been some confusion on structure of the project. The reviewer is correct that the partner (The Wonderful Company) has not yet decided on a third-party technology or scale to convert their waste. Of the many factors under consideration, finding a reliable system (>85% uptime) to reduce waste, while generating profitable electricity (with renewable energy credits) and biochar sales, will be key. Depending on the situation, capital and operating costs, locations, demonstrated reliability etc., this could be several small units operated in parallel or a few larger units.

- The comment regarding The Wonderful Company's role is noted; this may not have been made clear in the presentation. The Wonderful Company's role in this project is in providing financial support, strategic direction, information around the logistics of their process and potential conversion routes, and supplying the feedstock.

- The comment on innovation in the project is noted. The reviewer is correct in the sense that because the pistachio waste feed requires minimal processing for this application to meet the original project goals, the Jenike & Johanson design is based on their standard design practices. Distribution of feed material to the individual gasifiers was considered out of scope here because during the project V-Grid had concurrently developed and tested a prototype system for this purpose. We feel that the potential to pelletize fine material, followed by testing in a relevant setting, represents an innovation for the project.

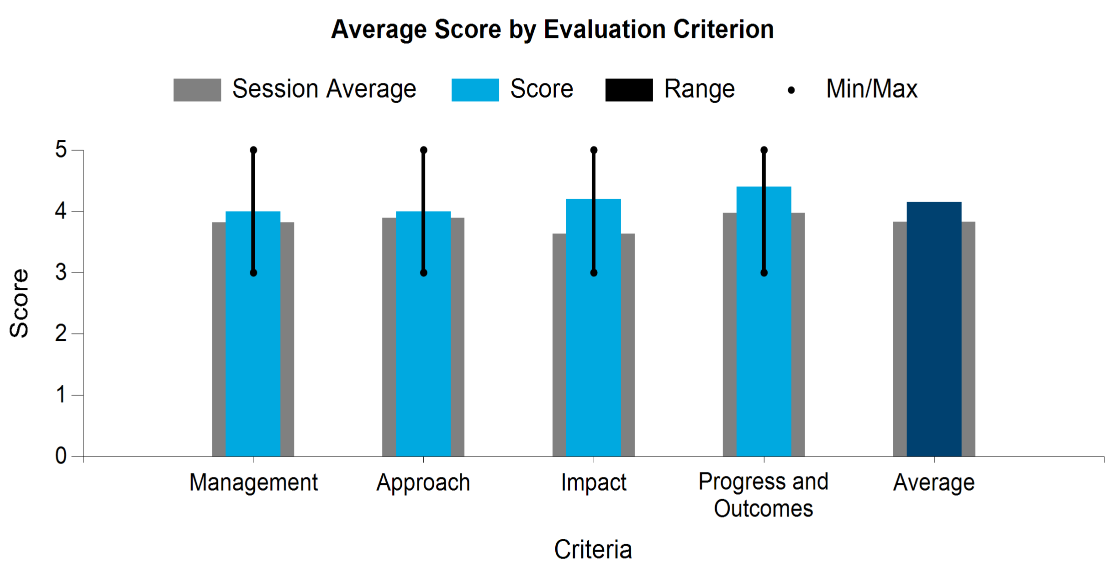
SMART TRANSFER CHUTES WITH IN-LINE ACOUSTIC SENSORS FOR BULK-SOLIDS HANDLING SOLUTIONS

Jenike & Johanson

PROJECT DESCRIPTION

WBS:	1.2.2.7601
Presenter(s):	Troy Semelsberger; Sheila Van Cuyk
Project Start Date:	04/01/2019
Planned Project End Date:	03/30/2021
Total DOE Funding:	$1,744,935

The long-term global challenge is increasing the operational reliability (or time on-stream) of integrated biorefineries. Currently the average operational reliability is around 30%. Our project is narrowly focused and directly aligns with the goals of the FCIC, and the challenges identified in the Advanced Development and Optimization and Biorefinery Optimization Workshops. Los Alamos National Laboratory, a world leader in acoustic sensors, is partnered with Jenike & Johanson (the world leader in bulk solids handling solutions) to develop three innovative technologies to improve the operational reliability of integrated biorefineries. The three innovative technologies that we are designing, building, and demonstrating are: (1) an in-line acoustic sensor for continuous real-time monitoring of feedstock moisture content; (2) an in-line acoustic sensor for the real-time continuous monitoring of plug screw feeder wear and erosion; and (3) a "smart" chute integrated with our acoustic moisture sensor capable of discarding high moisture content. Our team has demonstrated that the moisture content of corn stover can be acoustically monitored in both static (non-flowing) and dynamic (flowing) conditions for moisture ranges of 15%–55%. The acoustic wear sensor for plug-screw feeders has been demonstrated to quantitatively measure the mass loss both in Comsol simulations and through experimental validation. The "smart" chute being developed by Jenike & Johanson will be integrated with our acoustic moisture sensor to actively discard high moisture content corn stover (>40%) that is known to cause bulk-solids handling issues.



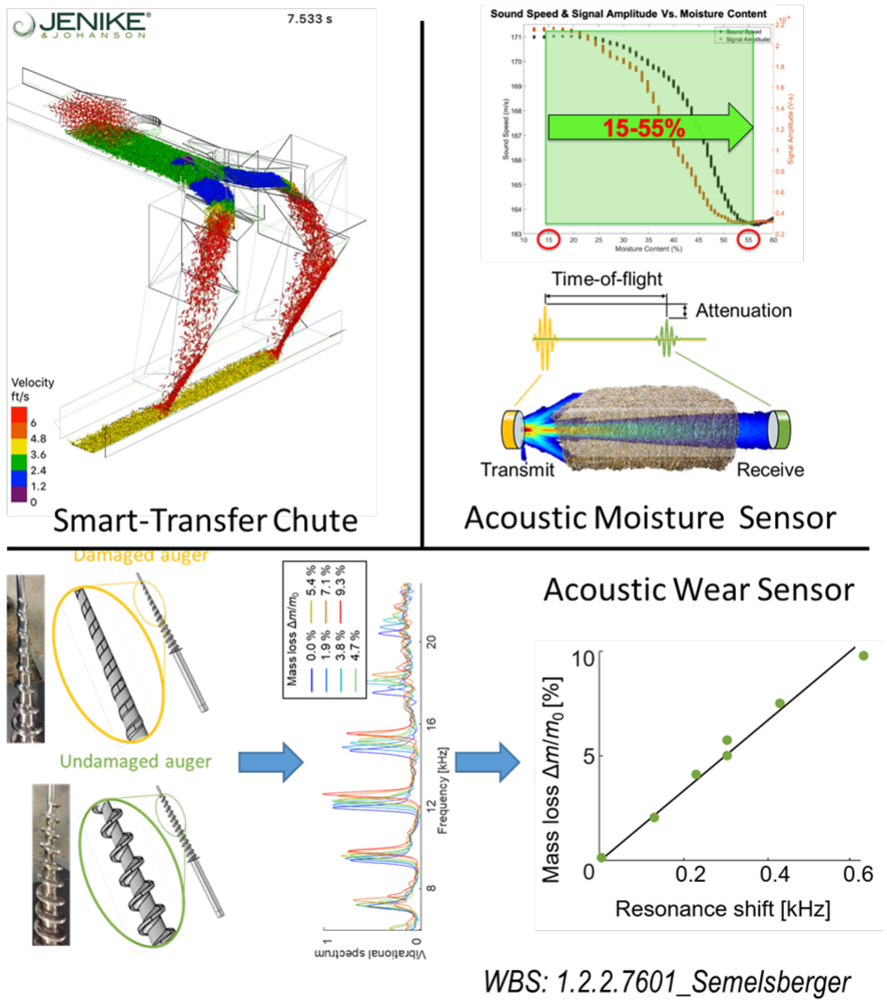


Photo courtesy of Jenike & Johanson

COMMENTS

- A more thorough discussion on the risks and mitigation strategies for sensor development, scale-up, and implementation is necessary to assess project management and likelihood of commercial success. The stated project goal is to "increase the overall integrated biorefinery operational reliability beyond 40%–50% time on-stream ... to 68%." An explanation of the basis for the current integrated biorefinery operational reliability of 40%–50% and how downtime is related to moisture variance and plug-screw feeder wear would be helpful for assessing project impact. It's not clear how the smart chute through moisture sensing control decreases maintenance downtime and costs.

- The acoustic measurement device will have to be validated in several different noisy environments to ensure that it can be effectively calibrated in the field against different background noises. The acoustic technology appears to rely on a consistent bulk density of the feedstock. If so, this technology would have to be used downstream of several units of operation where the feed becomes more homogeneous. The low end of 15% moisture is insufficient for many processes. It is not clear whether that was a limitation of the project scope or the technology. Validation of the acoustic device in more than one environment was acknowledged as critical but it isn't clear if it is planned at this time. The device may require an in-field calibration procedure, which could be complex and may drive costs up considerably.

This project appears to lack an in-field validation task for each of the technologies it is developing. Testing appears to be limited to in the lab, which generally cannot recreate all of the variables seen in an actual facility. However, the reviewer recognizes that there aren't an abundance of facilities available to test new equipment. Additional validation work is needed on the plug screw wear measurement device, but that effort is planned for future periods. The progress made to date is impressive and will provide valuable operational guidance to industry as well as researchers working to improve the performance of this device. The project is developing three different tools for industry, two of which work hand in hand. The smart chute/acoustic sensor could be a valuable process improvement for not only corn stover for which it's currently designed but other processes as well. Industry generally monitors moisture by feedstock sampling and misses slugs of high-moisture feedstock which can affect downstream processes. The ability to at least detect these high-moisture slugs could be valuable process information to have at a facility. While none of the technologies would make or break a facility, the each add to the ability of a plant to control and monitor performance. However, for facilities looking to control capital costs, these all appear to be "nice to have" rather than "need to have" items. The project should have shown more validation evidence that the acoustic filtering can differentiate the impact of one property versus another by modulating the wavelength. A simple validation study of a single feedstock at the same moisture content but different bulk densities should appear the same to the acoustic sensor. The reviewer would like to see evidence that this is true.

- The smart chutes and acoustic sensor DFO project combines a novel sensor approach targeting a clear need for biomaterials in addressing quality variability. The acoustic sensors appear to be an underutilized technology and well applied in this application. The smart chute has the potential to be an enabling piece in managing feedstock variability. However, as was discussed during the presentation, the impact on a continuous process by the interrupting the feed stream needs to be addressed in order to evaluate the utility.

- The use of acoustic sensors and a "smart chute" is particularly innovative. The management section of the project's presentation is particularly detailed and cites specific timing(s) in the communication strategy. The progress and outcomes section of the project's presentation details the cost of the various technologies used to measure moisture content in corn stover AND the cost is reasonable. The wall friction comments related to the smart chute design leaves the reader wanting a little more. For instance, what materials are best suitable (and commercially available) to minimize wall friction. The off-the-shelf capital costs of the wear sensor for plug-screw feeder augers is definitely transferable to industry today. This makes this particular project very exciting. The approach to measuring wear in plug-screw feeder augers is very interesting and innovative and could likely be accomplished using commercially available acoustic technologies. Collaborating with Jenike & Johanson on this project lends the approach merit. Overall, I am super excited about this project as it can benefit industry directly and in the near term. Commercialization could come quickly. Kudos!

- The use of acoustical sensing to measure plug screw wear gives a biorefinery the potential to do predictive maintenance without having to shut down for mechanical inspection. This innovation will improve the run time of an integrated biorefinery. The moisture sensor and smart chute are valuable innovations as demonstrated on corn stover. The technology will need to be demonstrated on additional feedstocks, especially woody biomass and MSW, to see significant adoption by biorefineries. It was not clear how the team is determining an improvement in operational reliability from 40%–50% to 68% as stated in the quad chart. The economics of the smart chute should also consider the costs associated with collecting off-spec material, re-processing it to the proper moisture, and reintroducing the material into the process.

PI RESPONSE TO REVIEWER COMMENTS

- Question: The acoustic measurement device will have to be validated in several different noisy environments to ensure that it can be effectively calibrated in the field against different background noises. Response: We totally agree with the reviewer's comments. While we performed one test (at Jenike & Johanson) and determined different noises that might be present in an industrial setting, additional measurements need to be performed.

- Question: The acoustic technology appears to rely on a consistent bulk density of the feedstock. If so, this technology would have to be used downstream of several units of operation where the feed becomes more homogeneous. The low end of 15% moisture is insufficient for many processes. Response: We agree with the reviewer's statement that many processes other than corn stover will require moisture measurements lower than 15%. We are in talks with industries that require the lower moisture measurements.
- Question: For this project the target moisture range was 15%–55%, where 30%–40% moisture was given to us as the problematic region for continuous bulk flow operation. It is not clear whether that was a limitation of the project scope or the technology. Validation of the acoustic device in more than one environment was acknowledged as critical but it isn't clear if it is planned at this time. Response: Validation of the acoustic device in more than one environment is definitely required. Validating our technology in multiple environments is outside the project scope; however, we expect to continue the maturation and refinement of this technology. Our goal is to install our technology at the National Renewable Energy Laboratory (NREL) and INL to continue to gather industrially relevant data on both of our technologies.
- Question: The device may require an in-field calibration procedure which could be complex and may drive costs up considerably. Response: The in-field calibration is, indeed, a procedure that can be somewhat complex. If the project moves toward the development of a prototype, we can plan for adaptation of the acoustics sensor to industrial settings and, more specifically, to a simplified calibration procedure.
- Question: This project appears to lack an in-field validation task for each of the technologies it is developing. Response: Typically, the in-field validation phase of technology development occurs after the proof-of-concept phase, which is what this project focused on. We hope to continue developing this technology with a strong in-field validation phase up at NREL and INL.
- Question: Testing appears to be limited to in the lab which generally cannot recreate all of the variables seen in an actual facility. Response: The reviewer is 100% correct. The lab cannot recreate the true industrial setting where our technologies will be installed; in fact, all facilities will be different. Continuing our technology development in relevant settings such as INL and NREL will provide a wealth of information that will further push our technology up in technology readiness level.
- Question: The project should have shown more validation evidence that the acoustic filtering can differentiate the impact of one property vs. another by modulating the wavelength. Response: The applications of the acoustic technology can be exploited to quantify the impacts of rocks, particle size, feedstock blends, and even flow rate. The sensitivity to these properties will need to be quantified as we progress through the TRL levels.
- Question: A simple validation study of a single feedstock at the same moisture content but different bulk densities should appear the same to the acoustic sensor. The reviewer would like to see evidence that this is true. Response: This is a great point that is encountered with the commercially available microwave moisture sensors. These tests are important and will be performed before the project ends.
- Question: The use of acoustical sensing to measure plug screw wear gives a biorefinery the potential to do predictive maintenance without having to shut down for mechanical inspection. This innovation will improve the run time of an integrated biorefinery. The moisture sensor and smart chute are valuable innovations as demonstrated on corn stover. The technology will need to be demonstrated on additional

feedstocks, especially woody biomass and MSW, to see significant adoption by biorefineries. Response: We agree with the reviewers that our technology is directly applicable to other feedstocks (woody biomass and MSW) and we would love the opportunity to extend our technology to fully explore other relevant feedstocks.

- Question: It was not clear how the team is determining an improvement in operational reliability from 40%–50% to 68% as stated in the quad chart. Response: Our estimates were back-of-the-envelope calculations based on the frequency of upsets related to moisture content. The true percentage improvement will only be quantified in the field over many months of operation.

- Question: The economics of the smart chute should also consider the costs associated with collecting off-spec material, re-processing it to the proper moisture, and reintroducing the material into the process. Response: Yes, this will need to be performed by the FCIC Task 8 team.

- Question: The Smart chutes and acoustic sensor DFO project combines a novel sensor approach targeting a clear need for biomaterials in addressing quality variability. The acoustic sensors appear to be an underutilized technology and well applied in this application. The smart chute has the potential to be an enabling piece in managing feedstock variability. However, as was discussed during the presentation, the impact on a continuous process by the interrupting the feed stream needs to be addressed in order to evaluate the utility. Response: Interruptions in the feed stream by diverting the problematic material will likely be augmented with a surge bin that results in an overall continuous process with minimal or no changes in feed rates.

- Question: A more thorough discussion on the risks and mitigation strategies for sensor development, scale-up, and implementation is necessary to assess Project Management and likelihood of commercial success. The stated project goal is to “increase the overall IBR operational reliability beyond 40%–50% time on-stream ... to 68%.” An explanation of the basis for the current IBR operational reliability of 40%–50% and how downtime is related to moisture variance and plug-screw feeder wear would be helpful for assessing project impact. Response: Estimations were provided by INL and NREL based on their decades of experience with their process development units.

- Question: It’s not clear how the smart chute through moisture sensing control decreases maintenance downtime and costs. Response: The premise is that material with high moisture contents (30%–40%) are responsible for many of the process upsets (i.e., blockages and clogs) that result in process shutdowns. Controlling the incoming feedstock by diverting the high moisture content from the processing train eliminates the likelihood of an unplanned plant shutdown.

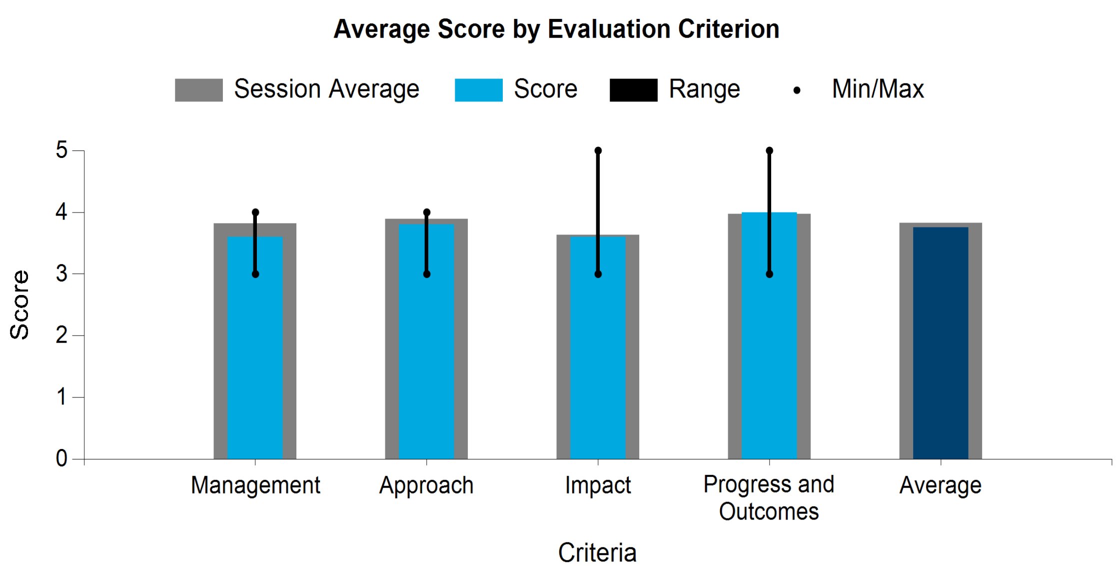
TASK 1—MATERIALS OF CONSTRUCTION

FCIC

PROJECT DESCRIPTION

WBS:	Task 1
Presenter(s):	Jun Qu; Tim Theiss
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,536,000

FCIC's Task 1 Materials of Construction uses integrated efforts of characterization, modeling, and testing to gain fundamental understanding of the wear mechanisms of biomass preprocessing equipment, develop analytical models to predict wear and establish material property specifications, and identify candidate mitigations via both feedstock modifications to reduce abrasiveness and more wear-resistant tools. The knowledge and tools developed in this task will enable rapid mitigation selection for sustainable performance and product quality during biomass preprocessing. Currently, the team has gained fundamental understanding of the wear mechanisms of both hammer mill and knife mill, developed protocols for extraction and characterization of extrinsic and intrinsic inorganics, constructed an analytical erosion model for predicting wear of hammer mill, and identified low-cost feedstock modifications. We are evaluating candidate tool coatings and surface treatments using bench-scale abrasion and erosion tests, and developing an analytical abrasive wear model to predict the impact of feedstock and tool material properties on knife mill durability and performance. In the rest of FY2021, the team plans to fabricate prototypes of prototype knives using top candidate materials, conduct small knife mill testing to demonstrate improved tool life, and deliver a TEA.



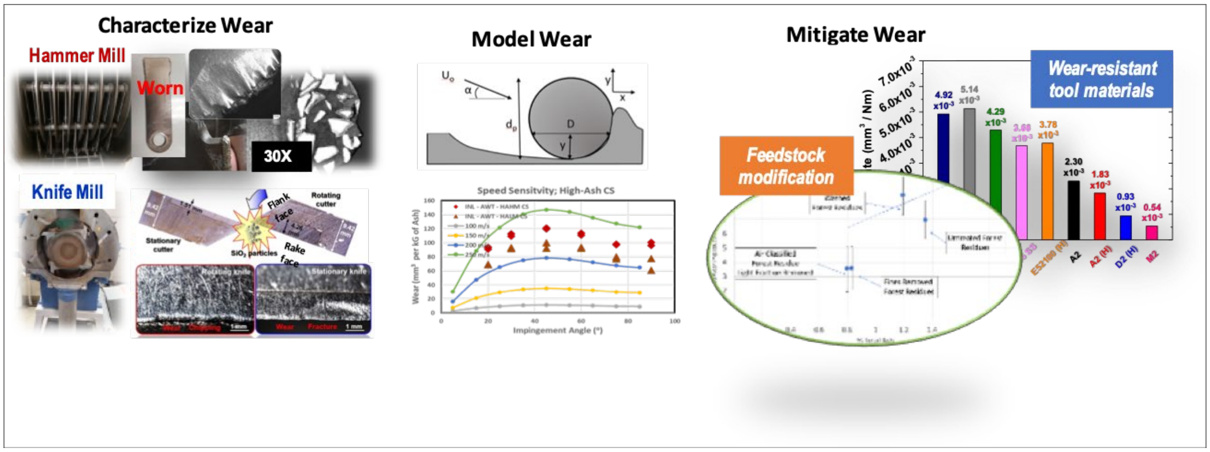


Photo courtesy of FCIC

COMMENTS

- Task 1 applies deep understanding of the mechanisms of wear and an impressive, complementary pairing of fundamentals and experimental results. The presentation clearly explained the rationale applied and then followed with the benefit of the understanding. I appreciated the results being translated into clear estimate of economic benefit. Perhaps the challenge to the team is commercializing these developments into existing applications in the near term.

- The expected levels of extrinsic ash in feedstocks by area or species would be a helpful guide to biorefineries because the total ash can be at least partially controlled either through collection methodologies or air classification in the plant. This type of work can be used to help biorefineries produce better feedstock specifications, processes, and sampling methodologies. Lessons from hammer mill work are being translated to the knife mill. Good to see that effort was not done in parallel and that work on the knife mill only started when the hammer mill effort had been validated. Project is communicating with and coordinating work with both other national labs and industry. It would be good to understand whether the effort from this work is planned to result in new offerings from the OEMs. The presentation did not adequately demonstrate the overall impact of the work on the TEA. It is believable that the improvements could result in real dollars on the OpEx side of an analysis through increased uptime and better knowledge of spares; however, this is inferred rather than demonstrated in the presentation. Currently the work appears to be limited to the upstream milling equipment. However, wear should also be reviewed in softer materials such as seals, belts, and other equipment. This could be addressed in a larger roadmap. Project provided a good description of the past and future validation work on this project. It appears that the approach taken on this project is yielding actionable results. Methodology for development of the cost basis for air classification (0.84) would have been appreciated. Similar work can and should be planned for other feedstocks beyond wood. A preventative maintenance prediction tool would be a very beneficial project for start-up and smaller companies that do not have access to that kind of information. During the Peer Review presentations, this project team learned about some work on silica that a different project discovered (feedstock variability group). This shows that the data from that group are not being properly disseminated as planned. FCIC should investigate how this particular piece of knowledge slipped through the cracks.

- The focus transition from a hammer mill to a knife mill is likely a positive course change for the project. The management approach for this project is less detailed (or takes a different approach) than that of other project presentations in that it does not define responsibility of subtasks. Noting collaboration of this task with FCIC's Tasks 1, 2, 5, and 8 is a strong attribute of this project. The project has identified that extrinsic inorganics cause more wear than intrinsic inorganics. The progress and outcomes section of the project presentation is very detailed. The Crumbler approach is both exciting and novel. Identifying extrinsic (vs. intrinsic) materials as a predominant cause of cutter wear is super interesting. The identification of best practices for use of certain tool steels for thin and thick cutters is innovative. The details presented in the presentation that surround this approach lend merit to the project and its goals. This task, along with the Forest Concepts DFO, is in my opinion an effective approach to the transference of technology to industry. This and the Forest Concepts DFO presentation were some of the most interesting presentations/projects because of this feature.

- There are several biorefinery unit operations whose processing equipment experiences materials of construction related corrosion, wear, and failure beyond milling including reaction vessels, plug screw feeders, and pulp disc refiners. An explanation for why this task chose to focus on milling wear only would be beneficial, particularly in terms of estimated impact to biorefinery downtime and operations and capital costs. To determine impact, more discussion is necessary on the industrial relevance of the hammermill and knife mill and the typical lifetime of wear parts for biomass processing, replacement costs, downtime to change parts, and impact of wear on particle size uniformity. The performance metrics and success factors for this task are not clear.

- This task has done an excellent job of experimentally identifying knife materials and coatings to reduce wear and increase knife life. The task characterized CMAs for pine residue and correlated to a lab-scale impact test (hammer mill), but did not show the impact of material variability on knife wear. The team identified and effectively described two wear mechanisms—erosive and abrasive—adding to the body of knowledge for wear in both knife and hammer mills. A predictive wear model incorporating the two mechanisms is needed to advance the state of technology. Although the overall FCIC objective (slide 2) states the purpose of this task is to develop tools that specify materials that do not “corrode, wear, or break at unacceptable rates,” this task focused only on milling knife or hammer wear. Slide 20 as well as the milestone table in the additional slide section is an excellent way to cover progress and timing in project management.

PI RESPONSE TO REVIEWER COMMENTS

- We truly appreciate the overall positive and encouraging feedback from the reviewers. Critical comments are answered here.

- Reviewer 1: (1a) Q: It would be good to understand whether the effort from this work is planned to result in new offerings from the OEMs. A: Yes. We are indeed communicating with OEMs to plan future work. (1b) Q: The presentation did not adequately demonstrate the overall impact of the work on the TEA. It is believable that the improvements could result in real dollars on the OpEx side of an analysis through increased uptime and better knowledge of spares; however, this is inferred rather than demonstrated in the presentation. A: More comprehensive TEA is scheduled to be conducted jointly with FCIC Task 8 in Q4 of FY22. (1c) Q: Currently the work appears to be limited to the upstream milling equipment. However, wear should also be reviewed in softer materials such as seals, belts, and other equipment. This could be addressed in a larger roadmap. A: Fully agreed and will add the wear issues of seals, belts, and other equipment into the work scope in the next phase. (1d) Q: During the Peer Review presentations, this project team learned about some work on silica that a different project discovered (feedstock variability group). This shows that the data from that group are not being properly disseminated as planned. FCIC should investigate how this particular piece of knowledge slipped through the cracks. A: Sorry for the confusion. We were aware of the Task 2’s interesting observation that bale degradation may lead to translocation/migration of the intrinsic silica within corn stover tissue, but have not studied its specific impact on the tool wear yet. This could fit in the work scope in next phase.

- Reviewer 2: (2a) Q: Perhaps the challenge to the team is commercializing these developments into existing applications in the near term. A: We have started communicating with OEMs for technology implementation.
- Reviewer 3: (3a) Q: The management approach for this project is less detailed (or takes a different approach) than that of other project presentations in that it does not define responsibility of subtasks. A: Subtask 1.1 conducts tribosystem analysis and develops wear mitigations, while Subtask 1.3 develops predictive wear models.
- Reviewer 4: (4a) Q: There are several biorefinery unit operations whose processing equipment experiences materials of construction related corrosion, wear, and failure beyond milling including reaction vessels, plug screw feeders, and pulp disc refiners. An explanation for why this task chose to focus on milling wear only would be beneficial, particularly in terms of estimated impact to biorefinery downtime and operations and capital costs. A: We fully agree that many units in biomass preprocessing experience wear issues and need to be addressed. We chose to study the milling wear as a starting point for this program and plan to expand the work scope to address the wear issues in other biorefinery units in next phase. (4b) Q: To determine impact, more discussion is necessary on the industrial relevance of the hammermill and knife mill and the typical lifetime of wear parts for biomass processing, replacement costs, downtime to change parts, and impact of wear on particle size uniformity. A: Yes. We plan to collaborate with FCIC Task 8 to conduct a comprehensive TEA to determine the impact. (4c) Q: The performance metrics and success factors for this task are not clear. A: The performance metrics and success factors include tool life extension, throughput increase, and energy savings and the resulted in improvement on overall economics by considering replacement costs and downtime.
- Reviewer 5: (5a) Q: The task characterized CMAs for pine residue and correlated to a lab-scale impact test (hammer mill), but did not show the impact of material variability on knife wear. A: We agree and are planning to run systematic knife mill tests to determine the impact of material variability on knife wear. (5b) Q: Although the overall FCIC objective (slide 2) states the purpose of this task is to develop tools that specify materials that do not “corrode, wear, or break at unacceptable rates,” this task focused only on milling knife or hammer wear. A: Yes. Many units in biomass preprocessing experience excessive material degradation problems and need to be addressed. We chose to study the milling wear as a starting point for this program and plan to expand the work scope to address the wear issues in other biorefinery units, such as screw feeders, seals, and belts, in next phase.

TASK 2—FEEDSTOCK VARIABILITY

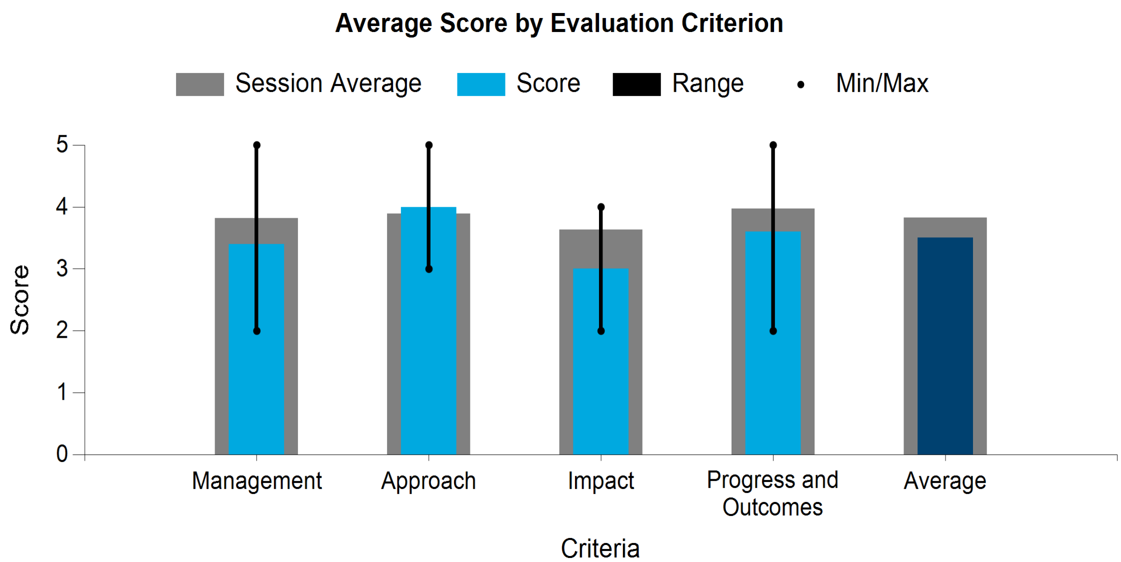
FCIC

PROJECT DESCRIPTION

WBS:	Task 2
Presenter(s):	Allison Ray; Richard Hess
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$3,885,000

The Feedstock Variability Task has a primary objective to develop tools that quantify and understand the sources of variability; to inform strategies that reduce variability; and identify critical material attributes (CMAs) and their impacts in collaboration with FCIC teams in Materials Handling, Preprocessing, Conversion, and Crosscutting Analyses. The biorefining industry has mostly ignored the complexity of lignocellulosic biomass and feedstock variability. The industry lacks a fundamental understanding of CMAs and critical quality attributes (CQAs), their magnitude, range, and distribution in available resources, and their impact on integrated feeding, preprocessing, and conversion. A multi-scale approach is required to understand how molecular and micro-scale attributes (compositional, structural, and physicochemical) manifest in macro-scale biomass behavior in feeding, preprocessing, and conversion operations. Process designers, plant engineers, and investors will directly benefit from the fundamental understanding generated by this science. Fundamental knowledge is critical to de-risking the biorefining industry and overcoming biorefinery failures caused by unknown and uncontrolled feedstock variability from the field through final products.

A multi-scale approach enables a fundamental understanding of how the structural and physicochemical attributes of cell wall composition and architecture underpin flow behavior, mechanical and thermochemical deconstruction in the conversion of biomass to products. We are organized into five key activities: (1) variability, transport, and synergistic impacts of inorganic species; (2) quantify and understand variability of molecular-scale organic attributes; (3) feedstock variability at the micro-scale; (4) feedstock variability at the macro-scale; and (5) data analytics for identifying CMAs of feedstocks.



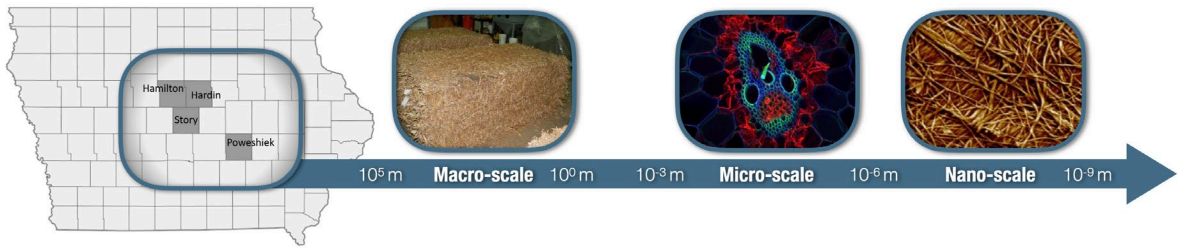


Photo courtesy of FCIC

COMMENTS

- It isn't clear whether regional mineral variability in soils has an impact on the variability of feedstock. The presentation makes it appear that the team was starting with little or no data on the degradation of biomass despite years of work in the field on this very topic. Certainly there had to have been a baseline to work off of. It would have been beneficial to understand what information that baseline lacked and what gaps this effort meant to fill in. Despite the work being spread across six national labs, the team appears to have been able to successfully manage the project and keep progress moving forward. This project provides the basis for best practices, but falls short of actually providing those best practices itself. Certain insights discussed in the presentation: cover bales for less degradation, leaves degrade faster than cobs, did not require any research to confirm. If there were any "ah-ha" moments in this work, they were not made clear nor was the future development path to impact biorefineries. Because of the nature of its harvesting cycle, a feedstock like corn stover is bound to have variability at the plant gate throughout the year. It isn't clear if FCIC has sufficient information to understand the variability of corn stover throughout the aging process. The effort appears to be almost entirely focused on corn stover and wood chips. The reason for this choice could have been expanded either in this presentation or at a higher level. A best practice for sampling different feedstocks in different storage methods for accurate determination of characteristics (round bale, square bale, chipped in trucks, rail cars, etc.) would benefit the industry. The program needs to better communicate how an attribute is confirmed to be a critical attribute. The idea expressed during the meeting that a single CMA may represent several is a good sign that FCIC is working toward a specification that could be usable by industry. Nevertheless, FCIC will have to work to translate these new CMAs to industry and gain buy-in beyond what is typically accepted (ash, moisture content, fine material). Great to see work on identification of contaminants in bales and its potential to translate to pine. Very interesting to hear about understanding of ash to wear and equipment design! SiO_2 migrating to the outside of a particle during degradation leading to additional wear on equipment is a great example of first principles work. FCIC appears to be at the early stages of a long process of identifying the root causes of equipment failure from a chemistry and physics standpoint. As it is such a large effort, FCIC needs to better develop metrics for tracking progress and define what success looks like. Great to see needles/branches being specifically studied.

- Task 2 delivered an impressive set of examples where an advanced analytical technique was applied to a complicated material to deliver an observation demonstrating a physical phenomenon. The team presented good project execution and deep technical insights as to the interpretations. What remains to be written in this story is the application of these insights to a bioenergy process. It would be nice to see interpretations impact the supply chain or manufacturing process and generate the return on investment.

- The material attributes being developed are novel and increase the level of understanding of the impact of material variability. There is a need to determine the criticality of these attributes on the process parameters and determine if critical to industry. Task 2 should push these attributes to other tasks in order to determine their importance in the models being developed and to validate experimentally. Project management could use some form of work breakdown structure (WBS) or milestone timeline that demonstrates increased collaboration of this task across FCIC.

- The project management team appears to be adequate to achieve the desired goals and outcomes including specific resources for each of the subtasks. The subtasks appear to be well covered by the requisite expertise and number of leads. The communication strategy outlined in the management approach is concisely described and should be highly effective. The approach challenges don't specifically address a method to identify/classify and/or or track feedstock contaminants, which can be a major impediment to upstream processes. The section of the presentation related to the translocation of silica is particularly interesting, and the project appears to be taking that on as a primary goal of the project. The project's impact approaches are well defined and likely achievable. In addition, the industrial engagement vision should support the project's outcomes well. The project identifies a well-known issue in biorefining (feedstock variations) and the relevant challenges associated. The progress and outcomes associated with the project are described in great detail. Further, the characterization technologies mentioned should support industry well if brought to market.

- There was no mitigation strategy discussed for the critical risk identified by the PI for "translating fundamental understanding of...feedstock variability into knowledge and tools that can be easily transferred to industry." While the characterization work is impressive, there needs to be discussion on how this information specifically informs real-world strategies to reduce the impact of the observed feedstock variability on industrial operations. Cross-review of the findings by the FCIC preprocessing and conversion groups and industry advisors could help better define the industry relevance and real-world implementation strategy.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you for the comments. We agree that there is need for controlled/coordinated studies to understand the variability of corn stover throughout the aging process. Our work is not comprehensive, but we believe it is a strong contribution to the literature. Regional variability in soil mineral content does have an impact on the variability of feedstock, as demonstrated in our paper by Ray et al. (2020), entitled "Multiscale Characterization of Lignocellulosic Biomass Variability and Its Implications to Preprocessing and Conversion: a Case Study for Corn Stover." Several previous papers have discussed biomass storage and biomass degradation with a primary focus on bulk compositional changes and dry matter loss, which we have cited in our recent publications. However, our research demonstrates novelty in providing mechanistic insight to modes of degradation (https://doi.org/10.1021/acssuschemeng.9b06524), how degradation varies at anatomical and tissue scales, degradation impacts on thermophysical surface properties that impact feeding and handling (https://doi.org/10.1021/acssuschemeng.0c03356; https://doi.org/10.1021/acssuschemeng.9b06759), in addition to degradation-induced variations on the fate of inorganic components in biomass (https://doi.org/10.1021/acssuschemeng.9b06977). Our studies go far beyond traditional measures of bulk composition and ash. Regarding the focus on corn stover and woody residues—this decision was made by BETO to focus the initial work of the FCIC—Task 2 has been working to understand the inherent and introduced variability of these two model feedstock resources (one herbaceous, one woody) to identify potential CMAs. In the future, the FCIC may expand the portfolio of materials, and Task 2 will continue its work focused on the understanding of attributes to enable feedstock agnostic pathways to sustainable utilization. Task 2 focused on identifying sources of variability across different feedstocks and/or different states of the same feedstock. Using this data, we proposed certain features as CMAs to help guide research in other tasks. One of the task's goals is to generate hypotheses for other tasks to investigate whether the variable attributes we've identified are critical to their processes. This year, we have four joint milestones with other FCIC tasks to push the attributes across the value chain. We agree that it would improve FCIC's impact to enlist more milestones related to attributes in other tasks. This integration will be a focus of future work. We validated criticality through models built using k-means clustering and measurements of organic and inorganic features. We identified three CMAs, moisture, total ash, and extractives content, along with belt speed as a critical process parameter (CPP), which combined explain 67% of the variability in grinder energy consumption the low-temperature conversion pathway.

- We aim to illustrate the value of the research investments by publishing our findings, industry outreach, and engagement with other key stakeholders. For example, the inherent and introduced variability characterization results and fundamental understanding provide opportunities for developing advanced preprocessing technologies for selective fractionation and separation. Targeted preprocessing strategies can be employed to reduce the contents of unfavorable inorganic species and/or improve feedstock quality for conversion to fuel intermediate or product. Our advanced characterization approach for a fundamental understanding of properties of anatomical fractions suggests utilization pathways that are tailored to material properties, informs plant breeders and biorefining operators on plant fractions suitable for bioconversion to product intermediates and provides insights into harvest timing and sustainability (e.g., harvest after leaves have dropped). We believe that variability research highlights that quality becomes increasingly important in the context of profitable fuels and chemicals. Enhanced connection with preprocessing and conversion data are the goal of our end-of-project Q4 milestone and will continue during future work. At the end of our presentation, we described a red-green-blue image analysis approach that can be used to assess biomass quality based on the presence of dirt/silica contaminants or signs of degradation (described further in Ray et al. (https://doi.org/10.1021/acssuschemeng.9b06763). The extension of this tool was described in our recent FY21 Q2 milestone to enable process control and optimization by providing information for sorting corn stover/pine based on material attributes. These tools hold promise for the development of a rapid screening tool that could be deployed by farmers for in-field assessment or by operators for in-line process measurement and downstream controls and optimization. We agree that cross-review of the findings by the FCIC preprocessing and conversion groups and industry advisors is important to ensure industry relevance and real-world implementation strategy, which is why we have standing monthly meetings with them.

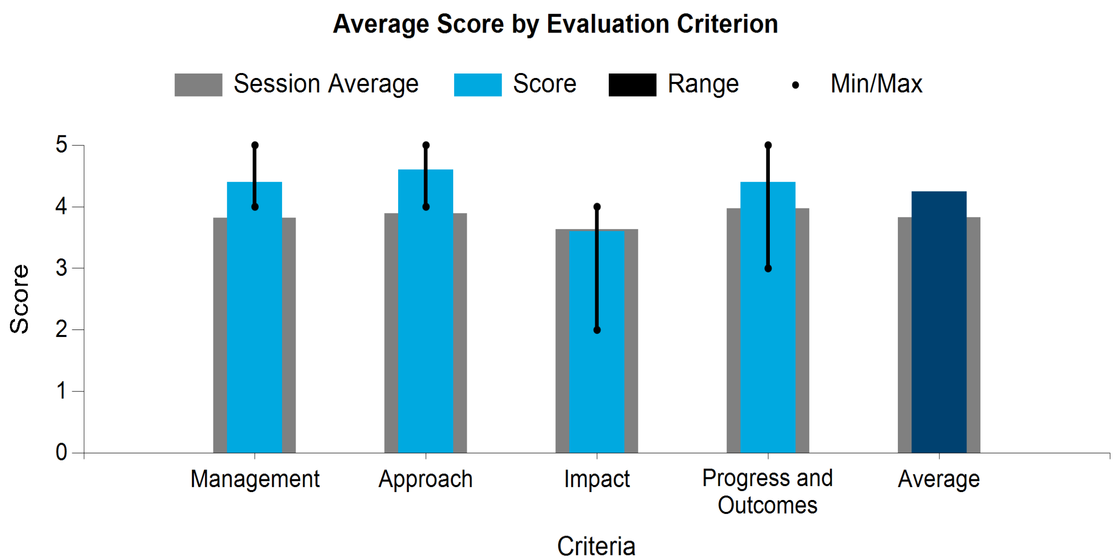
TASK 3—MATERIAL HANDLING

FCIC

PROJECT DESCRIPTION

WBS:	Task 3
Presenter(s):	Yidong Xia; Richard Hess
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$4,074,000

The overarching objective of the project is to develop first principles-based design tools that enable continuous, steady, trouble-free bulk flow transport through the processing train to the reactor throat. The project takes a synergistic approach, including integrated multiscale characterization, experimental flow testing, and physics-based modeling to understand, model, validate, and solve the biomass feeding and handling problems. The scope of work consists of (1) establishing controlled particle and bulk flow tests using industry-relevant biomass feedstocks and for evaluating flow performance under various combinations of CMAs and CPPs; (2) developing experiment-validated, physics-based discrete particle models for gaining a fundamental understanding of flow characteristics and upscaling of first-principles based constitutive models as input to continuum flow simulations; (3) developing experiment-validated, physics-based continuum-mechanics models for predictive studies of engineering-scale flow performance under relevant combinations of CMAs and CPPs; and (4) inputting experimental and simulation data in LabKey to manage data flow and correlate biomass flow performance with CMAs and CPPs. The project will generate a working envelope of CMAs and CPPs for achieving operational stability of biomass material handling (i.e., design charts for consistent hopper flow). Computational tools implemented with the developed flow models will be released as open-source software and/or open-source add-on modules for proprietary software upon the completion of the project.



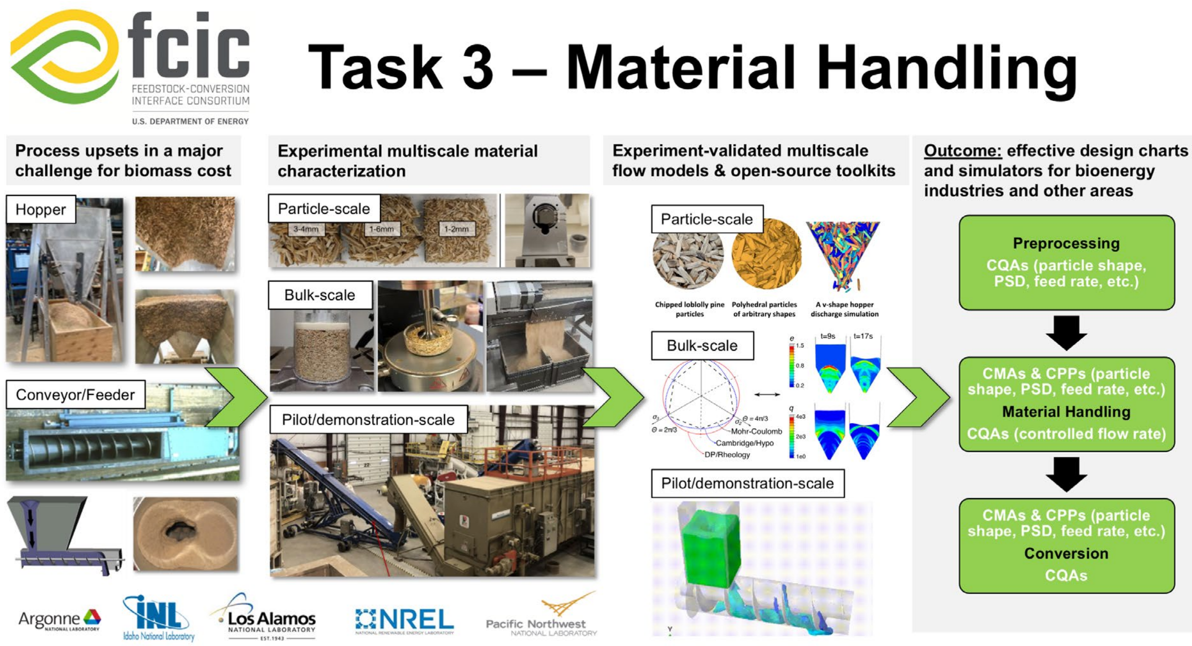


Photo courtesy of FCIC

COMMENTS

- Excellent work on the various modeling approaches. Slide 9 is an excellent representation of how QbD applies to the project. It could also be used to represent the progress on the project. The hopper flow model should be validated at larger scale. Biomass flow against the walls of the hopper may be a function for both hopper volume and hopper geometry. Consider expanding the collaboration with Jenike & Johanson to guide the modeling and larger-scale validation. The impact of porosity, pore volume, and density on biorefinery operations was not clear.

- Reorganization of the effort has made the tasks more clear and highlights the interdependence of each. The management of this project has shown the ability to continue to make progress while managing across several national labs. Validation testing should include the ability to cause an upset by creating conditions predicted by the model to cause an upset. It is not clear whether this type of experimentation was performed or the results of it. Duration of experiments performed to validate the model is geared for short-term impacts. Many issues are long term such as the buildup of constituents (rag layers, material failure). Appreciate the study being done on temperature dependence of flow characteristics. While research at higher temperatures may not be done at this time, it is important for both researchers and industry to understand when that effort might be done and what sort of effort will be needed to do the same modeling but at higher temperatures. I would appreciate knowing whether it would be more efficient to expand the temperature scale at this time or later when this medium-temperature pyrolysis work is completed and validated. The accuracy of the models run on high-performance computers with complex shapes compared with spherical shapes done on desktops was not differentiated. This left the reviewer unsure of why we'd need to use high-performance computers if we could get the same results with a desktop. The project has demonstrated that they are finding new and interesting impacts of currently understood biomass variables (moisture) as well as not previously studied variables such as the location of that water within the biomass. It is important that this team be working with a group of managers and engineers who can start drawing the plans from taking this research from a journal paper into a real-world application. Size of biomass is small (6 mm on slide 23)—experimentation seems to be ignoring 25 or 50 mm chips. Although many technologies use the smaller diameter chips, many others are still based on a larger chip size. Validation testing cannot ignore these other technologies. Project is working on complementary research on porosity with another group and is not only aware of their activities but is also actively communicating with that group as well. Project is working to provide industry models that it can use on computers with a reasonable level of computing power. Effort is being made to make this work accessible for all.

- The development of the discrete element model and reactive transport models are significant accomplishments, especially when considering the challenges that solid transport gives to the bioenergy industry. The technical challenges accepted by the team are substantial. I believe that the efforts are successful but wish that the demonstration of successful modeling could have been more clearly communicated. The presentation of the models was rushed and the slides do not tell the story very effectively on their own. Can these tools be demonstrated with real-world utilization? Can the team solve a known problem with these tools and apply TEA to demonstrate the benefit?

- The project appears to have clear delegations of major responsibilities. The impact section of the project's presentation notes the casting of a wide net via the dissemination approach (e.g., industry, academia). The communication strategy appears to be well developed although there is less clarity related to the laboratory-industry partnership meetings (e.g., frequency). The technical approach is particularly detailed, most notably "experiment-validated, physics-based continuum finite element and finite volume models for predictive studies of engineering-scale flow performance under relevant combinations of CMAs and CPPs," which could yield useful fruit. The impact of open-source modeling and software packages being made available to the public is a benefit of this project's impact. The project's modeling of temperature modeling of a pyrolysis feeder is an innovative attribute. The project's approach in progress and outcomes is very detailed and covers multiple characterizations of biomass flow to reactor throats. Overall, this is a really interesting topic and could provide valuable tools to industry in the future.

- The simple, direct explanation of the project's relevance to industry is exemplary for the program. Example flowsheet clearly defining the hopper designs' material attributes, CPPs, and CQAs is exemplary. Would have liked to see the same for the other process units studied in this task. Involving modelers in experimental design and testing as a project risk mitigation strategy is commendable. Process upsets in handling do not increase the cost of the biomass but the production cost of the final biofuel and co-products. An additional challenge of the project perceived by this reviewer is adaptation of open-source models by the general public and equipment suppliers. It's not clear if the models are "user friendly" enough for nonexperts to utilize to investigate the impact of their specific material attributes on equipment design and operation.

PI RESPONSE TO REVIEWER COMMENTS

- "Validation testing should include the ability to cause an upset by creating conditions predicted by the model to cause an upset. It is not clear whether this type of experimentation was performed or the results of it. Duration of experiments performed to validate the model is geared for short term impacts. Many issues are long term such as the buildup of constituents (rag layers, material failure)." Reply: This project has carried out a rigorous experimental testing plan to quantify the relations between the hopper inclination angle and the critical arching distance (a major process upset in hopper flow). The related experimental data has been used to support the development and validation of the multiscale computational flow models in this project. Upon validation, the continuum-mechanics based bulk models are used to predict the initial bulk density in realistic operation conditions. Our bulk models have revealed that the initial bulk density plays a critical role in determining the discharge flow characteristics and critical arching distance. As part of an iterative research approach between experiment and modeling, the modelers instructed the design of new experimental hopper flow conditions to confirm the numerical findings.

- "While research at higher temperatures may not be done at this time, it is important for both researchers and industry to understand when that effort might be done and what sort of effort will be needed to do the same modeling but at higher temperatures." "I would appreciate knowing whether it would be more efficient to expand the temperature scale at this time or later when this medium-temperature pyrolysis work is completed and validated." Reply: We presume that this question is in regard to modeling of the pyrolysis feeder. This work is currently targeted to NREL's pyrolysis system that has exhibited feeding problems. However, the model is setup for arbitrary ambient and reactor temperatures, and so higher temperatures could be modeled now. Applying the model to different feeder- and cooling-system configurations would likely mean some revisions to the domain and boundaries but is quite feasible.

- "The accuracy of the models run on high-performance computers with complex shapes compared with spherical shapes done on desktops was not differentiated. This left the reviewer unsure of why we'd need to use a high-performance computer if we could get the same results with a desktop." Reply: Sorry for missing some key details in the presentation. Even on high-performance computers, complex-shape particle models can simulate only laboratory-scale benchmark operations but provide "first-principles" understanding of biomass particle flow physics (e.g., particle entanglement and interlocking). The sphere-based particle model reduces the computing cost with trade-offs of minimizing particle shape complexities and introducing complex force-displacement relations. The sphere-based particle model makes it easier for engineers to adopt to simulate the same laboratory-scale problem on a desktop. The sphere-based model can also run on high-performance computers for pilot-scale problems and can serve as a numerical reference for continuum-based flow models.

- "It is important that this team be working with a group of managers and engineers who can start drawing the plans from taking this research from a journal paper into a real-world application." Reply: The FCIC Task-3 Material Handling project in its past two and half years has focused on a rigorous strategy of reviewing, experimenting, down-selecting, validating, and advancing the suitable technology pathways for both the physical flow characterization and computational flow modeling and simulation approaches. The project team is nearing the preparedness of starting to extend our capability from lab-scale and pre-pilot-scale benchmark unit operations to pilot-scale and production-scale applications. We will work with the FCIC leadership and the FCIC industry advisory board to increase our impact in real-world applications.

- "Size of biomass is small (6 mm on slide 23)—experimentation seems to be ignoring 25 or 50 mm chips. Although many technologies use the smaller diameter chips, many others are still based on a larger chip size. Validation testing cannot ignore these other technologies." Reply: We thank the reviewers for this comment. Gasification uses 25 to 50 mm particles, while pyrolysis uses smaller particles (<6 mm). Because the scope of FCIC preprocessing and material handling tasks are focused on the feedstocks for the latter, we have not researched the larger particles. In general, the larger pine chips are not as prone to the same flow plugging and agglomeration issues currently cited and studied in FCIC.

- "I believe that the efforts are successful but wish that the demonstration of successful modeling could have been more clearly communicated." Reply: We struggled with how to clearly communicate all the important modeling achievements from our team along with the other essential components of the peer review presentation; clearly we missed the mark on this.

- "Can these tools be demonstrated with real-world utilization? Can the team solve a known problem with these tools and apply TEA to demonstrate the benefit?" Reply: One of the largest and most direct benefit to the economics of a process is through avoidance of process upsets and downtime. The tools we have been continuously developing are being demonstrated in practical hopper discharge and screw conveyer operations. Specifically, the development and validation testing for this task take place at INL in a custom angle-adjustable hopper, on the scale of 5–15 tons/hr. and demonstrated the operating conditions needed to avoid process upsets like hopper arching. While production-scale operations are certainly at higher capacities, this work demonstrated a clear step forward.

- "The communication strategy appears to be well developed although there is less clarity related to the laboratory-industry partnership meetings (e.g., frequency)." Reply: Laboratory-industry partnership meetings are mainly facilitated in the form of FCIC-DFO projects, where labs keep bi-weekly or monthly progress update with their industry partners.
- "Example flowsheet clearly defining the hopper designs' material attributes, CPPs, and CQAs is exemplary for the program. Would have liked to see the same for the other process units studied in this task." Reply: We thank the reviewer for their comments. Another process unit being studied in this project is the screw conveyor (also called the auger). The design and operation chart for screw conveyor is one of our end-of-project goals.
- "It's not clear if the models are 'user friendly' enough for nonexperts to utilize to investigate the impact of their specific material attributes on equipment design and operation." Reply: We agree that the current version of the models will not be very user friendly. In the engineering software industry, a user-friendly simulation package is normally the result of decade-long iterative effort in core feature and user-interface development and enhancement. User feedback is critically important to allow developers to plan how to continuously improve the user experience. Our open-source software strategy allows us to release the package and provide detailed user manual and examples for nonexperts.
- "The hopper flow model should be validated at larger scale." Reply: Pilot-scale (5 to 15 tons/hr.) and even production-scale (30 to 80 tons/hr.) hopper flow is within the sight of our project. To overcome the high cost of obtaining experimental hopper flow data in these scales, FCIC has been seeking a viable pathway to forge industrial collaboration (e.g., Jenike & Johanson) through BETO DFOs.
- "Biomass flow against the walls of the hopper may be a function for both hopper volume and hopper geometry. Consider expanding the collaboration with Jenike & Johanson to guide the modeling and larger-scale validation." Reply: According to our research, the geometric configuration and size of the hopper are some of the factors that influence the internal stress distribution of the feedstock materials in the hopper, which dominates the discharge flow characteristics. We chose to focus our effort on two major hopper geometries widely used in real-world applications (e.g., the wedge-shaped hopper and conical hopper).
- "The impact of porosity, pore volume, and density on biorefinery operations was not clear." Reply: We whole-heartedly agree that quantifying the impacts of these CMAs in relation to the other FCIC tasks and subtasks must be clearly made. Follow-on experiments correlating surface area, porosity, and density to wettability (i.e., capacity and rates), mechanical strength and discrete element modeling will be a FY21 priority.

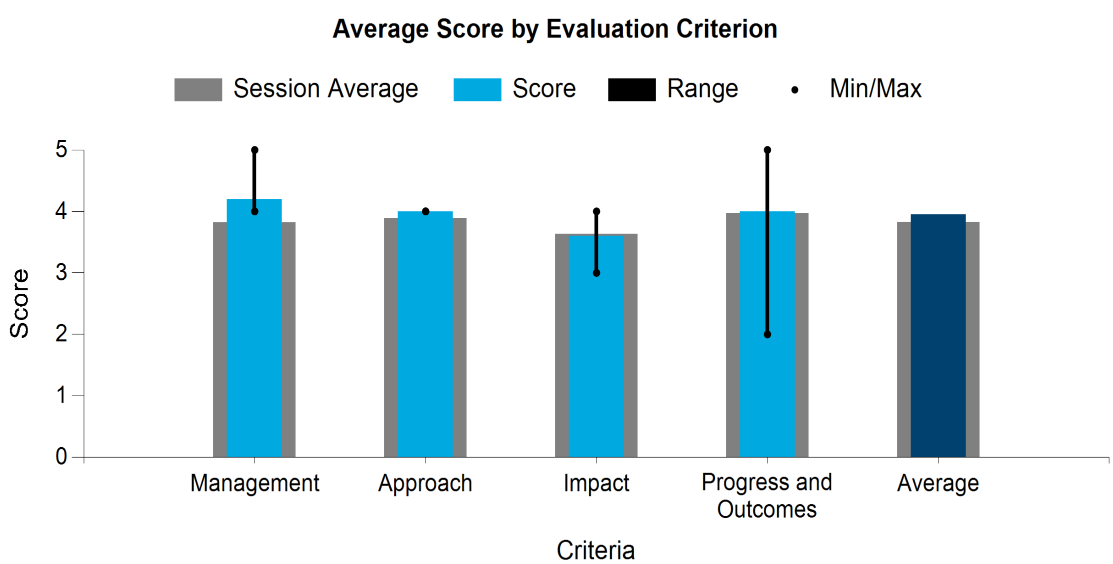
TASK 4—DATA MANAGEMENT

FCIC

PROJECT DESCRIPTION

WBS:	Task 4
Presenter(s):	Jim Collett; Asanga Padmaperuma
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,354,000

The objectives of the Data Integration Task are (1) to provide a web-based collaboration platform and database (the FCIC Data Hub) for integration, preservation, and sharing of FCIC data sets, metadata, and analytical results within a uniform QbD framework; and (2) to provide a portal on the Data Hub for industry stakeholder and public access to FCIC results, data, and software. The Data Hub's QbD framework provides workflows and data tables for cataloging and tracking critical property attributes of feedstocks, intermediates, and products as well as CPPs of unit operations within the low- and high-temperature conversion pathways. The interfaces of the QbD data tables provide easy, rapid, and transparent access to supporting data and evidence of criticality in biorefinery processes and materials. FCIC analysts, experimentalists, modelers, and managers benefit from having a shared, online workspace wherein data may be exchanged, tracked, transformed, analyzed, and preserved within a formal structure that supports efficient tracking of progress toward FCIC goals. Industry stakeholders seeking to build new bioeconomy infrastructure for the production of renewable fuels and chemicals benefit by having ready access to findable, accessible, interoperable, and reusable FCIC data and knowledge via the Data Hub web portal.



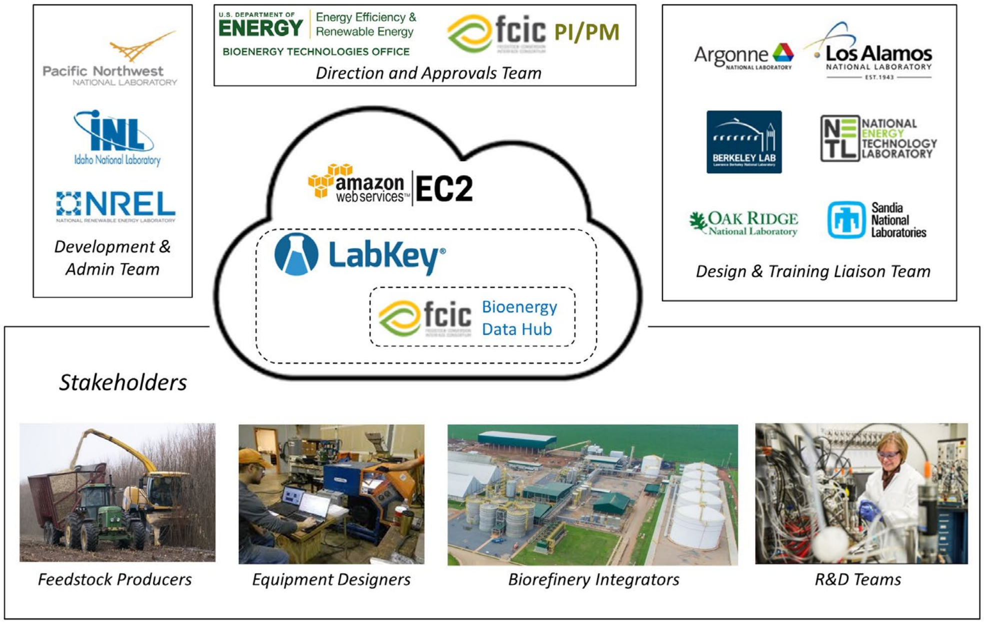


Photo courtesy of FCIC

COMMENTS

- Task 4 is a forward-looking and aggressive approach to creating significantly improved data access for FCIC and beyond. Getting data out of spreadsheets and into accessible form can be transformational. The technical approach appears sound but, frankly, outside of my skill set. Task progress is too early to judge for impact. An upcoming key measure of the development will be use. Will the tools that are developed be used? Will efficiencies or new concepts be advanced? How can we measure the successes enabled?

- The project is very ambitious in the amount of data and information it is encompassing. Standardizing QbD nomenclature as well as linking to other programs such as the Bioenergy Feedstock Library will be key to institutionalizing the concept across FCIC. Although this effort is great for FCIC internal collaboration, the challenge will be to get industry and even other technology areas of BETO to adopt the standardized nomenclature and start using the data sets and reports. The beta testing using the industry advisory board and getting input from the DFO partners is a good start. Ease of use will be key to the adoption of this technology. The data set on high-temperature conversion does not have any DFO or industry partner using the pyrolysis technology for the production of biofuels. This will limit the applicability of the current data sets in this space. More extensive input from industry as well as beta-testing by industry users will be key to determining the value to the biorefinery community.

- The project's approach in utilizing a public web portal to disseminate information is a positive attribute of the project. The management group appears to be a slightly leaner than that of other projects we have reviewed, but that may be because the implementation of the project doesn't require more than the identified resources. The technical challenges shown in the project's approach are clearly defined. I note that the second objective of the three objectives (establish controlled vocabularies, data standards, etc.) will likely be highly challenging. The project's approach to experimental data integration could likely be useful to industry and other stakeholders. The project appears to be in good hands by virtue of highly experienced subtask leads. It is not clear what will happen if the funding of the LabKey software is discontinued in the future. A "Plan B" doesn't appear to be mentioned. The progress and outcomes section of the project's presentation is very detailed and provides proper identification of risk mitigation strategies. I also agree that the utilization of structured query language code will reduce errors and improve trust in large data sets for the bioenergy industry. Generally speaking, this is an exciting approach to managing large data sets and I think we are all anxious to see a slice of the application going public this year.

- The web-based data management tools under development are impressive and exciting. Consider mitigation strategies for additional project risks including poor/insufficient (1) promotion of the database website (visibility) to the public, and (2) public adoption of the tool resulting from lack of training or ignorance of the tool's many capabilities and benefits.
- This reviewer is pleased that data integration has commanded its own unit within FCIC. This is an important goal of disseminating data in a coherent manner, and a huge undertaking within BETO that is clearly advancing toward its goal of a comprehensive data hub. From other presentations it appears that some data sets are going to be added onto this with different user interface layouts. If true, this would harm the overall effort of a consistent platform. The data need to be accessed, entered, and viewed in a consistent manner to give people confidence that the data are accurate as well as to provide a consistency in quality required for such an effort. The tool could be of use to government/industry partnerships when trading samples and information back and forth. This would not only provide a quality document control platform but also continue to populate the overall database. The security of the public data was not clear in the presentation and who and how the data is tagged for public release. Recommend that only a small group of people be allowed to make data entries instead of anyone. Data can and will likely be entered sloppily by users in a rush to get the menial task over with. However, if a group of people had sole control, they could ensure that the data were equivalent, definitions were consistent, and experiments were taking the correct measurements. The project is not only for the final depository of data but could be used as a project planning tool as well. It has the potential to help guide projects toward the correct items to measure in their labs, and in their processes. Existing data have not been incorporated into the model at this time and are planned for the future. The basis of the web tool has been created in this last time period and future efforts will be made to populate it. It isn't clear whether other data sets such as Phyllis are being replaced by this data set or if they will coexist. If the latter, it isn't clear how people will come to rely on one over the other or why not. It isn't clear if the interface of the project was developed using standard user interface/user experience methodologies such as wire frames and clickable prototypes. There is a wide selection of user interfaces in the public space and the ones that are most often used are the ones most accessible and easiest to manage. If the project finds that interaction with the tool is difficult, it should step back and readdress the user experience through a product development mindset. This tool should be used as a specification for data collection for government projects. The same data, collected in the same ways, done on each project is the most important way of making this data set valuable. A publicly available tool that can provide data on a particular feedstock at a particular point in a system that has been vetted by national lab scientists is an exciting advancement. The "interoperable" mandate of the FAIR guidelines is unclear on how it relates to a singular database that is supposed to support all of BETO. I do not think that interoperability is always a good thing if it keeps systems alive that should be thrown into the fire.

PI RESPONSE TO REVIEWER COMMENTS

- We are grateful for the insightful recommendations from the Peer Review panel, and for their support for a comprehensive, online database framework that explains how particular feedstocks and intermediates affect the performance of specific unit operations in biorefineries. We agree that maximizing the value of the Bioenergy Data Hub will require researchers working across the nine national labs of the FCIC to agree upon and adhere to common standards for material and process data and metadata to ensure that their uploaded data sets will be findable, accessible, interoperable, and reusable by our industry stakeholders. A key, measurable objective for our task is to harmonize data sets from FCIC technical reports and journal articles, and then upload them to the Data Hub to enable integrated views of FCIC data within a single interface with standardized metadata and units of measure. Workflows for achieving such data integration will necessarily involve only a small, select group of data managers from each of the FCIC national labs to ensure data quality. We concur with the reviewers' observation that the Data Hub could be leveraged for planning and coordination of FCIC research campaigns; such efforts would be ideally led by the Task 8 Cross-Cutting Analysis Team to ensure that experimental data may be directly integrated into the Task 8 TEA/LCA case studies. We have designed the Data Hub to integrate FCIC experimental data with feedstock characterization data drawn from the Bioenergy Feedstock Library at INL, which serves as the primary repository for feedstock data and metadata across BETO projects. The Data Hub's open-source LabKey Server software efficiently supports such integration via built-in tools for creating query-based hyperlinks to specific items in external databases, streamlined upload/download workflows, and automated import/export script pipelines; these tools may be leveraged to exchange data with other online databases as well, such as the BETO-funded Knowledge Discovery Framework. Our uniform applications of QbD nomenclature within the Process Stream Critical Properties, Unit Operation Critical Process Parameters, and Technology Pathway Configuration data tables on the Data Hub are indeed standardizing the way we think and talk about biorefinery materials and processes within the FCIC. Further integration of the FCIC's QbD framework for biorefineries with the fully developed database schema of the Bioenergy Feedstock Library can form the basis of a new "Bioeconomy Feedstock Conversion Ontology" that provides a shareable, formally specified classification system for materials and processes to support biorefinery development and the creation of markets for renewable feedstocks, intermediates, and products.

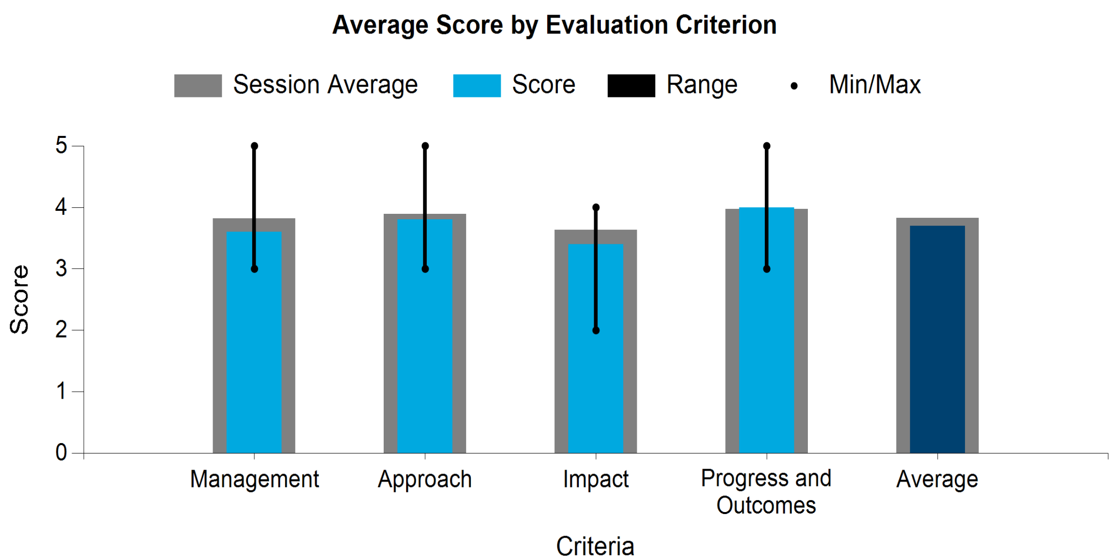
TASK 5—PREPROCESSING

FCIC

PROJECT DESCRIPTION

WBS:	Task 5
Presenter(s):	Richard Elander; Vicki Thompson; Richard Hess
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$4,060,000

The preprocessing task in FCIC seeks to develop science-based design and operation principles informed by TEA/LCA that result in predictable, reliable, and scalable performance of preprocessing unit operations (comminution, fractionation, deconstruction, and process control). This task uses a combined experimental/modeling approach to produce models for hammer/knife milling, air classification, packed bed deacetylation, and process control. These models will be capable of exploring a range of material attributes and process parameters that would be too costly for experimentation. Industry stakeholders will be able to use these tools to design the next generation of preprocessing equipment for biorefineries.



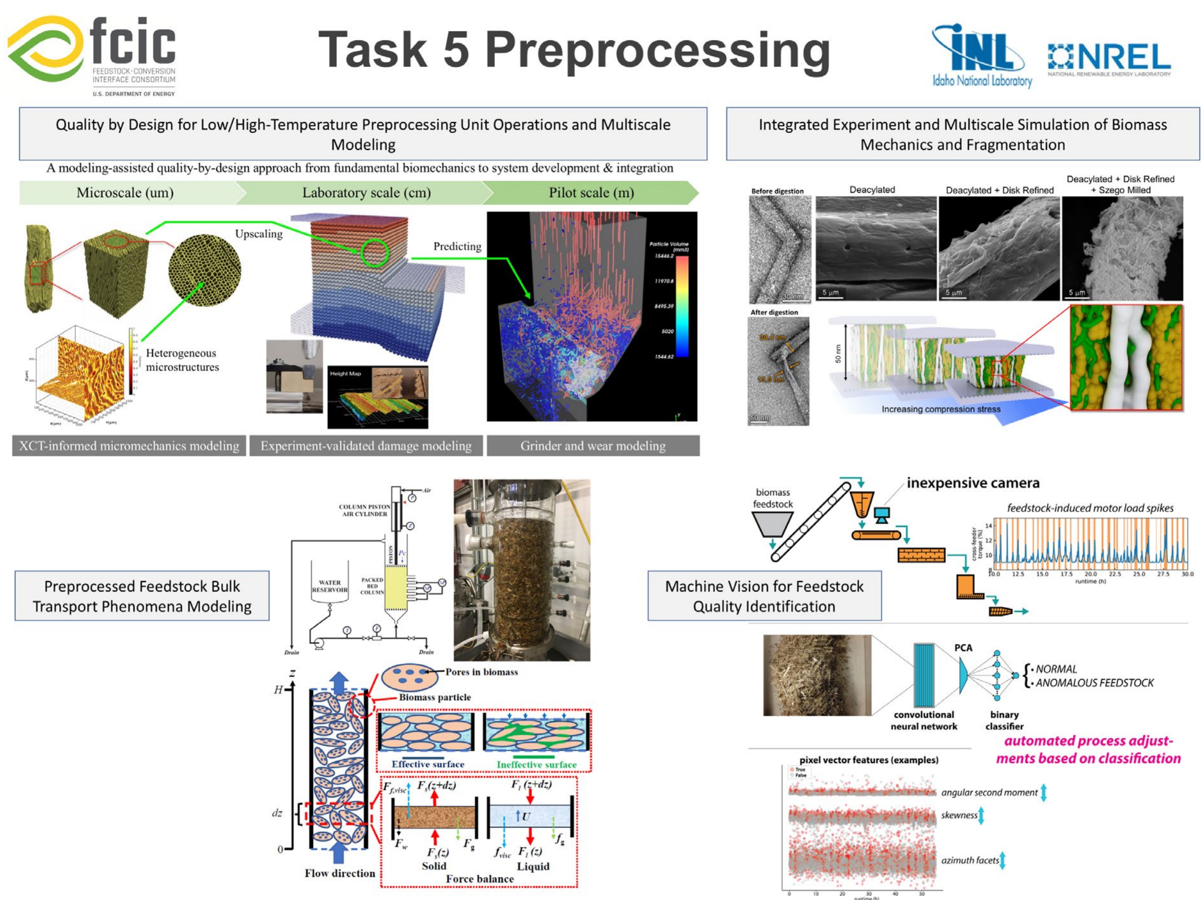


Photo courtesy of FCIC

COMMENTS

- Enable well-defined and homogeneous feedstocks from variable biomass resources. More discussion on why empirical methods are inadequate for preprocessing feedstocks in comminution, fractionation, and deconstruction unit operations would have been helpful for understanding the real-world relevance and impacts of the work performed. The modeling and computational capabilities of the team are impressive; however, the practical benefit of the sophisticated science was not clear for some tasks. The relevance for each task should be more clearly stated to justify the scientific deep dive. For example, stating why small, uniform particle size is so important for high temperature and low temperature conversion and why common milling operations are so detrimentally inadequate for efficient conversion would be very helpful. A flowsheet map of the relationship between material attributes, process parameters, and quality attributes for relevant subtasks would be helpful, similar to the "QbD for the Biomass Value Chain" provided for fermentation by Dr. Wolfrum in the FCIC overview talk. It was not clear for this task the relationship between them. Such descriptions would be very helpful in translating the importance of the science to industry.

- Task 5 did the best job of demonstrating the approach of applying first principles, validating empirically, and applying the knowledge to solving real-world problems. The development of models that are predictive and 80% (I believe) accurate on complex processing is remarkable. I appreciated the example of understanding corn stover anatomical fractions with different milling behaviors, proposing an advantaged process, and running the TEA to understand the economic advantage. Can these tools be applied to existing challenges such as understanding dried distiller grain flow or railcar filling for safety purposes or to improve transportation cost? Can materials be ground advantageously for better pelletizing (improved pellet durability) in bioenergy processes or deploy to another industry like animal feed pelleting?

- The change to the Kozeny-Carman equation was not defined or what it de-risked. Please provide more information. The project tasks all have the same theme and objective but there does not seem to be any interdependence. The metrics and experimental setups used as the basis for the models were not described either. This leaves the reviewer confused about what assumptions were necessary to build the models and how those models plan to be validated. The new knife model appears to be a valuable tool for the industry. It would be of interest to know what parameters related to the design specifications of the mill can be adjusted in the model. Particle size distribution model versus experimental is very impressive. This model could be valuable to industry to provide reliable guidance for more realistic experimental setups. The validation setup would have been beneficial to understand—whether there were multiple machines used or how the model and equipment behave under different process conditions (moisture, RPM) or over time (screen wear, tip speed loss) and its relationship to performance—and this could be an important tool in preventative maintenance. There does not appear to have been any validation of the mechanics of kink formation to date. It is not clear if that is in the scope of this project or not. A standardized experiment on hydrolysis performance would be a beneficial follow-up to this work. The project is achieving the goals that it set out to achieve through fundamental science to add to the set of scientific information that exists. However, the impact of several of the experiments shown in the presentation appear limited to tweaking a TEA and would not fundamentally shift the dynamics of a technology's profitability. If a cheap digital camera can be used to remove off-spec feedstock, this could be very valuable in not just the biorefinery industry but others as well. In larger part the project is looking at short-term equipment impacts (process upsets) and not at longer-term maintenance considerations. Although long-term testing costs more to do, the validation of this work will inform the TEA on mean time between outages, preventative maintenance cost expectations, number of spares that should be stockpiled, and other key risks at a facility. The reviewer does recognize that one needs to operate before you can assess how long you can operate. However, long-term maintenance costs should be a part of the overall program and planned accordingly.

- The model development for multiple processes was the strength of this task. The deacetylation experiments for various compressibility parameters provided a good validation of the corresponding model. The experimentation should be conducted for other models over a wider range of material attributes or process parameters. The impact of air classification on downstream processes should be supported by downstream experimental results. The relevance of the various models for scale up was discussed as a primary quality assessment of this work; however, validation for scaling up from lab to pilot scale is needed. The approach of having a team representative on other tasks and having joint milestones is a positive project management technique. Using a WBS to discuss progress would be beneficial.

- The project's management approach is clearly stated and the responsibilities are quite detailed. The communication strategy in the project's management approach has detailed timing milestones and appears to be reasonably achievable. The metrics in the project's technical approach are clearly identified. Task 5.5 (Machine Vision for Feedstock Quality Identification) is particularly innovative, and when combined with a feedforward loop, could be very effective in industry. The use of open-source model codes is a positive attribute of this project. The project states that the achievement of the Shear Fracture Analysis of Pine using particle tests to quantify the impact of material attributes on the force and fracture mechanisms was used to predict milling performance. This in and of itself is interesting but the project presentation doesn't cite what the effect of this had on predicting milling performance. The use of an advanced 3D analysis on the heterogenous porosity distribution is a positive attribute to the project. The discussion surrounding pilot-scale Milling Deconstruction Models is of particular interest leaving the reader wanting just a little bit more on that subject (lessons learned, success rate, mean time between failure, capacity factor and forced outage rates). Overall, the project's presentation is detailed and comprehensive and deserves kudos. The progress and outcomes section of the presentation is particularly detailed and supports the desired outcomes for the project.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the constructive comments from the reviewers. The traditional Kozeny-Carman equation only applies to rigid particle packing (i.e., incompressible bed). We modified the Kozeny-Carman equation to be applicable to a compressible packed bed by including the effect of the bed compressibility on porosity and specific surface area. This modification is critical to model biomass packed bed flow-through behavior because biomass particles are highly compressible. More details can be found in our recently published paper by Li et al. (https://doi.org/10.1016/j.cej.2021.128918). Due to the highly compressible nature of a biomass packed bed, the pressure drop induced by fluid flow-through at high liquid flow rates can lead to bed compression which will cause even higher pressure and eventual clogging of the column. The modification to Kozeny-Carman equation provides a tool to evaluate this behavior and to optimize reactor design parameters appropriately. The knife model provides adjustable process parameters, including feed rate, rotation speed, blade angle, and outlet sieve size. In addition, the model allows testing of various feedstock material attributes (e.g., particle size distribution, shape, density, and mechanical properties). Direct experimental validation that kink defects in cellulose are formed by mechanical deformation, and that cellulase enzymes preferentially initiate hydrolysis at those kink defects, has been published previously by our group (https://doi.org/10.1073/pnas.1900161116) and others (https://doi.org/10.1073/pnas.1912354116). Future modeling work will focus on predicting mechanical processing modes and stress thresholds that maximize formation of reactive defects. Validation of these predictions will indeed require validation in the form of hydrolysis assays which can be performed by the low-temperature conversion task within the FCIC. Investigation of a specific technology is outside the scope of this task and the consortium. The approach, rather, is to investigate and determine the criticality of fundamental properties as well as the ranges of those properties, which are barriers to the efficient process. The value of doing so is to understand how those barriers can be addressed in general. The comment regarding short-term impacts versus long-term maintenance requirements is noted. Efforts in FCIC Task 1 (Materials of Construction) are largely focused on equipment wear in preprocessing equipment, such as hammer and knife mills, as equipment wear due to the abrasive nature of biomass and wear-inducing contaminants (e.g., ash) represents a major consideration on long-term equipment lifetime and associated maintenance requirements. Efforts in Task 1 are closely aligned with Task 5, including researchers who are contributing to both tasks. The question regarding dried distiller's grain flow/railcar filling is an important issue, although this task is more focused on intermediate deconstruction methods, while FCIC Task-3 Material Handling is more closely investigating the flow and handling of materials. Materials can be deconstructed to improve the properties (durability) of pellets. That is not specifically studied in FCIC, although there is ongoing synergistic work that is being coordinated with the core program work at INL. The strength properties of the pine samples are being used and developed to combine with both discrete element model approaches for mill understanding, as well as the statistical prediction of performance through a population balance model framework. The ultimate goal of the computational models being developed for simulating the preprocessing, milling, and deacetylation operation units is to assist the experimental QbD approach by using the validated numerical models to accelerate testing and expand testing conditions that are normally expensive to prepare and repeat experimentally. Nevertheless, the development and validation of those numerical models, though enjoying a rapid progress over the recent few years, are still in an early stage due to the sophisticated nature of biomass materials. The continued development and deployment of those computational models will allow their practical benefit to manifest to the biorefinery industry. As one example, the tight control over the particle size being fed to the high-temperature reactor will allow for more effective and consistent conversion chemistry and reactor optimization. In the low-temperature conversion pathway, similar optimization can be achieved while avoiding generation of excess fines that can agglomerate or plug reactor functions during processing. We are now currently working on testing and validating models using a wider range of material attributes/process parameters, including covering a wider variety of corn stover preprocessing history such as moisture content prior to milling and extent of feedstock degradation. We are also measuring and validating model response to the effects of deacetylation process parameters (specifically the extent of reaction and the resulting change in particle attributes) on flow properties and modeling accuracy.

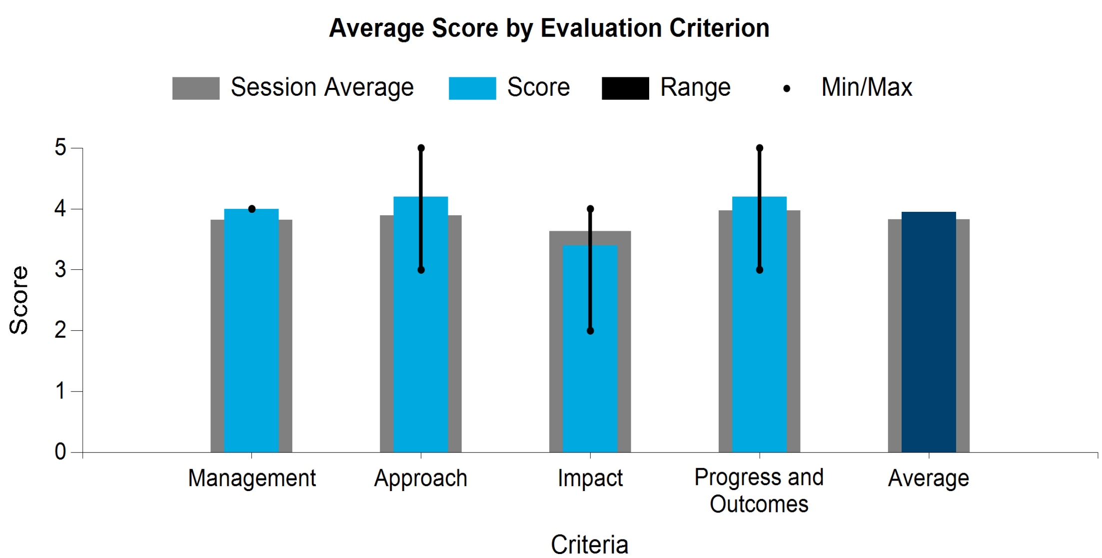
TASK 6—HIGH-TEMPERATURE CONVERSION

FCIC

PROJECT DESCRIPTION

WBS:	Task 6
Presenter(s):	Daniel Carpenter; Zia Abdullah
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$3,742,000

The impacts of feedstock variability on pyrolysis processes are significant but poorly defined. Current engineering designs are based on empirical guidelines, useful only over a narrow range of feedstock properties. The objectives of this project are to: (1) develop science-based knowledge of how feedstock attributes and operational parameters impact pyrolysis process reliability and product quality; and (2) build an experimental and computational toolset that predicts these outcomes, enabling processes to optimize reliability and product quality. Biomass is a complex feedstock. Controlling for and testing the effects of individual attributes is very challenging. This project couples multiscale experimentation and modeling to accurately capture the fundamental physics and chemistry of biomass flow and conversion behavior in feeding and pyrolysis reactor operations. Our focus is on pine residue attributes—anatomical fraction (bark, needles, wood), particle morphology (size/shape distribution, density, porosity), and chemical composition (extractives, biopolymers, alkali metals)—that impact product quality for downstream catalytic upgrading. Because detailed pyrolysis product characterization is limited, cutting-edge analytical techniques are being developed to reveal impactful product attributes. The tools and knowledge developed here will enable integrated pyrolysis-based processes that are more robust, flexible, and market-responsive with respect to feedstock variability.



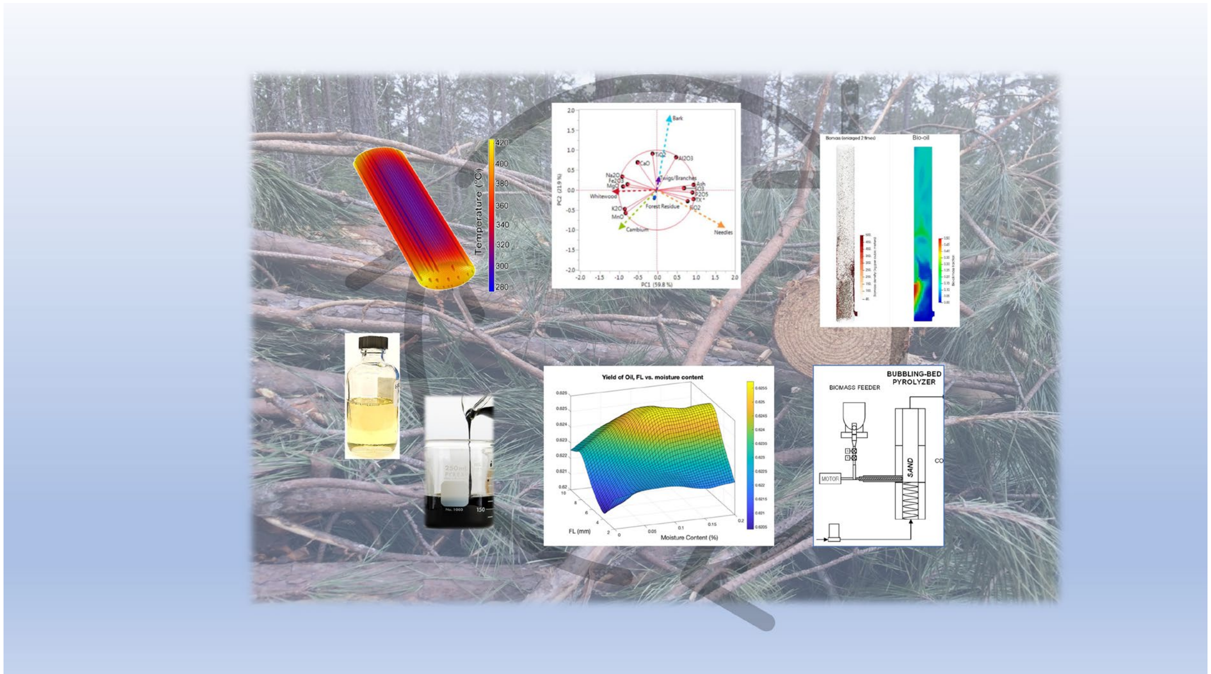


Photo courtesy of FCIC

COMMENTS

- "High temperature" must mean conditions beyond pyrolysis. There is no focus on higher-temperature gasification. Pyrolysis is one of the best examples of the chicken and the egg in R&D. How do you design a reactor when you don't know what the product has to look like, and how do you sell a product that you don't know you can make? The coordination and outreach on this project are impressive. The reviewer was pleased to see that the labs are reaching outside the national labs and collaborating directly with the kinetic group and modeling their work. Refining the Debiagi model to match what you are seeing experimentally represents the excellent adherence to scientific research principles, which is always the expectation when looking at national lab work. A massive scope of a project with truly impressive progress that provides tools that large and small organizations can use to plan and predict performance of their technology. The list of feedstocks for experimentation appeared to cover a significant selection of potential feeds for validation of the model. Further validation would be useful on a sample sourced from an industry partner off of their equipment. Iowa State, which is listed as a partner, operates multiple high-temperature systems, but it isn't clear if this information has been validated on their systems or not. The impacts of ash species in gasification are not well understood but they are known and have shown to have impacts on past DOE projects. The models would benefit from additional time and effort placed into identifying the impact of individual mineral species on gasification. It is unclear whether any cold flow analysis experimentation has been done to provide into computational fluid dynamic model of the fluidized bed. The Sobol sensitivity analysis is very interesting; it is hoped that the list of experiments in the additional slides will be used to validate this work. In general, significant work is being done but a clear validation plan was not presented. It isn't clear whether the list of experiments in the additional slides are planned for validation against all of the work that has been presented or if more is to be done. It is recommended to validate the model as best as possible on a continuous basis or at go/no-go decision points. This effort could be tied to improved metrics for tracking progress as has been discussed elsewhere in these comments.

- A direct summary message of the impact of feedstock CMAs on unit operation performance and product quality would make the impact and outcomes value proposition more clear. The performance metrics and success factors for this subtask are not clear.

- Including kinetics in these models is an excellent advancement of the state of technology. The final model should be able to predict the percent of carbon in the feedstock that is converted into the final blendstock (after hydrotreating). The additional slides showing the CMAs, CPPs, CQAs, and tech transfer were very informative for this task and would add value as part of the presentation. The planned FY21 case study, including the material classification to determine variability, will be critical to understanding the scale-up of this high-temperature conversion technology. An industry partner is needed to scale-up pyrolysis high-temperature conversion to realize the impact of this work. The use of a WBS or milestone timeline could improve coordination between the tasks including those with the Consortium of Computational Physics and Chemistry and ChemCatBio Consortia.

- Task 6 applies the commendable approach of developing science-based understanding and testing against empirical data. The models described are ambitious and based solidly in the physics, with results clearly applying to de-risking the technology. Additionally, using TEA to ground the results in the potential economic benefit is a strong tool. The impact of the work is difficult to grade. I would have liked to see more model results compared to empirical results to gain an impression on how well our phenomenological understanding holds up to experimental data. Also, how impactful are the developments, or developmental goals, in terms of economic impact? It appears the tools are there but insights that could be gained in applying these analyses were not obvious.

- The management approach is detailed, assigns responsibility in a clear manner, and has a robust communication plan. The project's approach is detailed and clear. The use of Debiagi/CRECK kinetics in the project's approach is notably innovative. Slide 11 of the project's approach identifies known challenges related to coupling analytical data to reality. The use of an open-source code modeling tool is a positive attribute to the project. The project's use of reduced-order simulation to derive feedstock product distribution versus feedstock chemical composition could very likely be useful to industry. The notes and comments in the project's presentation are extremely useful. The project's noted collaboration with Task 8 is a positive attribute. In general, the project's approach to progress and outcomes is very detailed and provides a great deal of merit to the proposed processes (e.g., slide 21).

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for their insights, questions, and suggestions to improve this project. Regarding expanding conversion conditions beyond pyrolysis to include gasification: a decision was made early on at the consortium level to focus on a single conversion technology and a single feedstock, in part to promote the focused development of enabling methodologies, workflows, and tools. We agree that an expansion to other process conditions such as gasification, as well as additional feedstocks, is prudent and will be included in the upcoming project planning cycle. However, to pursue gasification, additional resources will likely be required. Another important consideration related to gasification will be its carbon efficiency in comparison to pyrolysis, so a comparison on a life cycle basis will help to inform the priority of thermochemical conversion processes.

- We appreciate the reviewers' positive comments regarding external partnerships. To clarify the partnership with Iowa State University, the FCIC modeling toolset has been applied to a BETO-funded project on BioPower with Iowa State. That project was reviewed at the 2021 Peer Review and is titled "Enabling complex biomass feedstock for biopower combustion and autothermal pyrolysis" (WBS: 5.1.2.102); please see that project's review for more information. In short, the model developed for Iowa State's autothermal pyrolysis reactor has been validated with experimental data. Publications are being drafted on the research, so we expect to provide the final validated model result in open literature in the near future. We agree that having an industry partner involved in scaling up these technologies, as well as helping to validate and use models developed here, would be beneficial in demonstrating project impact. We will consider this in upcoming project planning.

- Regarding including the specific impacts of ash, this is an important point; we agree with this comment, and are actively looking to address this. The kinetic scheme could benefit from a more detailed treatment of the impacts of specific inorganic components to better predict yield and product distribution. Appropriate experimental and sample preparation techniques that can accurately isolate and measure these effects are also needed. Thank you for the comment about demonstrating project impact with more experimental data—these are fair points. The collection of experimental data has been significantly delayed in the past year due to lab closures, occupancy restrictions, etc. The experiments listed on slide 33 are in fact now underway to provide validation for the particle- and reactor-scale models, and the data will be available soon. Our approach to model development and validation is iterative with experimentation and is done on a continuous basis as data become available. As for economic impact, this was mentioned only briefly in the presentation (slide 20) in the context of applying machine learning techniques to develop techno-economic modules that can be used to quickly determine minimum fuel selling price (MFSP) impacts. The ongoing 13- and 23-year-old tree case study will have both TEA and LCA components to gauge cost and environmental impacts. Regarding computational fluid dynamics model validation, although not covered in detail due to time limitations at the Review, extensive cold flow experiments are a standard practice of National Energy Technology Laboratory in their development of appropriate drag models, in this case to capture three-phase flow behavior (biomass + sand + char).

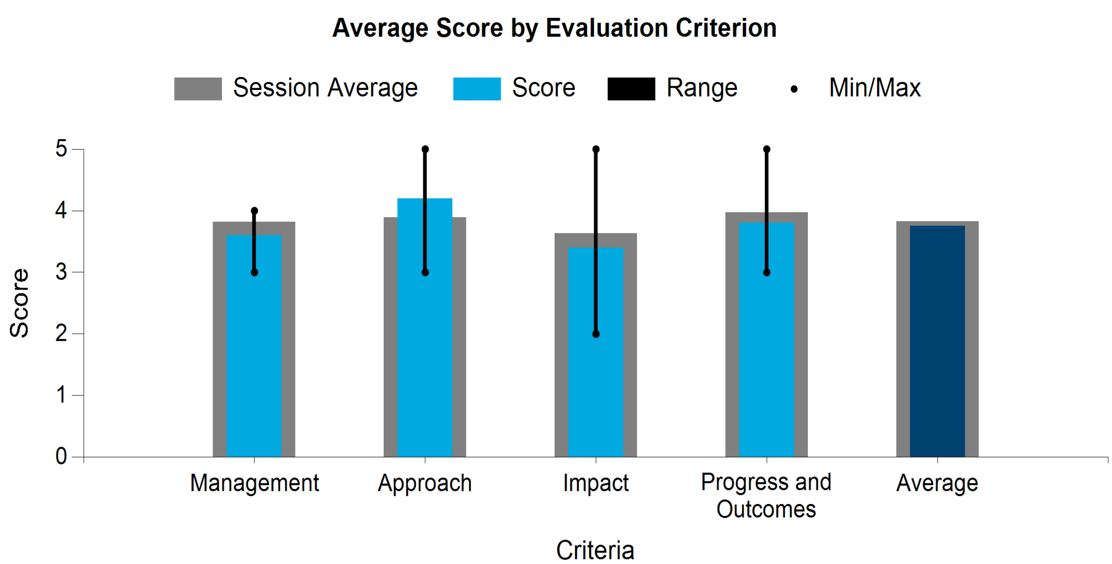
TASK 7—LOW-TEMPERATURE CONVERSION

FCIC

PROJECT DESCRIPTION

WBS:	Task 7
Presenter(s):	Meltem Urgun-Demirtas; Phil Laible
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$2,490,000

The objective of the Low-Temperature Conversion task is to determine the effects of biomass variability on biocatalytic conversion (using both sugar and lignin pathways) and to develop tools to mitigate the risks posed by this variability. Long-term goals are to operate the sequential cascade of processes intelligently by understanding critical attributes of materials passed downstream and by adjusting process parameters that allow for tolerance of upstream complications. Researchers are leveraging laboratory data and existing metabolic models to develop an artificial intelligence framework to predict the effects of feedstock variability on microbial conversion performance—to identify the genetic basis of the impact on conversion efficiency. This knowledge affords these approaches to adapt to and engineer around attributes of feedstocks that impact conversion negatively. Statistically significant changes (>15%) in biocatalytic productivity and substrate utilization for feedstocks of varying quality were observed. Strikingly, conversion performance was impacted differentially for the sugar- and lignin-converting organisms. Similar materials were also shown to affect valorization of lignin via chemical depolymerization approaches. Ranked lists of attributes and process parameters are being used to study operational ranges of impactful components in feedstock streams. These results are the first of their kind to determine the effects of feedstock variability on biological conversion of multiple streams arising from deacetylation and mechanical refining (DMR) pretreatment. These data will continue to drive development of a validated artificial intelligence tool able to predict the performance of new organisms on variable sugar and lignin streams.



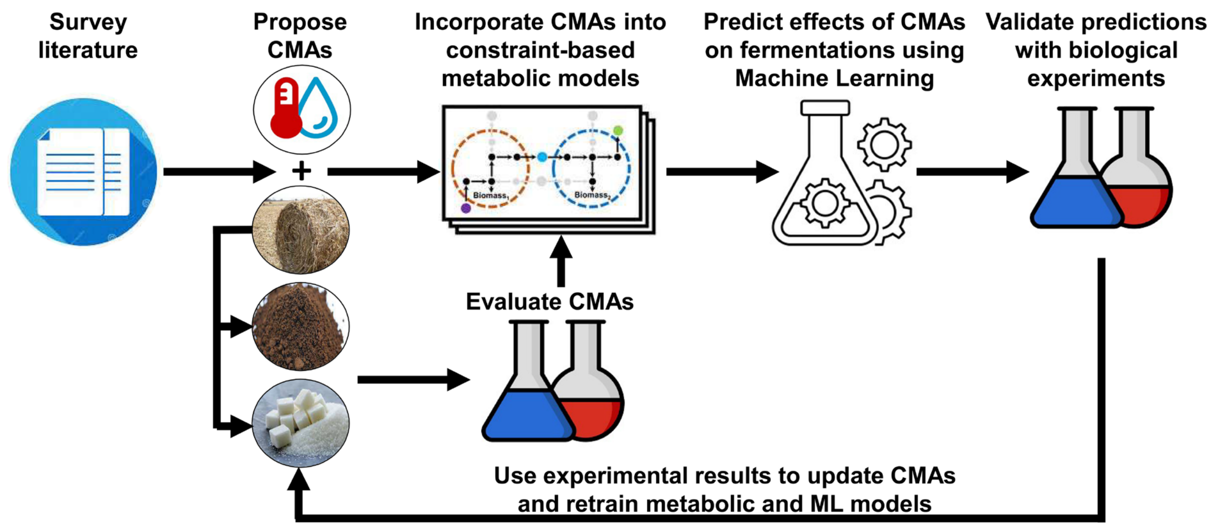


Photo courtesy of FCIC

COMMENTS

- Clear concise objectives that work together. Project has been able to manage tasks across several national labs and is bringing in the appropriate management tools into the project. The project was correct in assessing that variability of feedstock can become overwhelming, especially when degradation, location, and other factors come into play. It isn't clear how this project worked with other FCIC projects on the specific subject of feedstock variability, however. The experimental setup of the fermentation processes would have been of interest. Given the different requirements of each organism and the multitude of expected fermentation trials, I would expect to see a parallel train of fermenters operating under similarly controlled conditions. This tool has the potential to be immensely helpful in industry, but the experimentation all appears to be based on the DMR feed preparation process, which is not widely used in industry, if at all. This particular preparation method was selected based on the failures of weak acid hydrolysis on other projects. The adoption of this pretreatment method is not clear in industry and a poll or survey of new start-ups on their willingness to adopt the DMR process would be of benefit. If DMR is not adopted, the program risks undercutting the value of all of the work that they are currently doing. It isn't clear why C5 and C6 sugar yields are not individual attributes, as many organisms are compared based on these individual metrics. A predictive performance tool for a multitude of organisms could be immensely beneficial to the industry and provide new pathways for fuels and chemicals production. There isn't a clear handoff between the work being done in this program and additional work in other programs to advance the production of biofuels from these organisms through modified pathways. With the artificial intelligence built on the four pathways, it will be interesting to see how quickly new organisms and pathways can be brought into the FCIC predictive system. A future roadmap should help the public understand how quickly this might happen.

- Risk mitigation strategies are not discussed. The performance metrics and success factors for several subtasks are not clear. Please show the CMAs studied (and why selected) and conversion data to justify that feedstock variability influences titers of bioconversion processes for lignin and sugars. This first of a kind achievement linking feedstock variability with process performance should be covered in significantly more detail. It's not clear how the low-temperature process optimizations being conducted are relevant to feedstock variability (washing, base substitution, and neutralization). The stated achievements for this work are related to process optimization rather than further understanding of the effects of biomass feedstock variability and mitigation strategies on low-temperature processing. Brief discussion on why the DMR process was chosen along with the four organisms would be helpful, including the commercial relevance for these choices and parallels/ translatability with other conversion technologies and organisms currently being deployed.

- Task 7 brings an impressive breadth of technical developments. The presentation demonstrated deep technical insights for the task and strong approach in applying the current state to the next phases of development. The presentation did not convey well how all of these efforts tie into the overall approach in de-risking low-temperature conversion. Intuitively, the tasks all appear well selected but I would like to understand how the pieces fit together. It was not clear how this work impacts the eventual successful deployment of the technology.

- The experimental work demonstrated good progress in determining which material attributes are critical to both the biocatalysts and conversion. The artificial intelligence approach to correlating feedstock variability to catalyst and conversion performance will advance the state of technology. Understanding how the industry partners are participating or using the results of this project would be beneficial to assessing the impact of this work. The end of project milestone is well stated; however, there is not a clear understanding of which new material attributes from Task 2 will be used in this work. A more detailed discussion and milestone table of the integration of low-temperature conversion (slide 9) as well as the final milestone would add to the understanding of progress and outcomes.

- This project should couple well with Task 4 (data integration). The management approach is well defined and clearly assigns subtask responsibility to individuals. The communication strategy is well defined and should help to support the merits of the project's goals. The use of artificial intelligence to follow the project's metrics is intriguing and innovative. More detail related to the projected use of artificial intelligence would be helpful. The knowledge gap, achievement, and relevance shown in the progress and outcomes section of the project's presentation is innovative. The project clearly delineates known knowledge gaps, the project's achievement in each area, and the relevance related to expected results. It is not clear in the presentation whether or not the approach is commercially viable and directly transferrable to industry. That may be because this is a new start project or I may be overlooking something. The mention of technology transfer in the additional slides does add some additional color.

PI RESPONSE TO REVIEWER COMMENTS

- The Low-Temperature Conversion team (Task 7) of the FCIC thanks the reviewers for their feedback and thoughtful comments. The low-temperature conversion approach has been added to ongoing consortium efforts in recent years. We agree that systematic assessment that links feedstock variability with low-temperature process performance will be impactful. In addition, the predictive artificial intelligence built on existing experimental pathways has the potential to advance the production of biofuels/bioproducts from a much wider range of systems (both natural and engineered).

- Pretreatment/organism justification: Universally, the reviewers would have liked to have more information justifying the use of the DMR process in Task 7. Why is it used by the FCIC? DMR is a low-pressure, low-severity pretreatment technology that produces very digestible material after enzymatic hydrolysis. BETO has invested heavily in R&D on the DMR process. Our task within the FCIC is specifically looking at the impact of feedstock variability on the performance of DMR/enzymatic hydrolysis derived streams (lignin and sugar hydrolysates). While we are working with a single pretreatment chemistry (DMR/enzymatic hydrolysis) we are looking for universal effects that may result from many other pretreatment choices (like weak acids, organosolv, ionic liquids, etc.). Thus, we expect our results will be informative for other fractionation processes that share common attributes in their streams. In the future as our research evolves, we can consider the benefits of expanding our research thrust into hydrolysates arising from different pretreatment methods. Regarding the selection of organisms, these microbes are utilized and developed in other projects in the BETO portfolio for the upgrading of sugars and lignin to biofuel and bioproduct precursors. Most importantly, these organisms are included in TEAs to report the state of technology to BETO every year toward decreasing the MFSP.

Examples of this state of technology work include Pseudomonas putida in “Biological Lignin Valorization,” Clostridium tyrobutyricum in “Biological Upgrading of Sugars,” and Rhodosporidium toruloides in the Agile BioFoundry (see below).

- Individual sugar attributes: We apologize for the confusion about C5 and C6 attributes. C5 and C6 sugars are indeed evaluated as individual attributes. In addition, C5 and C6 sugars are co-utilized by the organisms selected in this task (for sugars conversion), which is key to develop bioprocesses.
- Risk mitigation: A risk in this task is that there is not enough variability in the feedstocks to generate significant differences in the biological conversion processes. If that is indeed the case, we have the opportunity to additionally evaluate the effect of various CPPs that change the properties of the streams (e.g., increased washing steps during the pretreatment process). The goal of changing the washing and pretreatment strategies was to understand the effect of CPPs on bioconversion processes in addition to the identification of CMAs from feedstocks. This approach ties process optimization to our ability to understand the effects of feedstock variability on low-temperature conversion processes. We apologize for not being more detailed in our discussion of this approach.
- Inter-consortium coordination: The Low-Temperature Conversion team works closely with the Agile BioFoundry to coordinate performance advantages with sugar streams from variable feedstocks. The FCIC advances knowledge and artificial intelligence tools that identify genetic targets that can be implemented and tested by engineering efforts within the Agile BioFoundry. Similarly, DMR sugar and lignin streams are the subject of studies with the Bioenergy Separations Consortium. Advances and understanding derived from work within Task 7 of the FCIC influence the types of streams that are evaluated and processed using advanced separations technologies that they are championing.
- Intertask coordination: The Low-Temperature Conversion team has close ties with the Feedstock Variability and Preprocessing Teams (i) to coordinate acquisition of materials for our studies, (ii) to harmonize materials used in characterization efforts, and, in addition, (iii) to integrate raw material CMAs from Feedstock Variability and Preprocessing into modeling efforts being developed within the Low-Temperature Conversion task. We are working on a joint publication with our FCIC colleagues on these other tasks as the FY21 fiscal year closes. This publication will include TEA and LCAs by the Crosscutting Analyses team of advancements in processes that change the properties of sugar and lignin streams that are being studied and will have utilized results for modeling that were curated and stored by the Data Integration efforts of the consortium.

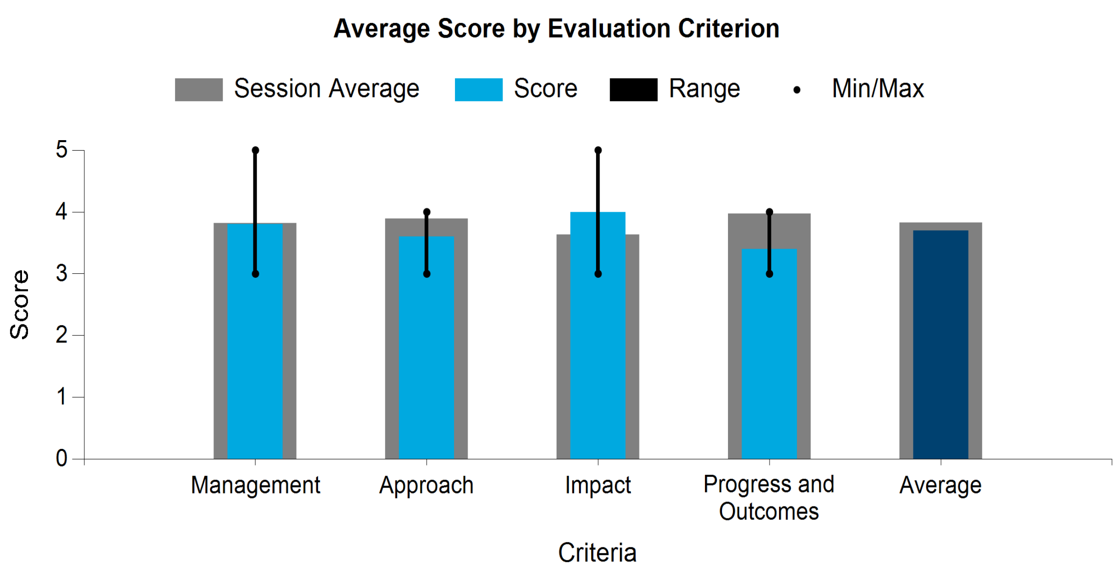
TASK 8—TEA/LCA

FCIC

PROJECT DESCRIPTION

WBS:	Task 8
Presenter(s):	Steve Phillips; Asanga Padmaperuma
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$2,499,000

This work provides intralaboratory, collaborative crosscutting analysis to the overall consortium. Our objective is to create and publish case studies to quantify and communicate industrially relevant, system-level cost and environmental impacts for the discoveries and innovations of the FCIC. Analysis tools are used to evaluate how feedstock variability affects economics and sustainability throughout the biomass-to-fuel value chain. The scope of work encompasses the value chain for high-temperature conversion of forest residues by ex situ catalytic fast pyrolysis and low-temperature corn stover deconstruction to cellulosic sugars and subsequent biological upgrading to multiple products. Case studies provide economic and sustainability information to help biorefinery stakeholders make informed decisions about feedstock collection, processing, and conversion processes to minimize or control the impacts of feedstock variability. Eight case studies were completed in FY21 Q1 with another 10 scheduled for completion in FY21. Preliminary results are presented to FCIC industry advisory board and BETO to receive feedback that is then incorporated into the final reports and other outreach presentations. The completed, vetted case studies will be disseminated to the public via technical/trade publications, conferences, webinars, and the FCIC website to provide thought leadership and guide research and industry toward higher impact biomass energy utilization.



Crosscutting TechnoEconomic & Sustainability Analyses

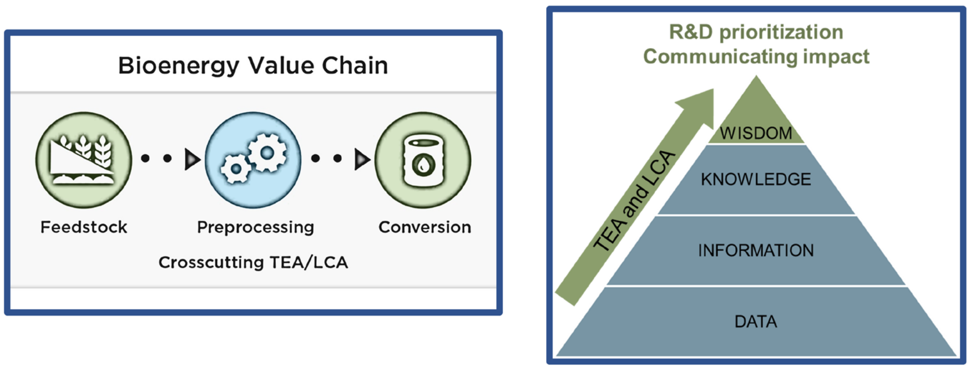


Photo courtesy of FCIC

COMMENTS

- The presentation does not spend any time detailing what is going into these estimates. The presentation provides the executive summaries of case studies done under this project, but the approach taken for any one of these is as necessary to discuss as the results of the TEA itself. In general, the reviewer would like to know how the current research is adjusting the model's calculation of long-term maintenance cost, and amount of spares (working capital). Further, other than cost of capital and its impact on internal rate of return, the reviewer is wondering if there is a particular restriction on the overall capital cost of a project, as certain levels of equity are simply not accessible for many plants, even if the payback is there in theory. The amount of time working on the model itself (the baseline model) instead of process variations to that model would be of interest. The assumptions the model is using for cost of capital, working capital requirements, equipment costs, in-process storage requirements (tankage), and other items would be valuable to improve upon as well as provide the other projects their TEA data to justify their development. The project has not researched and incorporated the capital and operating costs of the American Recovery and Reinvestment Act projects or validated their model against these projects. This should prove to be a worthwhile task. The presentation falls short of providing an overall recommendation for certain items studied. It wasn't clear what is the recommended approach to mildly or severely degraded corn stover from an LCA or TEA viewpoint according to the models. The cost/benefit analysis should have a result that can be shared based on current knowledge and estimates. The basis for MFSP is unclear for fuels such as pyrolysis oil, which really have no market and vary greatly by quality. Certain attributes such as oxygen content may make some fuels unsaleable, which may or may not be a part of the model. TEA effort appears to be well coordinated between projects and is being handled by a single group instead of anyone and everyone. Projects appear to be progressing in complexity but given the lack of actual data available from industry, the true test of a TEA has not yet been made. LCA work is not noted and appears to not be funded at this time. TEA work should be prioritized if there are conflicting needs within BETO.

- It was exciting to see the findings of each task translated to an actionable take-home message under the TEA task. This reviewer recommends incorporating the TEA take home message and Ishikawa relationship diagrams developed under Task 8 into each task's Peer Review presentations going forward, so that the industrial/operational relevance of their work and relationships between CMAs, CPPs, and CQAs are more clear. It's not clear what work is being done for the LCA/environmental impacts portion of the task or methodology, hypotheses, and relevance. From a project management perspective, it would be interesting to know more about the down-selection process and criteria used for determining which case studies are evaluated.

- Task 8 approach and position among the FCIC tasks is well applied and well incorporated. The modeling approach is sound and model results are justifiably relied upon for guiding research and external commercial development. Task 8 uses a strong process of prioritizing tasks or questions that have sufficient impact, data, and relevance as topics for analyses. Opportunity remains to complement the current activities in modeling well-developed concepts near the end of the project with additional modeling resources to apply existing models more frequently in guiding active projects. As we reviewed the other tasks, it is common that the economic benefit of a research proposal or task result is not understood or, at least, not reported. New and existing tasks could benefit by understanding more accurately where the proposed benefits are derived.

- The case study approach is a good way to breakdown the overall process into individual unit operations. The completed case studies focus on the added cost without quantifying the cost benefits. For instance, the case study on protecting corn stover bales from degradation described the added cost of protection but does not quantify the benefit of being able to use a greater percentage of the bale stack, making it difficult to know if the added cost is worth it. It appears the FY21 Case Study for the Pine Residue Pathway (slide 16) will integrate the impact of feedstock variability across the entire process pathway. Determining an estimated final MFSP, comparing the two feedstocks, will provide the biorefinery industry with an understanding of variability as well as the cost to reduce that variability.

- The project's management approach is concise, clearly defined, and assigns responsibilities. Communicating across four time zones could be an impediment to the project's progress and outcome. The dissention of information as shown in the impact section of the project's presentation could use more detail. For instance, the presentation mentions "various mediums" through which dissemination could occur, but doesn't mention specifically what those mediums might be. Exploring the value proposition of coatings or new alloys on knife wear is a worthwhile endeavor. Citing the value chain cost reductions related to corn stover storage options adds value to the project's presentation. Moisture control of stored corn stover is mentioned, but more detail on what is currently happening in both research and industry related to stored corn stover could be useful in supporting the project's goals. Notwithstanding, the project's presentation does make specific mention that minor improvements to the storage of stover can be accomplished economically. The case studies in the additional slides section lends merit to the project's expected outcomes.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful comments and the opportunity to incorporate them into the remaining work in 2021 and in the next research cycle for FCIC. Our responses to the comments are given below individually.

- Comment: TEA effort appears to be well coordinated between projects and is being handled by a single group instead of anyone and everyone. Response: This approach has worked well to draw on the TEA/LCA experience from across BETO-funded national laboratories and to maintain consistent modeling assumptions.

- Comment: The reviewer would like to know how the current research is adjusting the model's calculation of long-term maintenance cost, and amount of spares (working capital). Response: The available operating data does not support making long-term estimates of the impacts to maintenance costs due to component wear such a bearings and seals. Prior cost models typically used a factor based on the equipment cost. We appreciate this feedback and will include sensitivity of maintenance and working capital on the MFSP in future case studies, when possible.

- Comment: The amount of time working on the model itself (the baseline model) instead of process variations to that model would be of interest. Response: In most cases, our baseline modeling frameworks have been developed in other BETO-funded work, each model representing hundreds or thousands of hours of work over several years. Reports on the baseline analyses are available and describe the underlying assumptions and approaches for each model (see https://bioenergykdf.net/content/beto-biofuels-tea-database for a list of BETO-funded models). Our case studies use variations on the baseline models to estimate the impacts of mitigation strategies for research being done in the FCIC when possible. Because of increased granularity and non-steady-state operating considerations, some studies require the development of both baseline and variation models to answer the case study question.
- Comment: The presentation falls short of providing an overall recommendation for certain items studied. It wasn't clear what is the recommended approach to mildly or severely degraded corn stover from an LCA or TEA viewpoint according to the models. Response: There was insufficient time allocated for the presentation to cover each case study adequately. Case studies were intentionally limited in scope to answer specific questions and provide insights that will inform new case studies with broader scopes. We attempt to consider impacts downstream, but there are still gaps in the available data that need to be filled. We are using the new insights gained to inform recommendations for the FCIC work in outyears. For example, the presentation stated that the cost of improved storage would add $0.30/GGE to the MFSP. From other work by Task 8.4 (biochemical conversion), it was estimated that a 2 percentage-points increase in carbohydrates content would be needed to compensate for the additional storage costs. Additional cost savings are anticipated in pre-processing, but this was not within the scope of this case study and is a knowledge gap. LCA of the corn stover value chain was not funded in FCIC.
- Comment: Projects appear to be progressing in complexity but given the lack of actual data available from industry, the true test of a TEA has not yet been made. Response: We agree. The lack of industrial data available to national labs does limit some of their impact, but their overall utility in identifying the key cost drivers is still a valuable tool for guiding researchers.
- Comment: The project has not researched and incorporated the capital and operating costs of the American Recovery and Reinvestment Act projects or validated their model against these projects. This should prove to be a worthwhile task. Response: Unfortunately, the American Recovery and Reinvestment Act project cost information is not currently available to the national laboratories.
- Comment: The presentation does not spend any time detailing what is going into these estimates. The presentation provides the executive summaries of case studies done under this project, but the approach taken for any one of these is as necessary to discuss as the results of the TEA itself Response: There was insufficient time to cover the detailed methodology for each case study presented. The case study details will be available soon in the form of publications, conference presentations, and on the FCIC website. In general, the details were specific to a particular study and looked at feedstock attributes and how they were impacted by the change being studied. For example, the corn stover storage methods TEA case study was based on experimental data that tracked the composition of bales of stover that were covered different and monitored during the storage period. Models were developed using this data and the impacts to cost for storage and transportation from a wider area to compensate for losses of useable material to estimate the changes in feedstock cost delivered to the preprocessing step of the value chain. Other case studies have similar methodology particulate to their area of the value chain.
- Comment: Reviewer is wondering if there is a particular restriction on the overall capital cost of a project, as certain levels of equity are simply not accessible for many plants, even if the payback is there in theory. Response: Although there are no specified limitations on total capital investment to implement a mitigation strategy, we agree that it is an important metric to track and report. We typically calculate the installed equipment cost per unit of production (unit depends on area of value chain). The case

studies are all based on design reports done for BETO that are used to guide the research being pursued. An initial set of assumptions were used in those reports (2,000 dry tonnes/day feedstock, feedstock logistics, preprocessing methods, conversion methods, etc.) to set the baseline estimates for what a process might look like to process that amount of feedstock and what the MFSP would need to be to achieve a target internal rate of return using a common set of financial assumptions. Changes in MFSP will capture if a process change is cost-effective, but access to additional capital to implement a change depends on factors that are outside the scope of our studies currently.

- Comment: The assumptions the model is using for cost of capital, working capital requirements, equipment costs, in-process storage requirements (tankage), and other items would be valuable to improve upon as well as provide the other projects their TEA data to justify their development Response: The modeling assumptions are available in various reports covering each area of the value chain that are publicly available. For ex situ catalytic fast pyrolysis see Dutta et al. (https://doi.org/10.2172/1605092), and for DMR/enzymatic hydrolysis conversion of corn stover see Chen et al. (https://doi.org/10.1186/s13068-015-0358-0). These reports will provide further links to reports for the feedstock collection and pre-processing areas of the value chains.
- Comment: The cost/benefit analysis should have a result that can be shared based on current knowledge and estimates. The basis for MFSP is unclear for fuels such as pyrolysis oil that really have no market and vary greatly by quality. Certain attributes such as oxygen content may make some fuels unsaleable, which may or may not be a part of the model. Response: Our analyses are based on finished fuel blendstocks in the gasoline and distillate boiling point ranges. In the biochemical pathway, there is also a significant contribution from a lignin-derived co-product. The cost to deoxygenate intermediate streams are included in our conversion models.
- Comment: LCA work is not noted and appears to not be funded at this time. Response: LCA work is only planned for the catalytic fast pyrolysis of pine residues value chain due to budget constraints. Because LCA studies are based on the results from TEA case studies (e.g., chronologically), only one LCA study was completed in time for the Peer Review presentation. LCA studies are ongoing and will be available at the end of this year and in the next FCIC research cycle.
- Comment: As we reviewed the other tasks, it is common that the economic benefit of a research proposal or task result is not understood or, at least, not reported. Response: Sharing the results of our TEA/LCA is an important part of our role in the FCIC. Each experimental task had a TEA/LCA component of their research, but due to delays in data (pandemic caused), the TEA/LCAs were not completed in time for other tasks to reference. Task 8 will be providing this feedback during the remaining months of the FCIC and beyond. This is valuable feedback; in upcoming conference and webinar presentations we will integrate TEA/LCA into presentations of FCIC experimental research were possible.
- Comment: It appears the FY21 Case Study for the Pine Residue Pathway (slide 16) will integrate the impact of feedstock variability across the entire process pathway. Determining an estimated final MFSP, comparing the two feedstocks, will provide the biorefinery industry with an understanding of variability as well as the cost to reduce that variability. Response: This is an important series of linked studies. We are excited to get these done and share with external shareholders.
- Comment: The dissention of information as shown in the impact section of the project’s presentation could use more detail. Response: The anticipated dissemination media include webinars, recorded presentations, journal articles, conference talks, trade journals, FCIC website information sheets, etc.
- Comment: Moisture control of stored corn stover is mentioned, but more detail on what is currently happening in both research and industry related to stored corn stover could be useful in supporting the

project's goals. Response: Thank you for the suggestion. We will include this perspective in future case studies and follow-up work.

- Comment: Citing the value chain cost reductions related to corn stover storage options adds value to the project's presentation. Response: We agree. Thanks.
- Comment: Project's presentation does make specific mention that minor improvements to the storage of stover can be accomplished economically. The case studies in the additional slides section lends merit to the project's expected outcomes. Response: We agree. More details for this study will be available in published manuscripts.
- Comment: It was exciting to see the findings of each task translated to an actionable take-home message under the TEA task. This reviewer recommends incorporating the TEA take-home message and Ishikawa relationship diagrams developed under Task 8 into each task's Peer Review presentations going forward, so that the industrial/operational relevance of their work and relationships between CMAs, CPPs, and CQAs are more clear. Response: We have a lot of work ahead of us in this task to tie together all the case studies and develop insights into the next round of experimentation and case studies that would provide the most benefit to the biorefinery industry. Thank you for your suggestions.
- Comment: It's not clear what work is being done for the LCA/environmental impacts portion of the task or methodology, hypotheses, and relevance. From a project management perspective, it would be interesting to know more about the down-selection process and criteria used for determining which case studies are evaluated. Response: Due to budget constraints, our LCA analyses were limited to the forest residues value chain based on catalytic fast pyrolysis and hydrotreating conversion pathway. LCA follows the TEA in the workflow and were not completed in time for inclusion in the presentation. The down-selection process was left out of the presentation to allow time to present an overview of the case study approach being used.

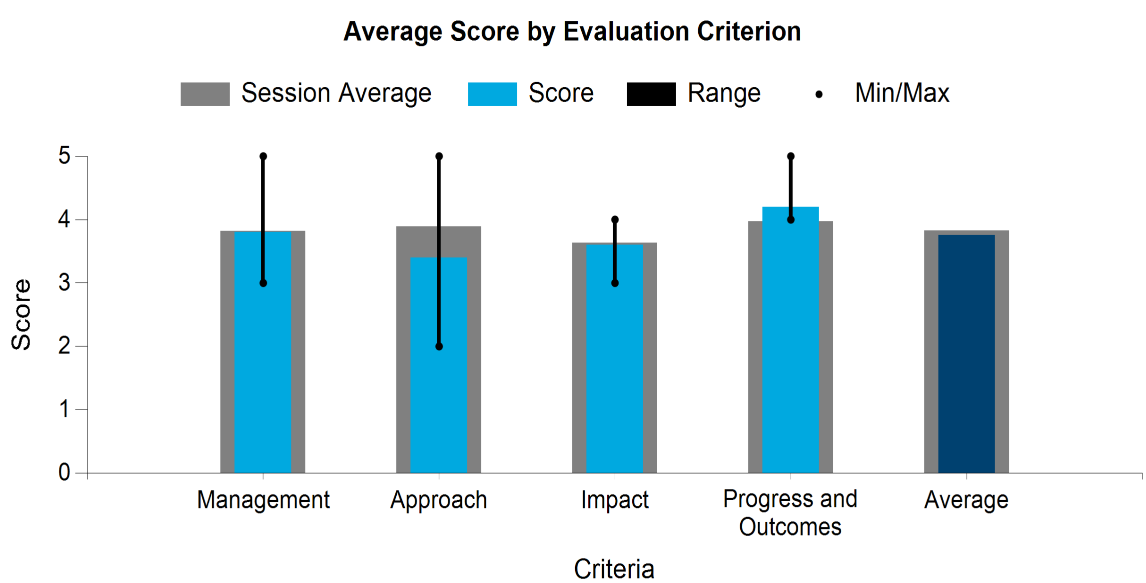
TASK X—PRINCIPAL INVESTIGATOR/PROJECT MANAGER

FCIC

PROJECT DESCRIPTION

WBS:	Task X
Presenter(s):	Amie Sluiter; Ed Wolfrum; Zia Abdullah
Project Start Date:	02/01/2019
Planned Project End Date:	09/30/2021
Total DOE Funding:	$1,381,000

The purpose of the FCIC Task X project is to provide the FCIC with technical oversight and organizational support, ensuring robust operational planning and execution, via a lead principal investigator and lead project manager. This project ensures that each of the nine participating national labs has access to material, information, and resources sufficient to produce and disseminate cutting-edge research. This task also ensures that research is well coordinated between individual research projects and aligned with BETO objectives. To ensure that the FCIC is responsive to industrial needs, the newly reestablished industry advisory board ensures consortium research is relevant to commercial interests and will have a meaningful impact on the biofuels community. This project is responsible for outreach to industrial stakeholders and maintains multiple avenues of communication such as public webinars, an informational website, and a public repository of publications. This task also provides central organization for our QbD framework, organizing, quantifying, and linking critical attributes across the value chain to provide a holistic picture of the impact of variability. The outcome of this project is a consortium that demonstrates scientific relevance, timely output, tools and knowledge that can be implemented in a biorefinery, and actively managed engaged stakeholders.



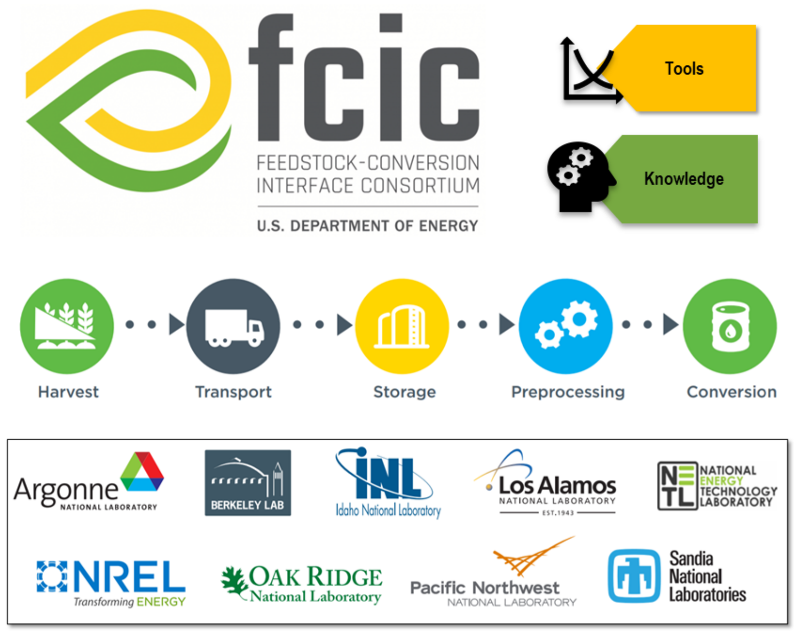


Photo courtesy of FCIC

COMMENTS

- Generally, you cannot argue with the outcomes of the FCIC program so far. The goals have been or are being met, and are on schedule. For the scale of this effort, which is significant, this is impressive but also makes the reviewer wonder whether the goals have been set too low for the team. It would be expected that some goals and deliverables have slipped, but that doesn't appear to be the case. I cannot fault the project management team for this, rather they should be praised, but with such a large task for such an important project, we need to be sure that we maximize our schedule. I would have expected the project manager presentation to be focused more on the management, approach, impact, and progress of the project manager function of the FCIC program. Rather than stating that there is a risk management plan, I would have like to have heard how risks are uncovered, tracked, and (where appropriate) provided with actionable tasks. I would have liked to have understood better how similar tasks are coordinated between projects or how data is gathered from other projects and disseminated to the subject matter experts for evaluation. I would like to know how the project managers are assessing progress during the course of scientific investigation and what metrics they are using to track progress. The outcomes of the project management function are impressive—a website, continued engagement and an advisory board, and most importantly on-schedule accomplished tasks. The project noted in their presentation that the best way of managing the project was by allowing cross collaboration. How this works should be better understood and then managed into future projects. The task of bringing the right feedstock through the plant gate and into the main process at maximum uptime is what I believe the goals of FCIC should be. Although impact of conversion is a logical question to address, this topic area can also distract from the overall goal. DOE rightfully does not pick winners, including feedstock types. However, the majority of research appears to be concentrated on corn stover and wood chips of a particular size. It is not clear whether this focus has come based on request from industry or whether it is based on the billion ton study. Certain past favorite feedstocks, such as switchgrass, were noticeably absent from the research. The measurement methodology of engagement is unclear. Attendance is a small effort that can be made by many parties looking to "green" their marketing by tagging themselves at a meeting. Sole Source Contracts, X-Prize like competitions, and other strategies have not been used to date in this environment. The current status of the 220 attributes for feedstock (or the specific number) needs to be better disseminated to industry. The process or model that causes BETO to name a particular attribute as a CMA should be well understood and verifiable by others. BETO needs to better define what variability causes something to become a CMA from a regular attribute. With each CMA, there needs to be a proposed mitigation plan as well. FCIC does not seem to be actively involved in all of the projects within BETO at this moment. FCIC should be involved in upfront risk analysis of projects as well as assessing the sampling and testing done on other projects for correlations between operations on those projects and their own models. Scale-up risk cannot be validated with the tools available at this time within the BETO organization. Additionally, there do not appear to be any active facilities testing corn stover at a large scale. The projects do not appear to be equipped with an estimate of the cost impact of a particular piece of research, leading the reviewer to question the priority of research at this time. Researchers do appear to be conscious of developing cost-effective solutions, but without an estimate of cost impact, how is this being done? TEA analysis appears to be worked on after the fact, but not upfront.

- The Task X objective is to provide scientific direction and ensure robust planning and execution. The program tasks presentations clearly demonstrate focus on understanding fit within the program organization, execute appropriate communication plans, and strive to meet milestones. The teams are technology focused and have a strong collaborative approach. In reviewing performance against the consortium refocus, the task frequently presented activity supporting QbD and nearly all appropriately apply first principles-based approach. The task addresses variability effects across each effort. The biggest gap is tasks demonstrating understanding of economic impact potential or delivery. TEA is clearly being performed for prioritized cases, but some tasks did not report benefit of that understanding.

- The FCIC program is clearly well-managed. While managing multiple partners is a challenge for any project, it is highly valuable to leverage the expertise and capabilities of a diverse group. I would have liked to see a summary of feedback collected from industry that informed the scientific goals of the research portfolio and set the metrics for "industrially relevant successful outcomes." It's not clear if feedback from enough pilot, demo, and commercial projects has been obtained to define the most pressing feedstock conversion issues for industry. Organizing the individual projects according to the tools and knowledge categories was impactful and appreciated.

- The project appears to have the requisite theoretical management approach necessary for proper execution that should provide for the desired outcome. The project management team of three overseeing the collaboration coordination of up to nine national laboratories could represent a distinct challenge. Mentioned as a challenge in the presentation, it is recognizably difficult to work across four time zones. It is not clear in the presentation what the "unified vision" might be, as it doesn't appear to be clearly stated. The impact of management roles related to the impact mission statement is clearly stated. The Project QbD Tools listed may benefit with the use of MS SharePoint and Smartsheet applications, if available. These tools could enhance collaboration if not already being utilized. The project's use of the new FCIC website appears to offer the necessary attributes necessary for external engagement as listed in the progress summary. Stakeholders in both public and private sectors are clearly identified. Citing industry as the first technical impact is an attribute of this presentation.

- This program is a very ambitious undertaking and is making progress toward creating a repository of information for FCIC. FCIC program management should ensure the results of one task are being utilized by others. For example, no other task appears to be using the material attributes developed by Task 2. Cross-task collaboration is key to the overall success of FCIC. More engagement with companies on the path to commercialization of sustainable aviation fuels and biochemicals is critical to meeting FCIC goals. Reviewing progress using a milestone table or WBS would strengthen the management section. There has been good work on identifying CMAs and CPPs. Adding control limits will increase the value of this approach especially when studying the impact of feedstock variability.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for thorough and thoughtful comments on the project. We appreciate the positive feedback regarding the success of consortium management and output. Below we provide specific responses to some the reviewer's comments:

- "There has been good work on identifying CMAs and CPPs. Adding control limits will increase the value of this approach especially when studying the impact of feedstock variability"; "The current status of the 220 attributes for feedstock (or the specific number) needs to be better disseminated to industry. The process or model that causes BETO to name a particular attribute as a CMA should be well understood and verifiable by others. BETO needs to better define what variability causes something to become a CMA from a regular attribute. With each CMA, there needs to be a proposed mitigation plan as well." This activity is ongoing, and as we identify CMAs and CPPs, we are updating this information for internal use. We will release this information on the FCIC Data Hub later in 2021. Regarding the process or model we use to determine criticality, FCIC researchers are relying on literature information and subject matter expertise. In FY2021, we began investigating Failure Mode and Effect Analysis, which is a well-accepted method used in QbD for analyzing risk. We will be reporting on this work later this year.

- "The majority of research appears to be concentrated on corn stover and wood chips of a particular size. It is not clear whether this focus has come based on request from industry or whether it is based on the billion-ton study." The feedstocks we are currently investigating, corn stover and pine, have been chosen by BETO to allow us to develop tools that can be generalized to other feedstocks. The issues we are investigating for these two feedstocks came from 2016 BETO Biorefinery Optimization Workshop, feedback from our industry advisory board, and lessons learned from laboratory pilot-scale biorefineries at NREL and INL.

- "The biggest gap is tasks demonstrating understanding of economic impact potential or delivery. TEAs are clearly being performed for prioritized cases, but some tasks did not report benefit of that understanding." A predominant goal of the consortium is to disseminate results to industry. Our TEA analyses generally require data generation from several sources, making the TEA results necessarily come after a portion of the experimental work. Readable TEA summaries will be available on the FCIC website later in FY21.

- "FCIC does not seem to be actively involved in all of the projects within BETO at this moment. FCIC should be involved in upfront risk analysis of projects as well as assessing the sampling and testing done on other projects for correlations between operations on those projects and their own models." We thank the reviewer for this suggestion and will work with our BETO sponsors to determine how best the FCIC can support other BETO projects in the future.

- "I would have expected the project management presentation to be focused more on the management, approach, impact, and progress of the project management function of the FCIC program. Rather than stating that there is a risk management plan, I would have like to have heard how risks are uncovered, tracked, and (where appropriate) provided with actionable tasks." As part of the project management strategy, Task X keeps milestone tables and tracks risk. The milestone table was not presented due to length and detail. Metrics for success are identified in each milestone. Risks are identified during meetings and calls, and managed with tracking, Gantt charts, and communication.