FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM

TECHNOLOGY AREA

CONTENTS

INTRODUCTION

The Feedstock-Conversion Interface Consortium (FCIC) is one of 12 technology areas that were reviewed during the 2023 Bioenergy Technologies Office (BETO) Project Peer Review, which took place April 3–7, 2023, in Denver, Colorado. A total of 11 presentations were reviewed in the FCIC session by six external experts from industry, academia, consulting, and other government agencies. 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 the Peer Review website: www.energy.gov/eere/bioenergy/2023-project-peer-review.

This review addressed a total U.S. Department of Energy (DOE) investment value of approximately $33.2 million, which represents approximately 6% of the BETO portfolio reviewed during the 2023 Peer Review. During the Project Peer Review meeting, the presenter for each project was given 10–20 minutes to deliver a presentation and respond to questions from the review panel.

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

BETO designated Mark Elless as the FCIC review lead, with contractor support from Atilio de Frias of Allegheny Science and Technology. In this capacity, Mark Elless was responsible for all aspects of review planning and implementation.

FEEDSTOCK-CONVERSION INTERFACE CONSORTIUM REVIEW PANEL

Name	Affiliation
Mr. Philip Weathers*	Weathers Associates Consulting
Mr. Chris Burk	Lee Enterprises Consulting
Ms. Bryna Guriel	Genomatica
Ms. Vicky Putsche	VLP Consulting Company
Dr. Julie Tucker	U.S. Department of Agriculture Forest Service
Dr. Paul Weider	Retired (Shell Oil)

* Lead Reviewer

FCIC REVIEW PANEL SUMMARY REPORT

Prepared by the FCIC Review Panel

INTRODUCTION

The FCIC is a collaborative program among nine different national laboratories, comprised of nine project tasks and one management task. The strategic focus of the consortium is to develop first-principles-based knowledge and tools to understand and mitigate the effects of biomass feedstock and process variability on biorefineries.

The program starts with the feedstock variability incurred during growth, harvest, and storage through preprocessing and into the throat of both high-temperature and low-temperature conversion reactors. The intent of the project tasks is to develop and implement mitigation strategies and tools to overcome the feedstock- and process-induced variability in the integrated operations of biorefineries.

The program also has crosscutting tasks to analyze the impact of these mitigation approaches on system reliability and process economics, as well as the environmental impacts of the integrated process. Future work will continue to optimize feedstock cost by developing high-value coproducts as well as by reducing the variability. The program also calls for in-line sensors and control logic to reduce the process variability and improve system reliability.

This feedback from the Peer Review panel will discuss how well the strategy has been implemented across the project tasks, the level of involvement of industry and other stakeholders, and the success the program has had in communicating and applying the tools that have been developed. The Peer Review panel will also offer key recommendations on how the program should evolve.

STRATEGY

The FCIC has a clear mission, which is defined as developing first-principles-based knowledge and tools to understand and mitigate the effects of biomass feedstock and process variability on biorefineries. The review panel recognizes that each of the tasks has individual goals and milestones. However, the reviewers felt the overall program lacked measurable goals and desired outcomes. Each individual task demonstrated the impact it had on a specific aspect of performance, but there needs to be a more complete demonstration and integration of the impact on the entire process, from preprocessing to the throat of the reactor. The panel did not observe significant collaboration across the tasks where the learnings from one task were being applied in the downstream tasks. One specific example was the lack of use of the characterization techniques developed by Task 2 in other tasks of the program.

There is a clear need for initial techno-economic models in each of the tasks, as well as interim techno-economic analyses (TEAs), as progress is made in improving operational reliability and minimum fuel selling price (MFSP). The lack of initial and progressive techno-economic models/analysis was identified as one of the primary gaps in assessing and achieving the strategic outcomes desired by this program.

The processes of feedstock growth, harvest, and storage are not adequately addressed in terms of their contribution to feedstock variability. The use of air classification for anatomical fractionation was mentioned in multiple reviews, but it is not clear whether fractionation is an economical way of reducing downstream variability or improving operational reliability. A TEA looking at the economic impact of discarding a significant portion of the biomass or processing the fractions separately would help determine whether fractionation is worth pursuing further.

Storage has been considered in terms of the impact of feedstock degradation, especially in bales of biomass; however, the potential of bale fires in corn stover, as experienced in pioneer biorefineries, necessitates that other storage formats of biomass be considered. Pelletizing and silage-style storage are two possibilities. An initial TEA and looking at technology to lower the cost and improve the life cycle analysis (LCA) of these alternatives should be conducted.

Although the FCIC mission includes the introduction of biomass to the throat of the reactor, this has not been thoroughly addressed. Flow of biomass into the reactor against pressure is an area of concern for biorefineries. The biomass coming into the reactor could be dry or mixed with another medium such as high-pressure steam. This is a technology gap that should be confirmed with industry and potentially added to the portfolio of FCIC tasks.

The review panel noted that the research done by the labs was excellent quality but appeared more academic in context. The FCIC program should be complimented on holding an information session with stakeholders and doing at least one industry survey for high-temperature conversion. To maintain program relevance, engagement with industry and other stakeholders must be an ongoing process. Stakeholder engagement should increase in both depth and breadth. The FCIC Industry Advisory Board (IAB) needs wider participation from biorefineries, technology providers, and the equipment industry. FCIC should consider adding representation from other federal agencies, such as the U.S. Forest Service and U.S. Department of Agriculture (USDA).

The use of additional information-gathering sessions could also help revise the priorities of the program. The program should consider gathering representatives from active biorefinery projects as well as from projects that failed to move to demonstration or commercialization, which could be useful in refining the list of critical priorities. These sessions should incorporate input from the Sustainable Aviation Fuel (SAF) Challenge and Multi-Year Program Plan 2023 (MYPP23) documents. BETO could also consider a coordinator to act as an interface between the consortia (FCIC, Conversion, etc.) and industry to both gather the needs of industry and communicate the technology and tools available at the national labs.

The use of funding opportunity announcements (FOAs) and cooperative research and development agreements (CRADAs) should be strengthened to move FCIC and national lab researchers closer to industry and other stakeholders. Each FOA/CRADA should have a participant(s) from the national labs to transfer the technology and learnings of FCIC and other consortia to the project as well as to identify additional gaps or risks that the national labs should be mitigating. Annual operating plan (AOP) funding could also be used to support researchers visiting biorefinery pilot and demonstration facilities to better understand the issues of operation. Preprocessing and material handling should consider doing experimental verification at equipment vendors' locations.

Diversity, equity, and inclusion (DEI) continues to be a work in progress. The FCIC task teams have tried to put together activities to support the intent of DEI, but the effectiveness varies between the tasks and is clearly challenging when taking a bottom-up approach without upper-level support or drive. The DEI effort needs to be more focused on specific, measurable, achievable, relevant, and time-bound (SMART) goals: for instance, the number of minority interns or postdocs who are part of the team, the percent of funding for minority-serving institution (MSI) researchers as part of the team, the number of field days hosted for science, technology, engineering, and mathematics (STEM) classes at national labs, a community-specific website, and information day events. One suggestion would be to focus DEI activity coordination at the FCIC or BETO management levels. Coordination activity could include setting specific goals and identifying activities and milestones for each of the task areas. A specific presentation of the DEI progress and impact could be part of the Peer Review.

STRATEGY IMPLEMENTATION AND PROGRESS

The funding for FCIC has been supporting the area of feedstock variability, specifically in the area of material handling and flowability. The tasks focused on preprocessing and material handling are most closely aligned with the priority of flowability. In each case, however, the focus is somewhat narrow. Preprocessing has focused most of its work on knife milling, with minimal effort being reported on other methods of comminution. Material handling has focused much of its work on hopper flow, with no studies of material conveyance in pipes, which is a source of concern while moving biomass from one unit operation to another in biorefineries. The panel also noted that significant effort has been spent on anatomical fractionation using air classification. The value of anatomical fractionation in improving the economics or operational reliability is unclear and may not add much value to the strategic goals. As a side observation, anatomical fractionation was tried in the cellulosic ethanol industry in the late 1970s.

The High-Temperature Conversion task has developed first-principles models for particle behavior in the reactor. The work of this task is at the leading edge of the technology. However, the models do not appear to address the introduction of the feedstock into the reactor throat against a pressure boundary, which is a primary barrier to biorefinery performance.

The Low-Temperature Conversion task has developed statistical models to determine the impact of feedstock variability on process yield. Much of the effort to date has been in comparing drought-stressed to non-drought-stressed corn stover, which showed insignificant differences in product yield. The task should demonstrate that their approach can identify differences in feedstock variability that impact process variability and recommend process changes to mitigate these differences.

With the recent publication of the SAF Grand Challenge Roadmap and the MYPP23 documents, the technology managers may want to consider a restatement of the program goals to better align with these recent strategies. This program has the potential to advance the supply, lower the cost, and improve the quality of feedstocks, which can improve operational reliability of biorefineries and lower the cost of SAF. Its goals and funding should support these strategies.

In addition, BETO should encourage direct interaction between FCIC/national lab researchers and industry using FOA, CRADA, and AOP funding sources. The increased engagement with industry, through multiple channels, is perhaps the best way of ensuring beneficial outcomes for both BETO and its industry partners.

RECOMMENDATIONS

- Strategic Alignment
    - Ensure that the mission of FCIC is aligned with the goals of the SAF Roadmap and MYPP23.
        - Focus on increasing the supply, improving the quality/consistency, and lowering the cost of the feedstock going to the biorefinery.
        - Ensure that all tasks are considering the three identified program feedstocks (corn stover, forest residue/thinnings, and municipal solid waste [MSW]).
        - Solicit input/feedback on FCIC activities and strategy from other federal agencies, such as the USDA and U.S. Forest Service.
        - Consider adding purpose-grown energy crops to the portfolio for evaluation.
    - Evaluate the feasibility and economics of pelletizing feedstock.
        - Consider using blended feedstocks of stover, forest residue, and MSW.
        - Focus on lower-cost pelletizing with improved consistency and quality.
    - Integrate FCIC learnings across the FCIC tasks.
        - Utilize the critical quality attributes (CQAs) from Task 2 in the downstream tasks.
        - Expand the work from Task 2 to include the upstream supply chain (growth, harvest, and storage).
        - Establish feedback from the conversion tasks to the upstream tasks to guide the mitigation of challenges and risks identified in the biorefinery.
- Strategic Partnerships
    - Industry
        - Expand the membership of the IAB to include representatives from biorefineries, especially at the demonstration and pioneer scale.

        - Use AOP and CRADA funding to enable researchers or staff to spend time in biorefineries to observe the operating issues firsthand and provide feedback to FCIC and the labs.
        - Fund FCIC/national lab participation in FOAs and CRADAs for pilot, demonstration, and pioneer plants.
        - Fund FCIC staff to work in equipment manufacturer facilities to utilize the models developed by FCIC and run verification on production-scale equipment.
    - Federal Agencies
        - Solicit input/feedback from the USDA and the U.S. Forest Service on improving feedstock availability, cost, and quality/consistency.
- Economic and Environmental Impact
    - TEA/Techno-Economic Modeling
        - Require an initial TEA/techno-economic model (TEM) for each task.
            - Update the models as the tasks progress, and use the level of improvement as interim goals.
            - Include the impact on MFSP and internal rate of return (IRR).
        - Require an initial TEA/TEM for FOAs and CRADAs.
            - Update the models at specified milestones.
            - Include the impact on MFSP and IRR.
        - Continue the application of scenario TEAs (Task 8).
            - Work with industry applications/scenarios to demonstrate the economic benefit of process alternatives.
    - Require LCA goals and calculations for tasks and FOAs.
        - Update LCA models at specified milestones.
- Measurable Goals
    - The overall FCIC program should have measurable (SMART) goals.
        - Progress toward these goals should be part of the Peer Review presentation.
        - Each task should ensure that the goals cover the use of all three feedstocks and consider a broader range of process options (such as multiple methods for comminution in preprocessing).
        - Each Peer Review presentation should discuss the progress in meeting the milestone timeline for the project.
- DEI
    - Consider consolidating the DEI efforts at the FCIC or BETO level.
        - Assign a DEI coordinator to work with the task teams in developing meaningful activities.
        - Give a DEI program update presentation at the Peer Review.
    - The DEI effort should be focused on SMART goals, for instance:
        - The number of minority interns or postdocs who are part of the team
        - The percent funding of MSI researchers as part of the team
        - The number of field days hosted for STEM classes at national labs
        - A community-specific website and information days.

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.

Based on the recommendations from the Fiscal Year (FY) 2021 Peer Review panelists, FCIC (a) implemented more SMART metrics, such as clear 1-year and 3-year outcomes, with an emphasis on examining new feedstocks for production of SAF; (b) continued to develop tools and knowledge for use by industry; and (c) released the FY 2023 CRADA call for more meaningful and diverse industry engagement. The office included many of these recommendations in its guidance and requirements as part of the FY 2022–2024 merit review process.

The recommendations listed above from the FY 2023 Peer Review panelists seek to extend these previous recommendations by aligning FCIC more strategically with the SAF Roadmap, developing more strategic partnerships with industry, further assessing the economic and environmental impacts of the tools developed, continuing to use SMART goals, and engaging in more meaningful DEI efforts, perhaps at the program rather than project level. Our response to these recommendations is given below.

Recommendation 1: Strategic Alignment

The reviewers noted that BETO should ensure that the mission of the FCIC is aligned to the SAF Roadmap and MYPP23. Specifically, FCIC should continue to (a) increase the supply, improve the quality, and lower the cost of producing conversion-ready feedstocks to the biorefinery; (b) ensure that all tasks consider the FCIC feedstocks (corn stover, pine residues/thinnings, and MSW); (c) solicit input from other federal agencies (e.g., USDA, Forest Service); and (d) consider adding a purpose-grown energy crop to the portfolio. The reviewers also noted that the flexibility and economics of pelletizing feedstocks should be evaluated, with blending of the three FCIC feedstocks considered and a focus on lower-cost pelletizing with improved consistency and quality. Finally, the reviewers recommend that BETO integrate the learnings of FCIC across all FCIC tasks by utilizing CQAs from Task 2 in all downstream tasks, expand Task 2 activities to include upstream activities, and establish feedback from the conversion tasks to the upstream tasks to guide future improvements.

BETO concurs with these recommendations. For several years, BETO has emphasized that increasing the supply, improving the quality, and reducing the cost are the three critical factors for producing conversion-ready feedstocks in the Renewable Carbon Resources (RCR) subprogram and will ensure that these critical factors are carried to the FCIC. While the emphasis has been on engaging industry for risk identification and tool development/effectiveness, we will solicit input from other federal agencies for their expertise in handling FCIC feedstocks and purpose-grown energy crops. Blending of feedstocks has not yet been conducted in FCIC, as a focus on individual feedstocks was deemed necessary to improve the conveyance of these feedstocks. Blending is seen as an opportunity to improve quality and/or decrease cost and remains a viable option in the future. In addition, high-moisture pelleting to reduce pelleting cost and improve conveyance has been completed in RCR; learnings from this study are available to FCIC. Finally, all of FCIC has adopted the quality-by-design (QbD) framework, with CQAs guiding the research and development (R&D) of all downstream tasks or hand offs. While upstream factors, such as growth, harvest, and storage, help inform the CQAs identified by Task 2, those upstream factors are considered outside the scope of FCIC and instead reside in RCR. Such factors are transferred to FCIC by core R&D conducted by RCR.

Lastly, the QbD framework has been adopted by other research projects outside of FCIC. For example, fast pyrolysis and sugar pretreatment projects funded in the conversion R&D space are now actively exploring the criticalities of various feedstock impurities to improve the robustness of the processes and catalysts being used.

Many FCIC researchers are involved in other research efforts within BETO and DOE-funded work, and this framework can be shared with those projects to enable their success.

Recommendation 2: Strategic Partnerships With Industry

The reviewers noted that FCIC should seek strategic partnerships with industry and federal agencies. For industry, the reviewers recommend that the IAB should include representatives from biorefineries, expand opportunities for FCIC researchers to visit biorefineries to see firsthand the problems they face, fund FCIC participation in FOAs/CRADAs for biorefineries at various scales, and fund FCIC researchers to work at equipment manufacturers to utilize the models developed by FCIC and run verification on production-scale equipment. For federal agencies, input should be solicited from the USDA and the Forest Service on improving feedstock supply, cost, and quality.

BETO strongly concurs with these recommendations. Each year, FCIC leadership examines the composition of the IAB to make sure that its members can provide insight on emerging areas of interest, and FCIC leadership will consider adding new members to this board with biorefinery experience. The partnerships to date on the previous CRADA calls have yielded high-quality collaborations and afforded opportunities for the consortium to apply the knowledge generated to date with industry. BETO awarded three projects its FY 2023 CRADA call, furthering its pursuit to transfer the tools and knowledge developed by FCIC researchers into the hands of industry. Industry response to this CRADA call was very strong and covered a variety of unit operations and fuel production pathways. The consortium will be encouraged to employ the strategies recommended by the review panel, particularly visiting biorefineries and equipment manufacturers to learn firsthand the issues that need to be solved and the modifications to existing equipment that are needed to better convey biomass. The ultimate objective of the consortium is to disseminate learnings to industry to aid in de-risking processes; success would include vendors and engineering firms using FCIC results to deliver performance-guaranteed processes and investors feeling sufficiently confident in these processes to invest. Finally, BETO has a strong collaboration with USDA, particularly through the Biomass R&D Board Interagency Working Groups on Feedstock Production and Management and Feedstock Logistics. Learnings from these working groups have and will continue to be transferred to FCIC.

Recommendation 3: Economic and Environmental Impact

The reviewers noted that initial TEAs should be included in all tasks and FCIC-related projects. BETO strongly concurs with this recommendation. BETO uses such measures to help direct the R&D of a project, providing economic considerations to inform a down-selection of possible future avenues of research. There are numerous TEAs and smaller case studies that have been developed by the experimental tasks and Task 8 that will be published in the very near future.

The environmental impact of the technology developed by FCIC is also of major importance to BETO. To help decarbonize the aviation sector, the carbon intensity of the processing needed to produce conversion-ready feedstocks that convey well in biorefineries must be kept to a minimum. Advances in unit operations that reduce those operations' energy input are needed to reduce the overall carbon footprint of the integrated system. We will ensure that all FCIC projects from FY 2024 onward will determine the carbon intensity of each unit operation examined for each feedstock. BETO acknowledges that LCA in the consortium up to this point has almost exclusively focused on carbon intensity, and other environmental sustainability considerations (water use, use of hazardous chemicals, emissions) have not been considered.

One such example is the work to evaluate milling energy consumption and associated emissions. The FCIC tasks extensively explored dry versus wet milling, and both economic and environmental trade-offs were quantified. Ultimately, it was determined that wet milling could result in economic and environmental improvements in the form of reduced electricity consumption, reduced particulate emissions, and overall improved carbon intensity.

Recommendation 4: Measurable Goals

The reviewers noted that FCIC should use SMART goals for clear assessment of goal completion. BETO concurs with this recommendation. We will continue the use of SMART goals to track progress more clearly as part of our active project management. We will ensure that future Peer Review presentations will include progress toward these goals and the expected timeline for completing these goals. In addition, BETO will ensure that all three feedstocks (i.e., corn stover, pine residues, and MSW) are represented with a range of preprocessing options for accomplishing each goal.

Recommendation 5: Diversity, Equity, and Inclusion

The panelists recommend that DEI activities should be implemented at an FCIC or BETO level, not at the project level, and that a DEI update at the program level should be provided at future Peer Reviews. BETO strongly concurs with this recommendation and with the proposed SMART metrics for tracking DEI progress. As part of the FY 2024 national laboratory funding cycle, BETO distributed updated suggestions and guidance on DEI activities. The guidance includes considerations and examples across multiple areas that researchers can consider: integrating into existing DEI program participation, opportunities for the research team, and considerations for the research process and outcomes.

In conclusion, FCIC appreciates the expert feedback from our 2023 independent peer reviewers and appreciates the overall sentiment expressed that FCIC is helping solve the conveyance issues caused by poor biomass quality that plagued the pioneer biorefineries. With the recommendations summarized above in hand, BETO will continue to improve the tool set that can be provided to future biorefineries to improve their biomass throughout. BETO looks forward to presenting the results of the FCIC to the public once again in 2025.

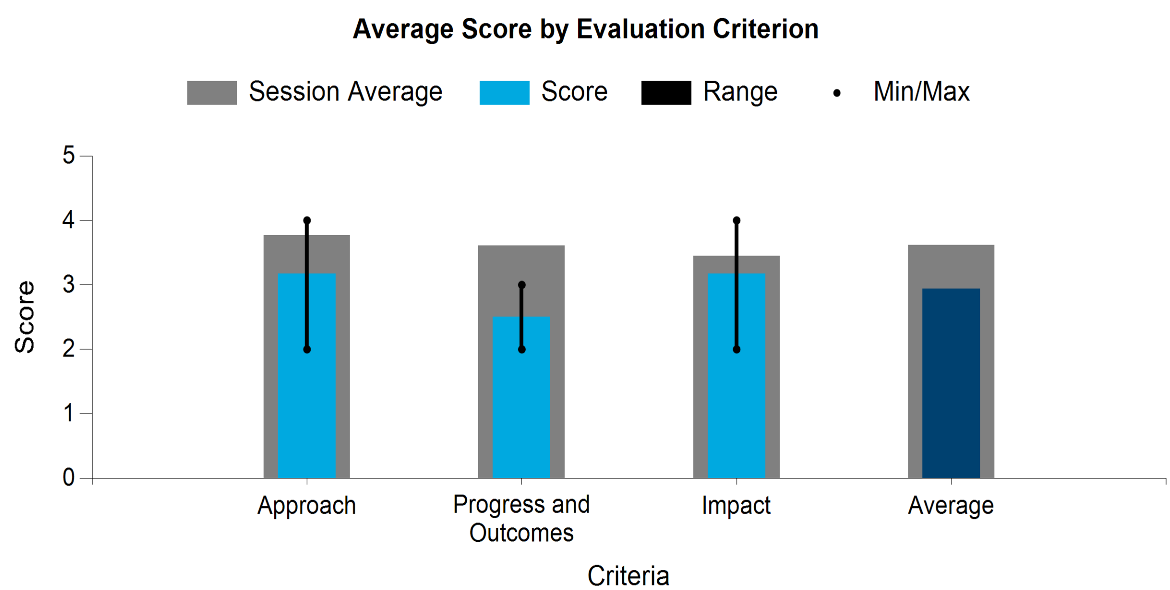
IDAHO NATIONAL LABORATORY DIRECTED FUNDING OPPORTUNITY: REAL TIME, INTEGRATED DYNAMIC CONTROL OPTIMIZATION TO IMPROVE THE OPERATIONAL RELIABILITY OF A BIOMASS DRYER

Idaho National Laboratory

PROJECT DESCRIPTION

WBS:	1.2.2.7801
Presenter(s):	Damon Hartley
Project Start Date:	11/16/2020
Planned Project End Date:	9/30/2023
Total Funding:	$4,018,684

Variations in feedstock characteristics (e.g., particle size distribution, moisture, ash, and heat content) negatively affect the integration of biomass feeding systems and conversion processes and result in low or unreliable onstream time and long start-up times. The main objective of this project is to achieve 90% uptime of our industrial partner's low-temperature dryer and achieve the target reduction of steam exploded wood fiber moisture from about 25% to about 12% (wet basis) before densification through the development of a new, real-time, integrated dynamic control optimization solution. The goal is that the new control system will ensure the reliable, cost-effective, robust, and continuous operation of a low-temperature biomass dryer. The control system will require the development of control algorithms and the integration of various FCIC resources (e.g., sensors, in-line instrumentation, predictive modeling of mechanical behavior of biomass particles, process development unit). Upon the completion of this project, a new, real-time, integrated, dynamic, optimal adaptive control system will be demonstrated, at industrial scale, that minimizes cost while improving operating reliability and throughput and maintaining performance of a low-temperature fluidized bed biomass dryer.



COMMENTS

- The project has a real and clear industrial application; however, the actual scope and impact (cost) beyond the Idaho Forest Group is unclear. The overall TEA and LCA are needed to be able to holistically assess the impact. If successful, this appears to be a reasonable process contribution for a relatively low project cost. It is unclear whether this will be made widely available to industry or only to the Idaho Forest Group.

- The researchers are developing a sensor with the potential to improve the operation reliability of biomass drying. It is great that they are developing it in collaboration with an industry partner. They have clear performance goals for the technology (90% uptime and >90% of material having 12%–16% moisture content), but without knowing the baseline state of the technology, it is difficult to judge the potential for impact.

- The presenter took over the project 6 months ago. The project partnered with a lumber producer, which is a strength of this project. The technical challenges are well- understood and accounted for, especially in the context of operational safety issues with personnel and explosion potential. The project has been very delayed, but has worked to address the factors contributing to the delays. The project is currently not yet achieving the project objective of 90% operational reliability. The project could improve its sharing of lessons learned with industry prior to project end, especially considering that the research was done at an actual forest products facility. At the end of the presentation, the presenter said that a demonstration will occur in Idaho at a facility. This will be an important sharing of lessons learned. The potential for this project to be a significant benefit for industry is great, but the actual benefit currently appears to be low to negligible. DEI was not an objective at the outset of the project, but the presenter indicated that rural communities would benefit from project lessons learned.

- The concept of using process analytical technology to optimize a biomass drier is sound. One can use this as a feed-forward control or a produced product measurement. It appears to this reviewer that the project is significantly behind in its progress and objectives. The instrumentation selected for the measurement has not been proven to be capable of accomplishing the project objectives. The near-infrared technique is a surface technique, and the drying will take place initially on the surface, so measurement after drying is unlikely to be informative of the bulk moisture content—this is exacerbated if the particles are "chip sized." A bulk technique (time-domain nuclear magnetic resonance [TD-NMR] or even air-driven fractionation) would provide a better value than a surface technique. TD-NMR has been applied in the food industry in an online (process analytical technology) basis, but one must ask how much value is captured by making this measurement. Other methods to consider for after drying include midinfrared emissions from the hot particles.

- The project develops a dryer control algorithm to obtain the specific moisture content of the exiting pine particles. The primary control variables are feed rate and firing rate (temperature input). The project has been delayed while implementing additional safety requirements from the industrial partner. Although the project measures particle size distribution, the information is used to detect relative shifts in particle size distribution, which acts as a critical process parameter. The principal investigator (PI) should include risks/mitigations if the combination of feed rate and firing rate proves insufficient to meet the moisture content at an economically feasible output rate. The PI is requesting a 1-year, no-cost extension but has not included a new timeline or milestone dates.

- Approach: The team outlined a plan to develop online instrumentation to ensure the onstream time and moisture content of biomass through a dryer. While feedstock variability and its issues are well known and identified as an issue, the team did not characterize their importance in drying. Biomass drying is conducted in numerous industries and processes, and it is not clear whether the team is improving their drying process or the industrial standard. Although the Idaho Forest Group is engaged in the project, it would have been good to engage one of the many dryer vendors. The type of dryer used, as well as the specifics of the types of biomass for drying, were not included. Will these technologies work as well with other setups? The team addressed DEI, although it was not required, and they have one industry partner.

- Progress: The project has been delayed due to the need for additional safety considerations as well as COVID. The team has done a nice job of adjusting and doing work where and when they can until the safety issues are resolved. The results are still preliminary, so it is difficult to assess whether significant progress has been made. Impacts: Having the control algorithm and interface software for industry could have a significant impact, but assessing the magnitude of this impact is difficult because the team did not conduct any economic or LCA analyses, and, as noted earlier, they did not provide specifics on the failure rate of industry standard dryers. It is unclear whether the protocols would be transferrable to other dryer types, feedstock types, etc.

PI RESPONSE TO REVIEWER COMMENTS

- This project has been significantly delayed due to required safety upgrades and supply chain delays as a result of the pandemic; however, we have been able to develop preliminary modeling frameworks, in the absence of data, that are substantially increasing the speed of advancement that we have been able to attain since the system became fully operational. As for the significance of the project, this project was developed in collaboration with our industry partner, who was having a significant problem with meeting target specifications and maintaining operability of the system. Although the baseline conditions were not directly measured, 90% uptime and 90% of the material meeting outlet specifications will be a substantial improvement over previous operation. However, because detailed information on the initial operation of the drying system was not collected and is not available, any TEA or LCA comparisons would be inaccurate and not appropriate for comparison. Additionally, we recognize the limitations of the sensors that are currently being used, but because the material is blended and homogenized as it is being fed, we feel that the measurements are sufficiently accurate to guide the adjustments of the system. We will also evaluate the accuracy after drying to ensure that the technique used to measure moisture content is accurate, appropriate, and adjusted as necessary. It is possible that there is not enough adjustment in the parameters that we can access to attain the project objectives. If that is the case, then the system will need to be redesigned, and that will be outside the scope of this project. However, even in this case, although the specific model that is being developed will not be directly applicable to other systems, the developed framework will still have wide applicability across different equipment and feedstock types where multiple processing parameters can be adjusted to meet a desired condition.

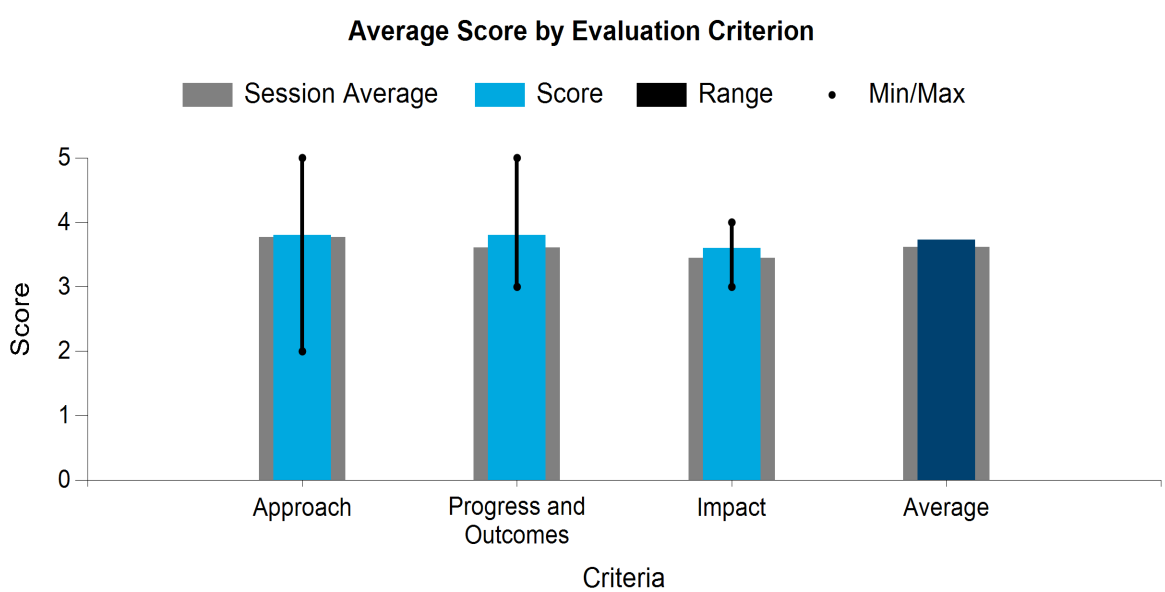
TASK 1 - MATERIALS OF CONSTRUCTION

Feedstock-Conversion Interface Consortium

WBS:	Task 1
Presenter(s):	Jun Qu
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$1,725,000

PROJECT DESCRIPTION

FCIC's Task 1, Materials of Construction, uses a systematic QbD approach with integrated efforts of characterization, modeling, and testing to gain fundamental understanding of the failure modes and wear mechanisms of biomass preprocessing tools. It develops analytical models to predict wear and establish material property specifications, selects and evaluates candidate mitigations based on modeling and lab-scale testing, identifies top-performing mitigation for process development unit validation, and shares the fundamentals and mitigations with the biomass industry. As of today, the team has gained fundamental understanding of the wear mechanisms of both hammer mills and knife mills, developed protocols for extraction and characterization of extrinsic and intrinsic inorganics, constructed analytical erosive and abrasive wear models, identified low-cost feedstock modifications for improving tool life, evaluated candidate tool coatings and surface treatments using bench-scale abrasion and erosion tests, and completed a set of small knife mill validation tests for candidate wear-resistant blade materials with TEA. We are currently developing bench-scale tests to study abrasiveness and fouling for both biomass and MSW and are planning for small shredder testing for validation of candidate wear-resistant blade materials.



COMMENTS

- Wear mechanisms that are based on feedstock variability (one of the main tenets of this overall project) were not well-presented within this task. Even though the wear solutions being proposed are interesting, little information was provided in terms of the overall process TEA or even LCA of these new/other materials and coatings, as IRR is not the best way to express the improvements.

- The researchers did excellent work on this task. In the approach, they clearly articulated the challenges and the metrics (both technical and economic) that they would use to measure progress. I have just one suggestion related to the general approach. It would be useful to see the economic metrics in the context of the larger system. How will these mechanism of corrosion improvements affect the minimum selling price? Also, it seems that the TEM could have been built prior to the research and used to direct efforts. Slide 19 presents a very nice TEA of the knife mill. This approach could be used as an example for other tasks. A few general comments/suggestions: (1) IRR loses its meaning at extreme values, so it's not the right choice to quantify these results. Simple payback period might be a better choice, in addition to percent reduction in minimum selling price. (2) It is unclear which factors are included in this analysis. For example, does it take into consideration production losses due to downtime? Or does it assume that multiple parallel machines alleviate this issue? (3) It would be great to see a tornado diagram showing the relative impact of the various process parameters on economic value metrics. It's great that the researchers made an open-source tool in Excel. I tried to download it, though, and could not get the form to work. Also, the download form requires too much personal information. Name, company, email, and state should be plenty. People shouldn't need to supply telephone numbers or mailing addresses.

- This task focus is much needed; however, it seems that most of the testing research is done in a lab rather than in the field. More of the latter than the former is needed. This task could benefit from working with industry so that most of the testing is done in actual industrial facilities. Testing of the same equipment at different facilities could have more illuminating results. Industry has a lot of operational challenges with equipment wear and tear as well as breakages that this task team could study with industry direction based on what the sector collectively identifies. It was very practical that the research showed higher throughput and lower energy consumption, and it was excellent that diverse costs associated with equipment materials performance were assessed. The material decision matrix will be very practical for industry. It's excellent that the team published an open-source prediction tool. There was no mention of DEI.

- This work is good; it combined solid engineering test data with sufficient modeling to guide the selection of construction materials for knife mills. Real data on the costs of operation of various materials was examined and presented. The results have an immediate impact on plant design and operability prediction for knife mill comminution. Knife mill comminution is one method of particle size reduction, and extension/comparison to other methods is important. I'm looking forward to the results on abrasion and gumming fouling. Extensions of wear and material selection to examining screw feeders (especially against back pressure) are urgently needed.

- The team has completed all the milestones defined in the original project plan. They have identified critical material attributes (CMAs) for feedstocks that impact tool wear rate as well as CMAs for knife mills' materials of construction. They defined three stages of knife wear and developed an Excel-based program for predicting edge recession rates in knife mill cutters. They demonstrated experimentally the improvement in knife wear by applying an iron-boride (Fe-B) coating or using tungsten-carbide (W-C) knives. They conducted a TEA based on a 350-day experimental study showing the advantage of Fe-B coating as well as tungsten-carbide (W-C) knives. However, Slide 19 does not explain why there is such a large difference between the IRR of Fe-B and W-C. It is not clear that the experimental study included feedstock other than "wet, dirty forest residue." Other tasks have focused on corn stover in addition to forest residues. The presentation did not address whether the CMAs change for forest residue versus corn stover or whether the wear model accounts for different feedstock characteristics. The next phase of this project should include additional materials, including corn stover and MSW (planned). The team should engage their industry partners to evaluate the correlation between their model and actual equipment performance as well as doing economic evaluations for their equipment (cost/benefit). This engagement could increase the acceptance of the model and material recommendations commercially. A DEI plan, to be completed by the end of the project, should be added to the milestones.

PI RESPONSE TO REVIEWER COMMENTS

- We truly appreciate the overall positive and encouraging feedback from the reviewers. Comments and questions are answered here.
- Reviewer 1, Q1: Wear mechanisms that are based on feedstock variability (one of the main tenets of this overall project) were not well-presented within this task. Response: The wear mechanisms for various types of feedstocks were investigated in FCIC 1.0 and determined to be strongly correlated to the extrinsic and intrinsic inorganic contents of the feedstock. Results were reported in the 2021 BETO Peer Review and published in a journal paper (https://dx.doi.org/10.1021/acssuschemeng.9b06429). The objectives of Task 1 in FCIC 2.0 are to develop and validate mitigation strategies for the wear issues of feedstock size reduction equipment.
- Q2: Even though the wear solutions being proposed are interesting, little information was provided in terms of the overall process TEA or even LCA of these new/other materials and coatings, as IRR is not the best way to express the improvements. Response: Limited to the 15 minutes of presentation time, we had to skip the details of the TEA process, which were reported in our recent journal paper (https://doi.org/10.1016/j.wear.2023.204714). We agree that IRR may not be the best for presenting the economic benefits of using new tool materials/coatings, because the tool cost typically is not considered a capital investment. This has been clarified in the publication and other measures, including the cost reduction in processing a unit weight of feedstock and MFSP.
- Reviewer 2, Q0: It would be useful to see the economic metrics in the context of the larger system. How will these mechanism of corrosion improvements affect the minimum selling price? Also, it seems that the TEM could have been built prior to the research and used to direct efforts. Response: The MFSP in dollars per gallon gasoline equivalent ($/GGE) was calculated to be $3.42, $3.37, and $3.35 for the baseline, iron-borided, and WC-Co (cobalt-doped tungsten carbide) blades, respectively. The MFSP values were actually presented in the table on Slide 19 of our Peer Review presentation.
- Q1: IRR loses its meaning at extreme values, so it’s not the right choice to quantify these results. Simple payback period might be a better choice, in addition to percent reduction in minimum selling price. Response: We agree and appreciate the suggestion for using the payback period.
- Q2: It is unclear which factors are included in this analysis. For example, does it take into consideration production losses due to downtime? Or does it assume that multiple parallel machines alleviate this issue? Response: Yes. The production losses due to downtime were taken into consideration in the calculation. Limited to the 15 minutes presentation time, we had to skip the details of the TEA process, which were reported in our recent journal paper (https://doi.org/10.1016/j.wear.2023.204714).
- Q3: It would be great to see a tornado diagram showing the relative impact of the various process parameters on economic value metrics. Response: We appreciate the suggestion and will generate a tornado diagram in the future presentation of economic impact.
- Q4: It’s great that the researchers made an open-source tool in Excel. I tried to download it, though, and could not get the form to work. Also, the download form requires too much personal information. Name, company, email, and state should be plenty. People shouldn’t need to supply telephone numbers or mailing addresses. Response: We will try to simplify the download form and add introduction.
- Reviewer 3, Q1: This task focus is much needed; however, it seems that most of the testing research is done in a lab rather than in the field. More of the former than the latter is needed. This task could benefit from working with industry so that most of the testing is done in actual industrial facilities. Testing of the same equipment at different facilities could have more illuminating results. Industry has a lot of operational challenges with equipment wear and tear as well as breakages that this task team could study

with industry direction based on what the sector collectively identifies. Response: We certainly agree with the reviewer. A round-robin type of study with multiple industrial partners testing the same equipment would be very beneficial for understanding the impact of feedstock variability and operating conditions to provide insights for developing more effective and economical mitigations. That would require a collective effort between BETO and industry.

- Q2: There was no mention of DEI. Response: FCIC thrives on the premise that diversity is essential, equity is inherent, inclusion is innate, and accessibility is achievable. These principles guide Task 1's vision to create a welcoming environment that attracts, supports, and inspires a diverse and engaged workforce; fuels its scientific mission and impact; and fosters greater accessibility for diverse communities.
- Reviewer 4, Q1: I'm looking forward to the results on abrasion and gumming fouling. Response: We are currently working on MSW-caused abrasive wear and gumming/fouling and will report in the next Peer Review.
- Q2: Extensions of wear and material selection to examining screw feeders (especially against back pressure) are urgently needed. Response: We fully agree and plan to propose this to BETO in FY 2024 or FY 2025.
- Reviewer 5, Q1: Slide 19 does not explain why there is such a large difference between the IRR of Fe-B and W-C. It is not clear that the experimental study included feedstock other than "wet, dirty forest residue." Response: Limited to the 15 minutes of presentation time, we had to skip the details of the TEA process and feedstock processed, which were reported in our recent journal paper (https://doi.org/10.1016/j.wear.2023.204714).
- Q2: The presentation did not address whether the CMAs change for forest residue versus corn stover or whether the wear model accounts for different feedstock characteristics. Response: Our earlier investigation suggested that the tool wear is more strongly correlated to the feedstock ash content than the type of feedstock itself (https://dx.doi.org/10.1021/acssuschemeng.9b06429). Therefore, the current version of the wear model simply uses the amount of ash as the input. The impact of feedstock type could be added to the model in future development.
- Q3: The next phase of this project should include additional materials, including corn stover and MSW (planned). The team should engage their industry partners to evaluate the correlation between their model and actual equipment performance as well as doing economic evaluations for their equipment (cost/benefit). This engagement could increase the acceptance of the model and material recommendations commercially. A DEI plan, to be completed by the end of the project, should be added to the milestones. Response: We agree and will work on them.

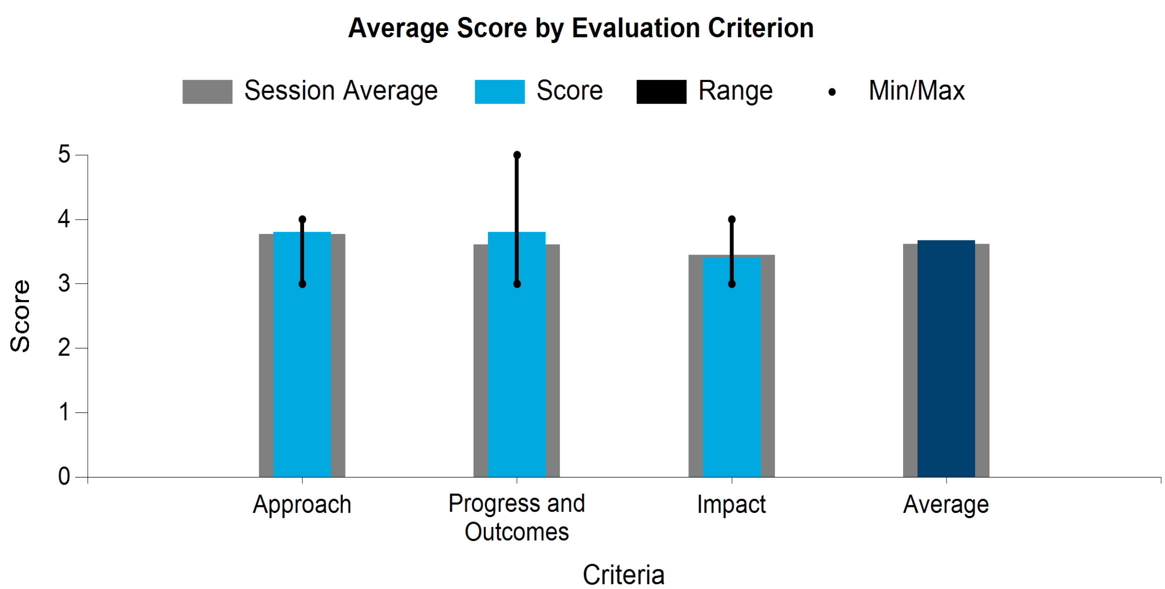
FCIC OVERVIEW AND TASK X - PROJECT MANAGEMENT

Feedstock-Conversion Interface Consortium

PROJECT DESCRIPTION

WBS:	Task X
Presenter(s):	Ed Wolfrum
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$2,150,000

FCIC is a collaborative project among nine different national laboratories, led by BETO, and is developing first-principles-based knowledge and tools to understand and mitigate the effects of biomass feedstock and process variability on biorefineries. The purpose of the FCIC Project Management task is to provide scientific direction and leadership to the consortium and to provide project management to ensure robust operational planning and execution. The key challenges are ensuring superior coordination and communication among researchers across nine tasks and nine national laboratories and ensuring industrially relevant outcomes. We are addressing these challenges by using robust, well-accepted project management tools to ensure good communication among all stakeholders, and by engaging industry in multiple ways to ensure the work we are doing is relevant.



COMMENTS

- The IAB should have more industry and less academia. Overall, the consortia appear to be thoughtfully designed, but the feedback loops between projects, data, CRADA calls, industry, etc., remain unclear. I understand that there are challenges with getting meaningful input from industry. Surveys appeared to be successful in the high-temperature conversion task. I suggest continuing to pursue all avenues for input. The Project Management task is clearly a challenge, with so many tasks and labs doing the work. It would have been helpful to understand how information and data are flowing between projects in order to inform the work being done.

- The plan is strategic and recognizes the need for industry engagement. FCIC should solicit priority needs from key sectors that need more research to catapult feedstock utilization, especially for SAF and biofuels, and support the sectors. FCIC is using diverse communication and outreach approaches via a website, fact sheets, webinars, and case studies to communicate about FCIC work. FCIC should count on this diversified approach but determine which audiences are still not being reached. I would like to hear more about another IAB and how it informs and directs prioritization of FCIC work. When a reviewer asked how the IAB engages with FCIC, there seemed to have been very little engagement recently, and communication primarily flows from DOE to the IAB rather than the reverse. This is a missed critical opportunity. Industry or sectors should be driving the direction of FCIC research. The presenter did not emphasize DEI.

- An overall comment: Presentations in this area tended to be a bit too “information rich”—too much data presented in a short time. The primary messages should be distilled and presented in a more concise manner. There were a tremendous number of acronyms used in these talks, often without definition of what they stood for. The use of QbD)—versus the old-school “product by process” championed by DuPont in the 1960s—can learn a lot by what the commodity chemicals industry handled back then. Anatomical fractionation of biomass has provided some very interesting science and engineering data, but I struggled with how this information will aid in processing or economics. The primary failure in feedstock handling of the pioneer biorefineries was the feed of biomass into “the throat” of pretreatment; this had to do with trying to push biomass into a high-pressure zone and not appreciating the complications that would result. Yet most of the properties presented here neglected the challenge of feedstock introduction into a high back pressure process. The communication of results and industrial outreach outlined in the presentation is critical and should be a two-way street—the programs can inform industry, and industry can refine focus. Related to the FY 2023 DEI plan, I suggest a contact between the National Renewable Energy Laboratory (NREL) and the newly opened Colorado State University Spur campus, where they have focused on water, food, and the environment. They are missing the critical energy component, and this would mesh well with the Colorado State University Spur mission and NREL’s DEI mission.

- The FCIC Project Management task has successfully implemented the QbD terminology across the nine program tasks and has created the common theme of “feedstock variability” across the tasks. The management team has set up a routine communication process among the tasks and across the nine national labs. They are using project management approaches to track the successful and timely completion of all FCIC milestones. They are supporting DEI goals by tracking plans for the tasks as well as having set up a DEI plan for the management team. They have identified key feedback from the 2022 Merit Review and recognized the need to form stronger partnerships with industry as well as continuing strong interaction with the IAB. The management team should help drive industry partnerships across the nine task areas and set goals to create CRADAs with both equipment manufacturers and biorefineries in as many of the task areas as possible. These partnerships will have the strongest potential for commercializing the FCIC technologies. A useful tool for the tasks to use in developing partnerships could be creating a database of companies developing both process equipment and biorefineries, including the technologies being developed and the state of their development. The use of a survey, as was done by Task 6, could be a useful approach. Partnerships with USDA and feedstock suppliers to assist in the reduction in variability from growth, harvest, and storage should be considered, especially for Task 2. Another way to increase involvement with both industry and academia would be to find ways for the various FCIC tasks to be involved in FOAs, especially pilot, demonstration, and pioneer plant FOAs. The management team should continue to focus on improving and integrating the QbD process across the tasks, ensuring the learnings from one task area are applied in downstream tasks. Developing control limits for critical process parameters (CPPs) would be a valuable tool in the operating environment for both preprocessing and biorefineries. A common feedstock suite of corn stover, forest residue, and MSW should apply to all tasks, including both the pyrolysis and gasification pathways of Task 6. As more companies are beginning to commercialize SAF, the team should consider the composition and size of the IAB. In other words, the IAB should include representatives from equipment companies and biorefineries (both low- and high-temperature technologies). The IAB could also act as a gateway to industry partnerships. The management team should also ensure that each of the tasks has completed a DEI milestone as part of their project goal.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their helpful and instructive comments and suggestions. We group these comments into two main opportunities for improvement: (1) increasing interaction with industry, and (2) strengthening our work supporting DEI. To improve our industry interactions, we will add additional industry (rather than academic) members to the existing FCIC IAB in 2023 to get more input at the overall FCIC level, as well as feedback on individual FCIC tasks. We believe the current FCIC CRADA call will provide additional avenues for industry interaction (as of this writing, over 25 industry proposals have been received and are undergoing review). If this CRADA call is successful, we will recommend issuing future calls as other BETO consortia (e.g., Agile BioFoundry, Chemical Catalysis for Bioenergy) have done. We will also develop and implement a plan to reach out to industry stakeholders, including existing BETO FOA recipients, to understand their needs more thoroughly. We will consider using one or more surveys (as suggested by one reviewer) to collect information more effectively. We will also consider developing an industry stakeholder database to understand and categorize specific industry needs that FCIC could address. We agree that our work in DEI needs improvement. We will add explicit consortium- and task-level DEI goals to our FY 2024 work plan to support our end-of-project goals, and we will reach out to local universities later in 2023 to better understand DEI engagement opportunities (as suggested by one reviewer).

TASK 2 - FEEDSTOCK VARIABILITY

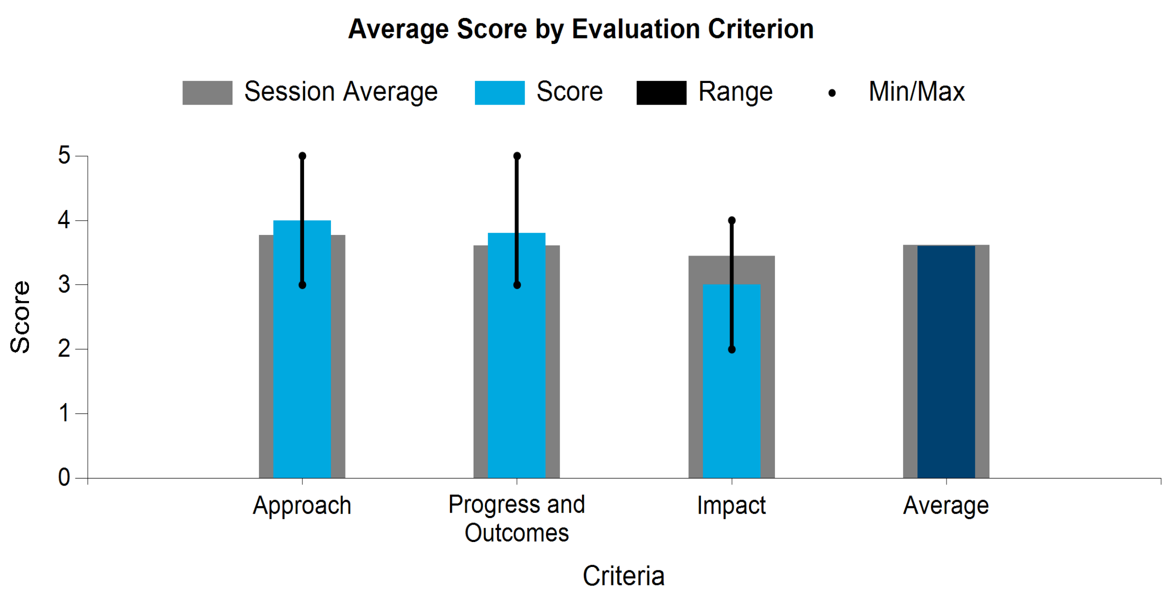
Feedstock-Conversion Interface Consortium

PROJECT DESCRIPTION

WBS:	Task 2
Presenter(s):	Bryon Donohoe
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$3,690,000

The feedstock variability project provides information and tools to detect and quantify initial feedstock material attributes and guide management methods for accommodating feedstock variability.

Lignocellulosic feedstocks are heterogeneous, making bioprocessing challenging. Advanced fractionation methods use chemical and physical qualities and how they vary across scales to optimize feedstock handling and customize pretreatment procedures to feedstock fractions with variable and multiscale recalcitrance factors. Quality and end-user application-specific routes can exploit feedstock variability to extract value from lignocellulosic biomass fractions. The key results from this project cover distribution, sources, and mitigation methods for inherent feedstock features that FCIC has shown to impact corn stover, pine residues, and MSW material handling, preprocessing, and conversion. This data is provided through peer-reviewed articles, trade journal submissions, and interactive feedstock variability models that let users decide whether a set of attribute combinations is useful. This fundamental understanding and characterization tools will help stakeholders establish attribute-driven, feedstock-independent strategies for assessing feedstock quality and choosing process designs that control or accommodate variability from the field to conversion. This information and resources will also enable feedstock valuation by critical attributes.



COMMENTS

- The metrics provided in this approach are very qualitative. The metrics for narrowing the attributes list are not well-defined; these metrics are critical and should be well-informed by industry. There is a good list of industry engagement for this type of work.

- The researchers seem to be doing an excellent job of quantifying and understanding the sources of biomass resource and feedstock variability. This may indeed be high-impact work. Surely some of these tools are more important than others. As a sorting tool, either TEA or interviews with industry partners might be used. Even if it is impossible to quantify impact with any precision, TEA could be used to identify problem areas that might benefit from one of the solutions that the feedstock variability team has developed or has considered pursuing. When narrowing down parameters, the team might consider two groups: (1) tools for routine measurements in design and operation feed systems, batches testing, etc., and (2) "big gun" techniques that might be used by researchers in special circumstances.

- There appears to be a heavy emphasis on corn with some work on MSW and wood, but no explanation for why. A strength of this task is engagement with diverse industries and companies. It would help to know how the team prioritizes which partners to work with. The team should prioritize research on the highest priorities identified by industries that are closest to commercialization or that have greatest potential for largest scale, are most environmentally beneficial, and have climate-friendly outcomes. Variability matters for some feedstock applications but not all. It would be helpful to understand how the team prioritizes which feedstocks need more variability research to advance greater utilization of that feedstock. The forestry sector has a unique need to produce homogeneous feedstock of a specific size and quality for all types of end uses. This task team should consider working with this sector to develop harvesting and in-field processing systems that can easily and economically create a more uniform desired feedstock. Task 2 should continue to publish work in trade journals. This is extremely important and will likely have greater impact than publishing in science journals. It is excellent that this team is developing best practices guides. The team should expand the number and diversity of best practices guidance documents.

- This is a task being pursued with a broad spectrum of analytical technologies that appears to use the best tool for the job rather than just being locked into near-infrared, which is refreshing. There is a tremendous amount of fundamental information presented here, but linking this to "real-world" attributes of biomass feedstock is not clearly delineated. This could just be because there is so much information presented in a short time. For instance, on Slide 21, in a small box on the side, it is noted that "10% increase in lignin => 25% increase in grinding energy" ... This is huge! This needs to be expanded upon, explaining how this is measured and what impact it has on overall processing. There are numerous other process variables other than drought stress to focus on, such as the effect of overfertilization on biomass properties, the impact of high chloride content of soils on biomass chlorine content (critical to both pyrolytic and enzyme processing), and grower-location-driven variation in biomass variability. I was impressed by the TD-NMR work presented and would like to see if this could be applied as an online technique.

- The team has made excellent progress in refining analytical methods for the six CMAs they have defined. They have effectively used these techniques to describe the impact of drought and storage conditions on corn stover. Subtask 2.9 calls for adding MSW as a feedstock for evaluation. Although they have meetings with the other task teams and have published various reports targeting these tasks, it is unclear whether Tasks 3, 5, 6, and 7 are using the six CMAs from this task in their evaluations. Task 7 utilized both drought-stressed and non-drought-stressed stover supplied by Task 2 for their evaluation, but it did not appear that they considered any of the six CMAs in that evaluation. Many of the other tasks are also using forest residue (pine) in addition to corn stover. Adding forest residue as a model feedstock will increase the linkages to the other tasks. Industrial engagement appears to be in the early stages of involvement. Two partners, Alder Fuels and VERDE Nanomaterials, are involved in producing biofuels or biomaterials and could provide valuable feedback on the impact of feedstock on their process. Adding preprocessing and material handling equipment manufacturers as partners would provide another source of input on the importance of these six CMAs. Slide 5 discusses CMA, CPP, and CQA for growth, harvest, and storage. Working with feedstock suppliers from growth through delivery on the importance of the CMAs to downstream processes could help these suppliers find ways to reduce feedstock variability. Overall, the team should look for ways to increase the relevance of their work to the other FCIC tasks as well as industry and demonstrate the advantages of utilizing these methods beyond the traditional compositional analysis.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the reviewers for their thoughtful comments and the time they took to understand our project and recommend changes. We appreciate the compliments on the breadth and depth of the analytical approaches we used to assess feedstock variability. We agree that rating the tools/techniques and reducing the list of attributes to the most important still requires work. We agree with the concept of characterization tools being divided into two groups ("routine" and "big gun"). The downstream study of conveyance efficiency, conversion yield, and TEA are our major criteria for narrowing the attributes list we are investigating. TEA is now being used; however, Task 2 should and will plan to employ industry interviews. We've done more work with pine residue than we've had time to present. Our first findings revealed decreased variability overall, which could be explained by shifting anatomical fraction ratios as the pine trees aged. These findings contributed to a greater emphasis on corn stover throughout the current evaluation period. However, we recognize the importance of broadening and balancing the feedstocks under consideration. We intend to get more involved with forestry and will look for appropriate relationships, particularly in the area of in-field processing technologies. Working with feedstock suppliers on issues ranging from growth to delivery would be another excellent opportunity to discover the significance of material attributes in downstream processes and help reduce feedstock unpredictability. We will begin with supplier interviews and work our way up from there. Determining and relating to "real-world" qualities will continue to be a core problem and fundamental focus of our work in the future. We also hear and understand that we must continue collaborating with the other FCIC activities to increase the relevance of our upstream variability analysis to the downstream conveyance and conversion operations. Finally, we welcome the new sources of variation proposals. This is another topic on which we can get more information from our feedstock supplier interviews.

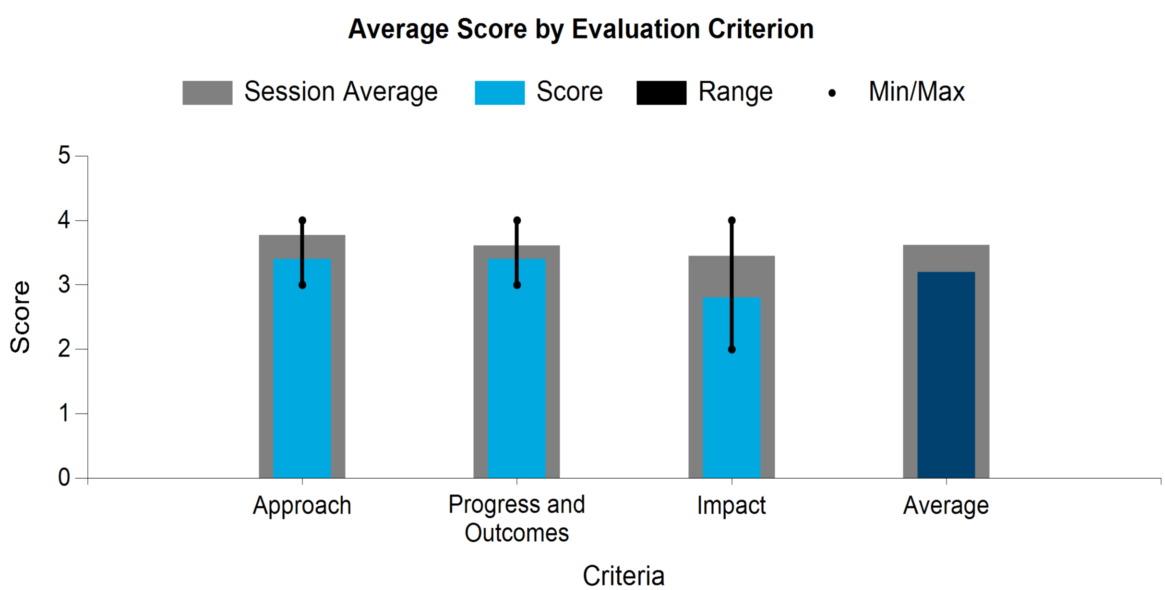
TASK 3 - MATERIAL HANDLING

Feedstock-Conversion Interface Consortium

PROJECT DESCRIPTION

WBS:	Task 3
Presenter(s):	Yidong Xia
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$5,130,000

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 establishing controlled particle and bulk flow tests using industry-relevant biomass feedstocks and for evaluating flow performance under various combinations of CMAs and CPPs; 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; and developing experiment-validated, physics-based continuum-mechanics models for predictive studies of engineering-scale flow performance under relevant combinations of CMAs and CPPs 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.



COMMENTS

- Materials handling is one of the most critical and underestimated aspects of a biorefinery. A widely available simulation tool could hold value to the industry; however, feedback should be requested from users of the models that have been released to assist with continuous improvement.

- The research team has used a first-principles approach to developing several design tools that will apparently be useful to industry. They should consider taking the concept of "impact" one step further, though. For example, one impact statement reads, "For handling operations with a high flow rate, the new model is essential to accurately predict the flow behavior and throughput." The question remains:

What will be the impact of being able to accurately predict flow behavior? In one slide, they present a graph of angle of repose and comminution energy versus nominal particle size. It would be useful and fairly straightforward to put some costs to these numbers. The importance of comminution energy can only be judged in the context of the total energy consumption for the larger process. Similarly, they might try to connect flowability to system downtime and put a cost on that. With the resulting model, they could tune the parameters toward a point or range of optimization.

- This task is more focused on developing tools to ameliorate material flow, but it would be equally impactful to study types of commercially available equipment that improve flow. These types of tests can be conducted at operating facilities, especially with forest biomass of varying size distributions. It is very helpful that this task defines the criteria and scope being used at the outset. It is unclear what is driving this team's focus on the wedge hopper and screw conveyor. Are those industry priorities? Wedge hopper design is an example of the type of work that would most benefit industry, because most material handling is done with commercially available equipment that is then modified when material handling problems are encountered. It is unclear how much testing the team conducts at industrial facilities. The team should prioritize this. The presenter mentioned DEI efforts. The team should continue to hire students from underrepresented universities.

- The approach of this project involves first-principles measurement, linking to real process behavior, and developing distributable computer models to test design. This results in a useful precommercial tool. The slide outlining the comminution energy of the Forest Concept Crumbler to flowability is a significant accomplishment—going from a 6-millimeter to 2-millimeter crumble takes six times the energy! This is critical to TEA and LCA as well as process economics. The stated objective, "develop tools that enable continuous, steady, trouble-free feed into reactors," hits on the critical failure points of the pioneering cellulosic biorefineries. However, the program's progress has taken this through to the "reactor throat" but does not deal with the reactor throat pushing feed biomass into the reactor (against pressure), which is the most critical step and where most failure in operability occurs. This is a disconnect that limits the commercialization impact.

- The team has made good progress on developing models and hopper design charts for granular flow in hoppers and identifying the appropriate CMAs and CPPs. Their implementation strategy is to provide these models as open source with a user manual. They have used lab-scale experiments to verify the flowability and hopper discharge models and created hopper design charts for use by industry. It appears that the experimental work has been completed using lab-scale or Idaho National Laboratory pilot equipment. The project should increase its interactions with industry partners. Creating CRADAs or other linkages with industry partners as they design and test new equipment would enhance the verification of the models and design charts. The quad chart discusses using milled corn stover and corn stover/paper blends as the model feedstock for this task. Adding nonrecyclable MSW and continuing the work with forest residue would provide better alignment with other FCIC tasks and be more relevant to potential industry partners. The modeling and experimental work should be expanded to screw conveyors because there was little information discussing the modeling or design charts of screw conveyors. The team should also survey industry to determine whether there are flowability issues in parts of the process beyond hoppers and screw feeders.

PI RESPONSE TO REVIEWER COMMENTS

- We sincerely thank the reviewers for their thoughtful and constructive comments on this project. Please find below our replies to the reviewers' comments. Interfacing with industry is vitally important to maintain relevant scope. Although interactions with industry have been limited up to this point, this project is developing a strategy to increase such interactions. BETO CRADA projects led by industry partners and supported by national labs, such as through the 2023 FCIC CRADA proposal call, provide a venue to allow national labs to directly engage with industry partners to resolve specific flowability issues at the industrial/commercial scale by leveraging the material handling expertise developed in this project. However, limited interaction does not mean no interaction. In conversations that we have had with those in industry, flowability issues have been identified as a significant problem at industrial/commercial scales. This has led the team to focus on feedstock flow studies based on wedge hoppers and screw conveyors because of the prevalence of these two types of units in industry. The wedge hopper used in this project is a custom design in which the exit opening size and side panel inclination angle can be easily adjusted. The design enables hopper discharge tests to create data for flow charts requiring only one hopper, instead of multiple hoppers with different configurations. The screw conveyor used in this project allows easy change of screw configurations to test for suitable screw designs depending on feedstock properties to avoid jamming or excess energy use. Beyond hoppers and screw feeders, flowability issues have also been pointed out by industry partners to occur in their specific handling units, but often in the units where feedstock flow is primarily driven by gravity. We also recognize that at the reactor throat, flow disruptions due to pressure-driven transport could and often do happen. In the past, this project focused on addressing some of the known challenges, e.g., transport in compressive screw feeders. Beyond specific equipment types, this project is also focusing on a variety of materials. In the third year of the current 3-year project, the team will experimentally and computationally study the flowability of nonrecyclable MSW following previously established research procedures based on granular biomass flow, and will synergistically collaborate with other FCIC tasks, such as Feedstock Variability and Preprocessing. The impact of an accurate flow model to predict flow behavior will de-risk the determination of design parameters of material handling units such as hoppers for industry users. For example, if a flow model overpredicts flow rate at the hopper exit, it could mislead equipment designers into using a smaller opening size than required. A smaller opening size would result in a lower flow rate (lower throughput) or clogging and arching. Since the initial release of these flow models, the project team has continued to improve the models by extending their applicability to material attributes and flow operation units, often upon application of these models to other BETO projects that involve industry partners and their modeling needs for predicting and assessing flow performance of specific feedstock materials.

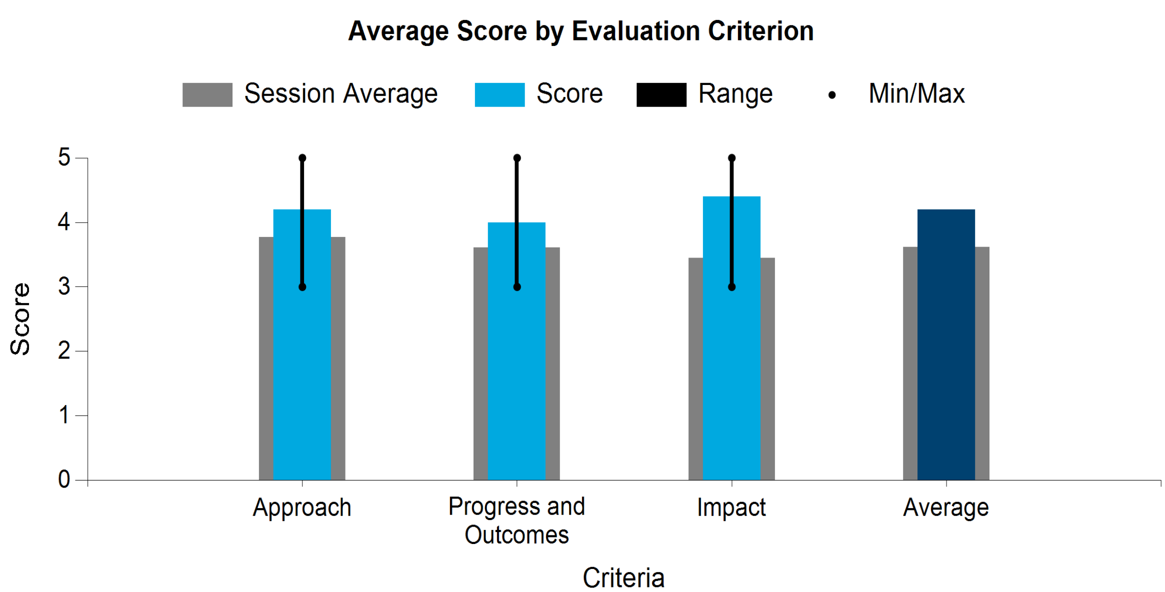
TASK 4 - DATA INTEGRATION AND WEB PORTAL

Feedstock-Conversion Interface Consortium

PROJECT DESCRIPTION

WBS:	Task 4
Presenter(s):	Rachel Emerson
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$1,650,000

The objectives of the Data Integration and Web Portal Task are (1) to provide a web-based collaboration platform and database (the FCIC Data Hub) for integration, preservation, and sharing of FCIC datasets, 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 QbD data table interfaces 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 production of renewable fuels and chemicals benefit from having ready access to findable, accessible, interoperable, and reusable FCIC data and knowledge via the Data Hub web portal.



COMMENTS

- Next to the TEA work, this is likely the next most impactful piece of this work, as it is the actual dissemination of the information being generated next to the available models, though it appears to be delayed until the Data Stakeholder Workshop, which is likely a valuable outreach activity within this work. Creating a user-friendly user interface as well as consistent data and nomenclature are/will be critical to overall success.

- This is a great resource in development. As discussed in the Q&A, it will be critical for BETO to secure long-term funding for it. While I think that this platform will be great for facilitating communication between national lab researchers and industry, I am not enthusiastic about the idea of including a forum or chat feature. There are other platforms that are designed for discussion, so I don't think that FCIC should spend their limited time duplicating that effort. Perhaps there could be a dedicated FCIC subreddit or something along those lines. I work with lots of start-ups to build TEMs for their technologies. NREL TEAs are very important to many of them as sources for base-case process designs, capital expenditure factors, equipment cost correlations, material prices, etc. The start-up community would really benefit if this web portal included that sort of information (e.g., case studies, databases of reference equipment/plant costs, raw material prices, etc.).
- Data integration across disciplines and diverse datasets in one portal will prove to be useful for multiple stakeholders, sectors, and researchers. It is excellent to have a repository of so much diverse research and products. It is very helpful that the database includes journal articles and case studies in the repository. A fair approach and harmonizing data are important priorities to continue. It's impressive that the team already assessed the impacts from and on ChatGPT. The team should consider whether and how to offer a peer-to-peer support communications platform as part of the database, where an online community might emerge for inter- and intrasector cross-pollination. The small team doesn't seem diverse, and there was no mention of DEI.
- I will start by saying that reviewing data portals is outside of my area of expertise. What has been done seems comprehensive and essential. A great invention means nothing if nobody knows about it, so communication should be as quick and broad as possible. The recording of data, methods, procedures, and conclusions is essential to accelerate and maintain a developing industry. Basing the Data Integration and Web Portal on commercial software is a wise decision; leave the software development to experts with a commercial incentive to improve. I would suggest having a messaging or (monitored) chatroom feature so that communication with and between PIs and industry is facilitated.
- The team has developed and deployed the FCIC Data Hub and populated it with QbD data, Task 8 case studies, publications, and presentations. They formed an advisory panel and received guidance on the functionality and content of the Data Hub. The have identified a Data Hub champion at each of the national labs to encourage the use of this tool, and they are working to create standard data terms. The Data Hub has been opened to non-DOE users on a limited basis. The team is currently evaluating the use of artificial intelligence in interpreting FCIC Data Hub knowledge. The team has made good progress on developing and populating the Data Hub. The task has an end-of-project milestone target of at least 100 active commercial users on the system. To achieve this goal, the team should set intermediate, quarterly goals for recruiting and involving active commercial users. The milestone to have 20 non-DOE users is due by March 31, 2023. It is not clear if this is on schedule. Similar goals should be set for researchers, academic partners, and staff. These intermediate goals should be visibly tracked using the User Activity Tracking module that has been developed. It appears that internal use of the Data Hub is behind schedule, as the inaugural Data Stakeholder Workshop scheduled for September 22 was delayed. The presentation mentions that the LabKey software is used in support of DEI in high schools. A more specific DEI activity could be identified for this task.

PI RESPONSE TO REVIEWER COMMENTS

- We are grateful for the insightful feedback from the Peer Review panel and for their service to BETO. Creating a user-friendly interface for the FCIC Bioenergy Data Hub that facilitates industry stakeholder access to harmonized and easily downloadable datasets has been a top priority for our team. We appreciate that bioenergy start-ups rely heavily on TEA models from the national laboratories to create base-case process designs; as such, we will continue to work with the Task 8 (Crosscutting Analysis) team to make FCIC case studies available via the Data Hub. Our use of commercial, built-for-purpose scientific data management and collaboration software for the Data Hub provides new channels of communication with our stakeholders, who now mainly access FCIC knowledge via published journal articles and technical reports. The software includes tools for issue tracking, discussions, and surveys that will help us build an interactive online community of Data Hub users working within the nascent bioeconomy. These innovations will also support greater DEI outreach, as will be emphasized by the Task X leadership team for the FCIC.

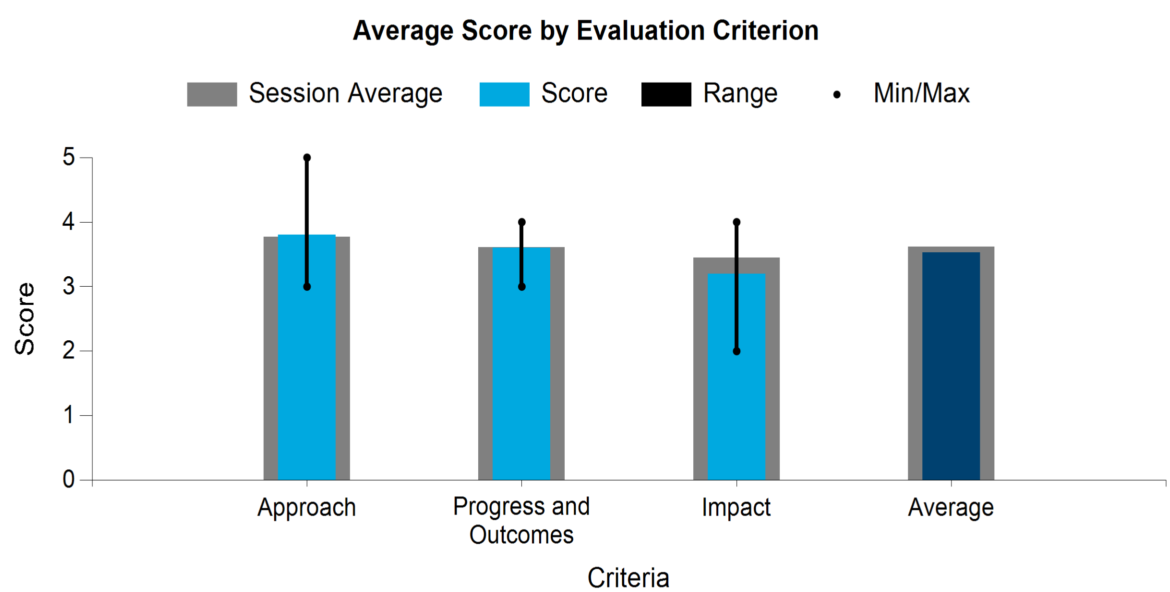
TASK 5 - PREPROCESSING

Feedstock-Conversion Interface Consortium

WBS:	Task 5
Presenter(s):	Jordan Klinger
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$6,225,000

PROJECT DESCRIPTION

The objectives of Task 5 are to develop first-principles-based comminution design manuals and machine-learning-trained process control algorithms to be used by mill manufacturers and biorefineries. Mill manufacturers will be able to develop new mill designs with the manuals to solve issues of fines generation and broad particle size distributions that negatively impact downstream flow and feeding (rat holing, bridging) and downstream conversion processes (over- and underconversion of biomass). Biorefineries will be able to utilize the process control algorithms and code, which analyze photographic images of the processed materials and determine whether they are out of specification in a feed-forward configuration, to adjust mill process parameters to correct the fault(s). Our multiscale approach considers feedstock attributes from molecular structure to bulk particle morphology, which enables identification of relationships between preprocessing and feedstock performance in downstream conversion processes. The external marketing plan for Task 5 involves several areas of focus in the research and engineering community. First is the continued R&D of open-source comminution simulation software and process control software, with ongoing releases (including updates, maintenance, and user-friendliness improvement) and peer-reviewed publications in industry-interested journals, e.g., *Powder Technology*, *Biomass and Bioenergy*, and *Biosystems Engineering*. Task 5's success in continued publications on comminution tools and models and process control software will allow the Task 5 team to disseminate proceedings in professional and trade conferences such as the American Society of Agricultural and Biological Engineers, International Powders and Bulk Solids conferences, and American Institute of Chemical Engineers annual meetings. Through these meetings, the Task 5 team will extend relationships with existing industrial partners (JRS, Forest Concepts) and new partners.



COMMENTS

- The impacts of this work could have cost implications, but this was not addressed in any TEA presented. This task appears to have more collaborators (some potential) than other tasks.
- The stated objective of this task was to "develop science-based design and operation principles informed by TEA/LCA that result in predictable, reliable, and scalable performance of preprocessing unit operations." TEA does not seem to show up anywhere in the work. The work done under this task may be very high value, but we cannot know without putting some dollar signs on it. That said, the researchers on this task seem to have collaborated well with industry partners, which speaks qualitatively to the relevance and value of what they are doing. Energy consumption and material loss are presented as "economic metrics" later in the presentation. These are perhaps "economic-adjacent metrics," but they are not really "economic metrics." An appropriate economic metric for this task (and others) might be something along the lines of "percentage reduction in predicted minimum selling price." This might then be further broken down into improvements due to reduced energy consumption and improvements due to reduced material loss. On Slide 13, the claim is made that the new tools will "allow biorefinery industries to quickly evaluate biomass quality, determine process parameters, and predict plant economics based on feedstock variabilities." It would be helpful for the reviewers (and probably the researchers also) to model a case study of how this would happen.
- This task seems well-organized and has a strategic approach to assessing and improving preprocessing issues. A weakness of this task is the fact that it is not working on several real-world preprocessing problems in the field. Some of the findings are insightful, but little is practical. The team should consider increasing engagement with industry at real facilities. The team should also consider scaling up pilot work to a larger-scale level before investing in even more associated analytical work. The focus is on comminution, which is OK as long as the preprocessing research need is greater for that compared to other preprocessing issues. The plans to incorporate this work into manuals and academic textbooks serve purposes beyond accelerating improvements in preprocessing. The presenter said that the goal is to incorporate the knowledge to diverse audiences, which is good. The presenter showed a slide illustrating the components of an MSW waste stream. Isn't this information already available? Not only that, but it seems little else was done, yet this task is focused on preprocessing. This MSW subtask work seems to have little value or practical application. DEI efforts include diverse initiatives, especially recruiting and job shadowing, which are very important.
- Comminution (size reduction) is one area of biomass preprocessing that has received too little attention. The industry has usually just resorted to hammer milling and "make it as small as we can afford." Thus, a step back to look at the fundamental mechanisms of fracture and size reduction to understand how to intelligently design equipment for a purpose has resulted in valuable modeling/design tools, at least for knife milling. The approach chosen and results presented seem comprehensive. I liked the linkage of micro-indentation studies to biomass bulk properties. There seem to have been a few discoveries *in silico* that have not been confirmed with experimental studies. What is missing here is that there are many different methods to accomplish comminution that rely on fundamentally different methods of fiber deconstruction. This work does not approach the optimization of particles size reduction by reduction methodology selection.
- The team continues to integrate experimental and modeling approaches to provide tools for preprocessing. The use of statistical models has enabled them to run smaller-scale experiments and still provide the verification of their physics-based models. The team has created a matrix of CMAs, CPPs, and CQAs across a variety of unit operations. They have identified mitigations for three primary risks. They are working to provide models for use by downstream tasks, such as Low-Temperature Conversion. The DEI plan of outreach to underrepresented high schools is a good approach for encouraging interest in bioenergy and STEM education. Specific milestones/goals for this outreach would strengthen the DEI plan. The team has made appropriate progress toward their end-of-project

milestone to provide mill manufacturers with design manuals for corn stover and forest residue. Comparing the CQAs across comminution types of equipment (e.g., knife mill, hammer mill, crumbler) to provide biorefineries with the optimum choice of milling equipment for the feedstock they use would be a significant contribution to biorefinery design. More extensive work on MSW is required. Identifying the breadth of MSW composition is needed; for example, are some facilities including organic material such as food waste? The team should consider collecting information from operating plants such as Fulcrum. The use of real-time image analysis is showing the capability of characterizing incoming feedstock to a biorefinery. The team should continue working with D3MAX to apply the technology to their process. Expanding the use of imaging technologies to other downstream processes should be considered, including high-temperature conversion biorefineries. The team has identified numerous preprocessing equipment manufacturers as potential partners for commercialization. More detail on the deliverables of these partnerships would be helpful in understanding the commercialization potential of the tools. Active engagement of additional partners should be considered for the next phase of this project.

PI RESPONSE TO REVIEWER COMMENTS

- We would like to thank the reviewers for their time and feedback on this project. Their thoughtful comments and expertise will guide the work scope development moving forward. Below are responses to select themes in the reviewers' feedback: the incorporation of TEA, seeking additional industrial guidance, and the value of MSW. TEA is a critical tool that should be used at every stage of a process to understand the cost-benefit trade-offs for a particular unit operation and/or process stage. It was an error in omission that the recent case study produced by Task 8 (presented shortly after this task) was not highlighted during this task review as well to show the complete story. During the development of experimental work in this task, for example, relevant pilot-scale process data were collected in the Biomass Feedstock National User Facility at Idaho National Laboratory for throughput and energy consumption of loblolly pine residues being size reduced in a hammer mill. In collaboration with Task 8, the research team collected these data in coordination with other ongoing studies to understand the fracture mechanics of particles as functions of impact velocity (and energy via the rotor speed) and moisture content (impacting the fundamental strength properties and behavior). As a result of this economic evaluation in the context of a high-temperature conversion pathway, we concluded that although pine particles are fundamentally more difficult to fracture and break at high-moisture conditions, milling the feedstock while it is wet resulted in significant cost savings. By staging the milling prior to drying, the overall comminution energy increased by more than a factor of two (from 26.2 kilowatt-hours/dry ton to 59.9 kilowatt-hours/dry ton); however, this increase in energy was dwarfed by the reduction in energy during drying (a decrease from 2,328 kilowatt-hours/dry ton to 1,238 kilowatt-hours/dry ton) through increased drying efficiency and lower entrance moisture. This energy savings represents a feedstock production cost reduction on the order of $17.10/dry ton. Considering the additional quality attributes that can be derived, such as increased overall operational effectiveness and reduction in fines, the base case MFSP dropped from $4.75/GGE to $3.51/GGE. The reviewers rightfully indicate that interfacing with industry to identify current barriers to commercial operations is essential to maintain relevance. Currently, the task maintains ongoing relationships with several comminution equipment manufacturers and feedstock suppliers, and is developing relationships, for example, within in-line vision and characterization companies. The task is continually seeking new partnerships, where possible, to apply the advanced learnings from our diverse preprocessing work to de-risk operation and improve reliability and understanding. For example, since the Peer Review (as publicly announced at the event), the 2023 FCIC CRADA call for proposals saw several new partnerships and connections form within this task. These funding opportunities led by industry provide targeted funding to apply FCIC knowledge and tools to overcome the current challenges and barriers industry is facing. These opportunities have been in the areas of comminution, material separations and variability, and chemical/mechanical deconstruction and fibrillation of biomass for access to carbohydrates and advanced conversion schemes. These real-world problems identified by industry range from very practical choices of selection of mill type to achieve particle size and morphology attributes, to what the impact of feedstock structure is on deconstruction performance and how these native structures, carbohydrate distributions, and fibrillation methods improve access to carbohydrates or formation of nanofibers. Although decisions regarding these engagements are still outstanding, it highlights the myriad industrial engagement opportunities the task can take advantage of in future work scope definition. Similarly, these recent engagements indicate a growing shift in the desire to potentially take advantage of municipal wastes and other waste feedstocks in industrial processes. Although this work scope and strategies are still being developed alongside other funded projects, the fundamental approach of the FCIC at large is needed to understand approaches to waste processing prior to adoption. Due to the availability and collection of MSW, the problem of waste accumulation is imperative across the country but can tend to disproportionately affect rural communities via landfill siting operations and land availability. Actively seeking waste solutions and development of businesses and innovation for these communities can provide strong leverage to address waste, as well as increase DEI and environmental justice. In addition to the current activity, these will be explored in future scope.

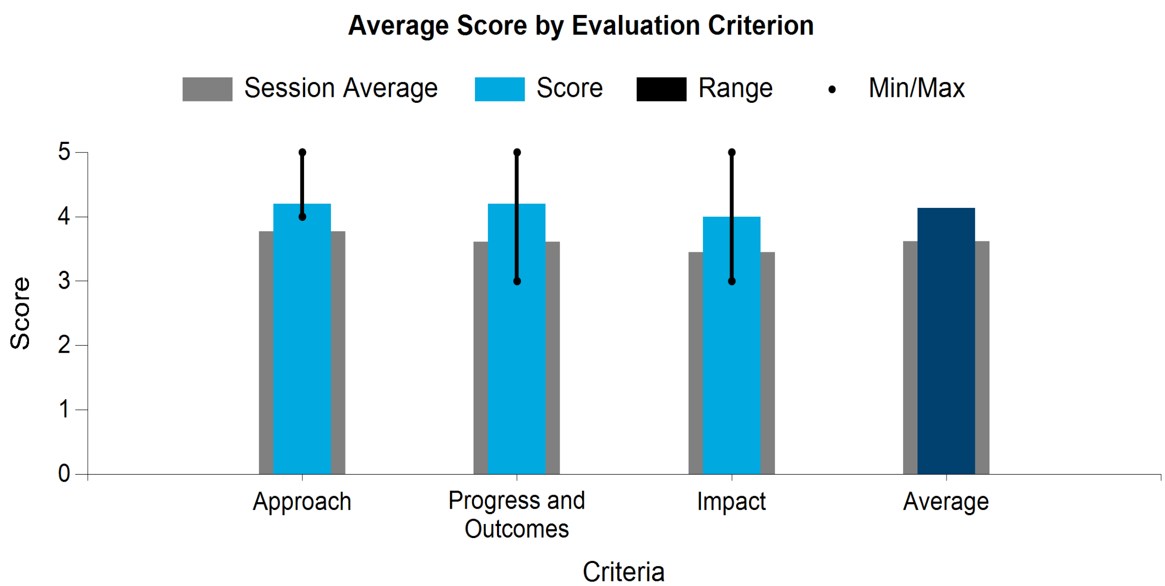
TASK 6 - HIGH-TEMPERATURE CONVERSION

Feedstock-Conversion Interface Consortium

PROJECT DESCRIPTION

WBS:	Task 6
Presenter(s):	Jim Parks
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$5,250,000

FCIC's High-Temperature Conversion Task (Task 6) addresses challenges with thermochemical conversion of diverse feedstocks. Conversion unit operations include fast pyrolysis and gasification. Feedstocks range from complex mixtures of woody biomass (forest residues) to MSW. The research identifies and quantifies the feedstock CMAs and product CQAs, consistent with FCIC's overarching approach embracing the QbD methodology. A primary outcome targeted by the research is experimentally validated computational modeling tool sets that can be used by the bioenergy industry to efficiently scale up and operate bioenergy technologies.



COMMENTS

- Valuable data and models were generated covering both pyrolysis and gasification. There was nice utilization of industry surveys and a summary of feedback on CMAs. It would be good to understand if additional feedback was solicited or received from industry, and if so, what that feedback was. There appears to be a current gap/inconsistency in the validation of the computational fluid dynamics (CFD) gasification model, which has been validated on feedstocks outside of the pine and corn stover that have been the express focus of the consortia.

- The researchers have done very nice and well-thought-out work. They did a great job of bridging the divide between science and industry, e.g., through industry surveys and by developing lower-order versions of their software to be used in Aspen TEA. At the beginning of the presentation, it would have been useful to know the breakdown of the costs typically associated with pyrolysis and gasification. This would have helped put the value and direction of their work into context. The researchers developed a lower-order version of their model for Aspen; they might also consider using their findings to develop an even-lower-order one for Microsoft Excel/Visual Basic for Applications. Reactants might be simplified to cellulose, hemicellulose, lignin, extractives, metaplastics, and water, and products might be simplified to char, oil, and light gases (or something like that). The Excel model could be used to perform sensitivity analyses on the feedstock compositions and yields to better understand the impact of these variables on process economics. An Excel model is also much more accessible than an Aspen model, and it might allow users besides the modelers to have a new window into the process.

- This task is extremely well-organized and presented. The application of the research outcomes for industry needs is significant. The team should continue to research gasification and pyrolysis for forestry feedstock because more research, modeling tools, and data are needed to better understand the conversion rates and economics of forestry feedstock of varying attributes to SAF and other high-value and even lower-value intermediates. It is very good that the team is doing validation at multiple scales. It's unclear why the team measured the breakdown of the forestry residue by weight but didn't measure the British thermal unit/energy value of each component, which is likely more valuable information for a final energy product. The TEA analysis is very insightful. Estimating translatable real-world costs is most helpful. It is fantastic to hear that the researchers reached out to and solicited input from industry leads. They should do more of this as often is practical. This appears to be a very diverse team in terms of gender, age, and ethnicity, which is fantastic. Communication and dissemination of research appears to be sound.

- This is a very difficult area with extremely complex interactions of heat and mass flow, reaction residence time, and many unknown factors. The objective of developing a "multiscale experimental and computational framework" is therefore a daunting task. In the presentation (Slide 18), a "generally good agreement" for model predictions is claimed, but objectively I must disagree with this assessment. If you look at the chart of model mass to experimental mass, there is a definitive skew in the experimental results from the predicted results. Good agreement would require the residuals of the experimental results to the prediction line to be randomly distributed about the line; instead, there is a definitive skew where the model mass fails to track the observed experimental mass (model mass holds at 60%–63%, whereas the experimental mass rises to almost 75%). This type of skew generally indicates something "missing" from the model. The new "micro- and macro-scale instruments" looked intriguing, but we ran out of time to discuss or highlight these.

- The team has made excellent progress in both modeling and experimental verification of the models. The progress is impressive on both pyrolysis and gasification (which was added after the 2021 Peer Review). The modeling efforts range from an extensive CFD model to TEA using Aspen. They have identified critical CMAs through experimentation as well as surveying 28 industry technology providers. They have created a partnership with the Sustainable Energy Research Centre in Italy to obtain gasification experimental results while the NREL gasifier is being recommissioned. The team has completed most of the end-of-project milestones listed in the quad chart and has used the industry technology provider survey to create the initial industry engagement toward commercialization. The opportunities during the second half of this project are:

    1. Develop a plan for addressing DEI in the project.

    2. Develop a strategy to lower the MFSP for both the pyrolysis and gasification pathways.

    3. Develop CPPs for both pyrolysis and gasification.

    4. Include MSW and corn stover along with woody biomass as feedstocks for both pyrolysis and gasification.

    5. Create additional industry engagement by developing partnerships for using the models and knowledge from this project in demonstration or commercialization efforts for both pyrolysis and gasification. Visits and presentations to pilot and demonstration facilities should be

considered. These partnerships could be funded by either CRADA agreements or funding opportunities.

PI RESPONSE TO REVIEWER COMMENTS

- The FCIC High-Temperature Conversion Task (Task 6) team appreciates the feedback provided by the review panel. Several positive comments were provided by the reviewers on the overall high-temperature conversion approach that covers both pyrolysis and gasification pathways. The reviewers complimented our focus on addressing the complex challenges associated with thermochemical feedstock conversion; the multiscale approach that combines both experiments and modeling; the overall approach bridging science and industry-relevant tools and knowledge; the overall outcomes of the project, including the data, models, and tool sets; the communication and dissemination of the research outcomes; the task's industry engagement; the inclusion of TEAs; and the diversity of the team toward DEI goals. We will continue the approaches leading to these positive outcomes. Several comments from the review panel offered valuable constructive feedback, including: (1) quantifying the outcomes of feedstock conversion in terms of energy content (e.g., British thermal unit) in addition to cost, yield, and life cycle carbon; (2) balancing the resource allocation between fast pyrolysis and gasification and providing further breakdown on the associated resource allocation between those pathways in future reviews; (3) pursuing further interactions with industry in the form of site visits and presentations; (4) developing more specific plans for DEI efforts; and (5) continuing the development of low-order models that can be used in techno-economic and life cycle analyses, and even providing more lower-order versions of the models in perhaps Microsoft Excel format that can be used by an even broader range of bioenergy industry stakeholders. This task considers all of these comments as relevant and useful and will incorporate these comments into our future plans. Another constructive comment related to including more feedstocks such as corn stover in the research and including MSW and woody forest residues in both gasification and fast pyrolysis pathways. While the task agrees that more research outcomes for more feedstocks would be highly beneficial, it will be extremely challenging to study all of these feedstocks for all pathways based on the current resources allocated to the FCIC. Nonetheless, this task will continue to develop tools that are generally effective for research of a wide range of feedstocks, and we will incorporate more feedstocks into our studies if additional resources can be made available. An additional constructive and guiding reviewer comment was to develop a strategy to lower the MFSP for both pyrolysis and gasification pathways. This comment is good feedback and challenges the team to go beyond the current status of calculating MFSP for a wide range of feedstocks and to, based on our tool sets, actually define strategies for lowering MFSP. The review panel had one negative comment on the characterization of the agreement between experimental and model results; a reviewer noted "a definitive skew in the experimental results from the predicted results." While we recognize that the agreement between experimental and model results was not exact, our comparison between experimental and model results was obtained by taking a fundamental science-based approach that incorporated extensive feedstock physical and chemical characterization, a chemical conversion kinetic scheme that included 25 reactant and intermediate species and 31 product species, and complete capture of any feedstock particle effects due to size, shape, and even biomass microstructure. By incorporating all these chemical and physical phenomena into our models, we were able to predict the outcomes of experiments very closely for an extremely wide range of forest residue feedstocks. The agreement was obtained without additional model calibration or fitting and demonstrates that our model is robust and capable as a valuable tool to industry despite the vast variability in bioenergy feedstocks. We consider our model as state of the art for fast pyrolysis, and to our knowledge, no other entity has demonstrated such an advanced fast pyrolysis model. Multiple reviewers noted and complimented the utility of the model outcomes, and we seek to improve upon our state of the art. The utilization of these modeling and knowledge outcomes will enable industry stakeholders reduce MSFP for sustainable fuel production in a cost-effective manner. Overall, we appreciate all the feedback from the review panel and look forward to incorporating the guidance as we move forward in the FCIC program.

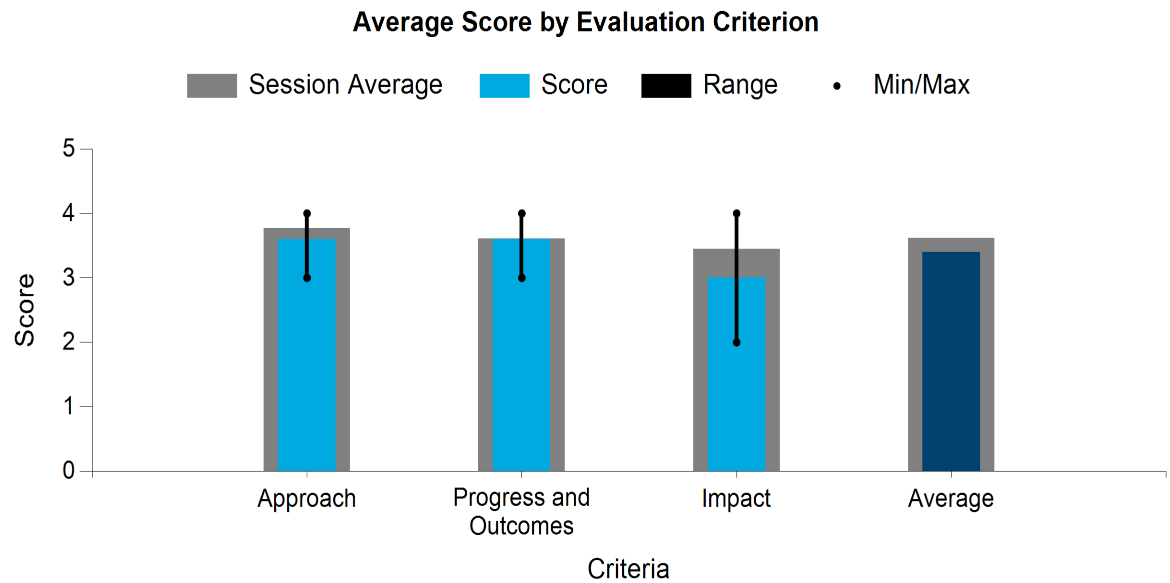
TASK 7 - LOW-TEMPERATURE CONVERSION

Feedstock-Conversion Interface Consortium

WBS:	Task 7
Presenter(s):	Phil Laible
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$3,210,000

PROJECT DESCRIPTION

The objective of this task is to determine the effects of feedstock variability on biocatalytic conversion (by both sugar and lignin pathways) and to develop tools to mitigate the risks posed. Long-term goals are to intelligently operate the sequential cascade of unit operations by understanding critical attributes of materials to adjust process parameters, limit impacts, and maximize feedstock utilization. Researchers are leveraging laboratory data and existing metabolic models to develop an integrated framework that predicts the effects of feedstock variability on microbial conversion performance, by identifying the genetic basis of the effects on conversion efficiency. This knowledge lets these approaches adapt to and/or engineer around attributes of feedstocks that negatively affect conversion. Impacts on productivity and substrate utilization have been observed for feedstock streams derived from both intrinsic and process-derived variability—in many cases differentially for the sugar- and lignin-converting organisms. Operational ranges of critical components in feedstock streams have been determined. These results are the first of their kind to determine the effects of feedstock variability on biological conversion of streams arising from multiple pretreatment/deconstruction operations, driving development of validated modeling tools that can predict performance of new organisms on variable sugar and lignin streams from corn stover.



COMMENTS

- Having a baseline process is valuable, but it would also be extremely informative to utilize a variety of enzyme cocktails to better understand and optimize based on the feedstock input. This task should also consider other potentially viable pretreatment processes (steam explosions, ammonia fiber expansion, etc.). I appreciate that the task, at least visually, showed the interconnection between this task and others on Slide 4. I would have appreciated TEA information and any support on whether there is actual viability in lignin utilization beyond heat/power.

- This presentation was difficult to follow. The approach and progress came across as scattered, and the impact vague. The third bullet point on the impact slide claims that the results of this task “enable sustained high levels of production in low-temperature conversion processes,” but it’s unclear what exactly this means or if something like it has been accomplished. The goals as described on the project overview slide are similarly vague, so perhaps the researchers would benefit from more specific goals to begin with. The presentation mentioned crosscutting/TEA in places, but costs were never mentioned.

- It’s excellent that the team works across multiple consortia and among five different organizations. The narrow focus is acceptable and is likely needed to best leverage resources. It isn’t clear why the team only focused on MSW. The presenter mentioned that the team looks forward to working with bioproducers, but it probably would have been better to do that in an earlier phase. Opportunities for commercialization are far too attenuated at this stage. The team could benefit from industry engagement. The team appears to be diverse in terms of gender, age, and ethnicity. There was no mention of DEI efforts.

- This presentation focused on the impacts of feedstock variation on low-temperature processes for the conversion to SAF. The focus was on drought-stressed versus non-drought-stressed corn stover. The team tested with deacetylation and mechanical refining (DMR) versus diluted acid versus reductive catalytic fractionation and found no substantial difference between drought-stressed and non-drought-stressed stover, irrespective of processing method. Thus, the main conclusion is that drought stress is not really a concern. Although this appears to be a significant relief, it does not show that this research approach can highlight differences in feedstock variability and recommend differences in processing when a real differentiation occurs. This unfortunately dulls the impact of the work. DMR is touted by the federal labs but appears not to be taken up by industry.

- The team has continued to evaluate material attributes for corn stover, focusing on drought-stressed versus non-stressed stover. The results to date show insignificant impact on the utilization of lignin or sugar in product formation, thus de-risking this source of variability for biorefineries. They have continued to use artificial intelligence to “train” their metabolic models to study the effect of material variability on conversion variability, developing significant interaction networks. The team continues to study the impact of corn stover material variability as well as process variability by focusing on understanding the operating ranges of bioprocesses. They are also beginning to characterize MSW. The team states that they will expand DEI outreach through presentations to MSIs and farming communities. Creating some specific end-of-project DEI milestones and goals would strengthen the commitment to this activity. The shift to studying the impact of material variability on operating ranges of the conversion processes would appear to be a valuable next step. The intent to use CRADA and other BETO projects to validate the model predictions, as well as working with industry to evaluate feedstock variability on SAF precursors, would provide the most benefit from this program on downstream processes. Using an industry survey to gather information about which feedstocks are being pursued could be used to expand the work of this task. Engaging industry partners who are developing biorefineries at demonstration or commercial scale should be a priority task for the next phase of this project and should be included as part of the end-of-project goal and milestone. Corn stover, forest residue, and MSW are becoming the standard suite of feedstocks for a number the FCIC tasks. Further development of low-temperature conversion should include forest residues in addition to corn stover and MSW.

PI RESPONSE TO REVIEWER COMMENTS

- We thank the review team for their interest in the work of FCIC’s low-temperature conversion team. We appreciate both their recognition of the success of our approach and their suggestions for improvement.

We agree that this consortium activity should be kept as industrially relevant as possible using a variety of outreach approaches (including new ones like the potential use of an industry survey). We note that (1) the current experimental strategy toward evaluating feedstock variability was supplemented by crosscutting discussions with industrial entities at meetings or in one-on-one interviews at venues (identifying DMR approaches as unrelatable), and (2) these discussions continue routinely with interactions at various institutions (e.g., persistent demonstrations and technology transfers at the Advanced Biofuels and Bioproducts Process Development Unit at Lawrence Berkeley National Laboratory) to inform our technical strategy. We will also use our recently completed report on the impact of feedstock variability in outreach efforts over the next 18 months to increase awareness of our findings and better gauge adjustments to our approach and collaborations (including intergovernmental agencies and academic research teams). We share the reviewers' interest in expanding as much as practicable into additional pretreatment and deconstruction processes (as well as new enzyme cocktails)—especially those that are most recognized and relatable to the biomanufacturing community. These experiments, where possible, will continue to gather data for predictive modeling within Task 7, as well as techno-economic evaluations and LCAs via collaborative FCIC tasks. We also agree that increasing the number of different feedstocks and pretreatment chemistries, including work on sugar and lignin streams from MSW, will strengthen our outreach messages and better position the FCIC for more discussions with a larger audience. We will need to work with FCIC and BETO leadership to evaluate the feasibility of studying forest residues within our current resources.

TASK 8 - CROSSCUTTING ANALYSIS

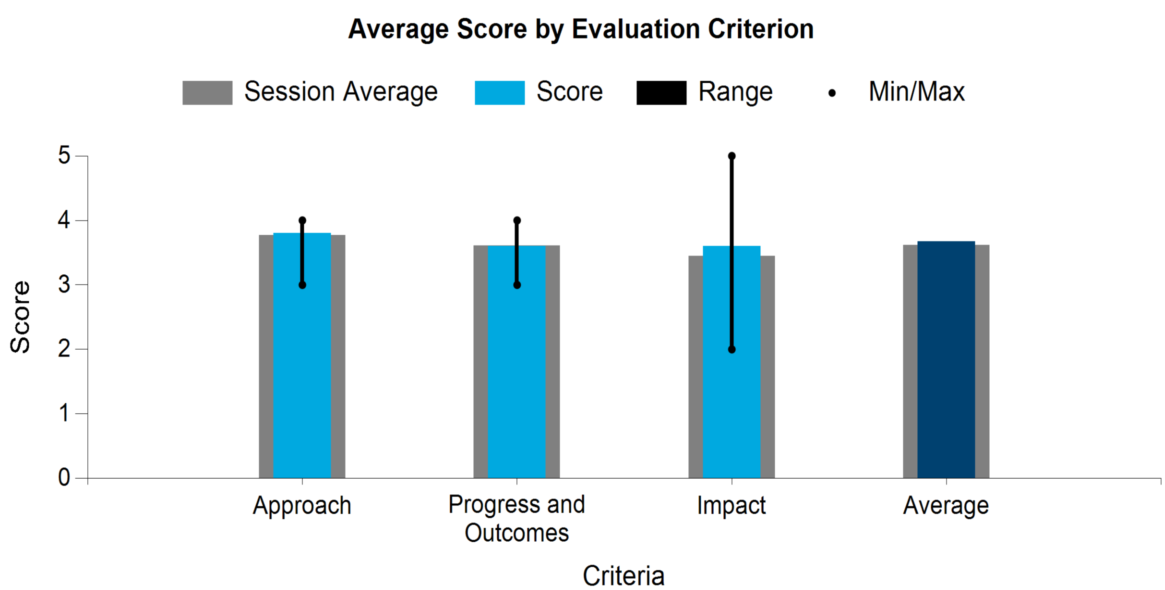
Feedstock-Conversion Interface Consortium

WBS:	Task 8
Presenter(s):	Steven Phillips
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$3,750,000

PROJECT DESCRIPTION

The objective of the Crosscutting Analysis task is to quantify and communicate industrially relevant, system-level cost and environmental impacts for FCIC's discoveries and innovations. TEA and LCA tools are used to evaluate how feedstock variability affects economics and sustainability metrics throughout the biomass-to-fuel value chain. Case studies incorporating information from FCIC experimental research, computational models, and literature into analysis models are used to estimate the impact of process changes and feedstock variability on process economics (e.g., biomass and fuel prices) and life cycle metrics (e.g., greenhouse gas emissions). The scope of work encompasses the field-to-fuel 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.

The case study results provide economic and sustainability information to equipment manufacturers, biorefinery owners, and operators to enable them to make informed decisions about feedstock collection and processing, conversion process design, equipment selection, and business feasibility, including key mitigation steps to minimize or control feedstock variability.



COMMENTS

- This is likely the most valuable task of the overall consortium. The case studies in this task and other tasks largely use TEA to examine the results of work that has already been completed. When used well, TEM is like Google Maps for technology development. Initially, it can help you estimate where you are and how far you are from your destination, and it can help you anticipate the best path to get from one to the other. Then, during the development process, it can be used to assess progress and adjust plans accordingly. I think that the top TEA priority for FCIC (or whatever the right part of the organization is) should be to develop baseline TEMs for a representative set of processes. These need to be models, not reports or "assessments." Initially, the models could be used to develop diagrams and sensitivity analyses to help direct and justify R&D resources. Tornado diagrams would be especially useful for understanding the relative impact of process and economic parameters. When using tornado diagrams in this way, it is important to use actual estimates for worst-case, expected, and best-case values, rather than constant percentage variations. The worst-case/expected/best-case values could be based on data analysis or expert judgment. Ideally, these models should be living documents, representing the best current understanding of the technology. As that understanding evolves, so should the models. Part of the "best current understanding" involves the uncertainty in economic and process parameters. These should be addressed explicitly via sensitivity analyses, e.g., tornado diagrams and the Monte Carlo method. With a more quantitative understanding of the sources of uncertainty, researchers can then make efforts to reduce it by collecting data, making process changes, or seeking out industry input. An additional use of these baseline TEMs would be to test new ideas. If a researcher has an idea for a particular process improvement, the first step might be to mock it up in the TEM. They might then "test" the potential impact of their ideas before ever setting foot in a lab, and in this way, focus their resources on the ideas with greatest potential. If it is possible, I tend to think that these models would be more useful in Microsoft Excel/Visual Basic for Applications. A well-built Excel model is so much more transparent and accessible than an Aspen simulation. The researchers could even make them open source, and perhaps solicit input from the public or other institutions. That said, Aspen simulation or CFD modeling might still be used to inform the coarser parameters used in the Excel models.

- This is a strong collaboration between four organizations, which diversifies approaches and thereby improves depth and breadth of engagement. The team is admittedly less comfortable communicating work to stakeholders. In that case, they should consider hiring or partnering with organizations that are comfortable doing that. Presentations to biorefinery stakeholders are important, but it is equally important to communicate work and share case studies with feedstock suppliers. The cost comparison case study for forestry feedstock is an example of key information that can inform industry decision-making. It is very good that the team is assessing systems and not just individual pieces of equipment. The presenter said that some industry feedback has been that scenarios studied don't represent real-world setups. This suggests a need for this team to engage with industry earlier on and explore opportunities to study real-world systems.

- TEA analysis was a critical parameter that was absent from most of the FCIC presentations. I understand that it wasn't a requirement, but the absence was noted. The TEA analysis of the cost/value of various anatomical fractions (Slide 15) was important and would have been a driving force/double-check on many of the papers presented outlining air-driven fractionation and performance of biomass, notably, that an MFSP of $8.76/GGE is a nonstarter! Given the time allotted for presentation, a comprehensive review of individual projects was not possible. A more generalized vision of how the TEA can be applied consistently across multiple platforms was desired. I believe the TEA should be applied earlier in a research project ("presume success"), and the cost predictions should be allowed to help drive early decision-making among various options—then validate!

- This task has developed an alternative approach to TEA/LCA that focuses on demonstrating the impact of feedstock variability on biorefinery design and operation using knowledge generated by other FCIC tasks. The case studies allow for the opportunity to test different process approaches. For instance, the case studies comparing wet milling to dry milling demonstrate the economic effects on the drying process of changing the preprocessing sequence in the biorefinery. The case studies will be disseminated through FCIC technical reports as well as a two-page summary and lessons learned available on the FCIC Data Hub. The case study on Slide 15 shows the difference in MFSP of processing individual fractions of corn stover compared to processing whole stover. However, it is unclear what impact this approach has on the volume of fuel produced for each fraction. An overall economic impact should consider the volumetric impact from discarding hard-to-process fractions versus processing whole stover, or the total cost of processing each fraction separately and then combining the total volume of fuel. It is difficult to assess progress because the end-of-project milestone only says that the team will publish the TEA/LCA lessons learned. There should be a goal for the number of case studies completed as well as the number of case studies that have gone through FCIC review. There is not a clear path for engaging industry except through publishing the two-page summary on the FCIC Data Hub. There should be a more proactive way of directly engaging biorefineries and equipment manufacturers by demonstrating this approach directly to industry. The team should consider financial measures in addition to MFSP to encourage industry partners to utilize the case study method. The end-of-project goal should include a DEI component.

PI RESPONSE TO REVIEWER COMMENTS

- Thank you for the valuable feedback recognizing the value of TEA in technology development. We agree that TEA serves as a valuable tool for estimating progress, guiding decision-making, and optimizing resource allocation. The reviewers' comments are helpful in clarifying our strategy moving forward. We agree with the need for more agile and transparent models, industry guidance, and consistent sensitivity analyses. Within BETO, there have been more in-depth models for specific pathways from biomass (stover and forest residues) as part of major reports called design cases. The design cases serve as baseline performance based on n^{th} plant TEA with annual periodic "State of Technology" updates to assess the progress toward the n^{th} plant performance. (See https://bioenergykdf.net/content/beto-biofuels-tea-database for a database of models that have been developed.) The design reports use tornado diagrams and sensitivity analyses to understand the impact of process and economic parameters in the models. We will explore opportunities to improve our use of sensitivity analysis in a case study. To the extent that funding is available, we agree that maintaining living documents that follow the evolving technology understanding is crucial. We appreciate your feedback on stakeholder communication and agree that communicating our work to both biorefinery stakeholders and feedstock suppliers is important. We will explore your suggestion of hiring or partnering with organizations experienced in stakeholder communication as a boost to our outreach efforts. We will work on expanding our communication efforts and engaging with industry partners earlier in the process to study real-world systems and improve the relevance of our work. We acknowledge the importance of applying TEA early in research projects and using cost predictions to guide early decision-making. Typically, these early estimates are done by other programs using the design report approach for each of the key areas of the field-to-fuel value chains. We will investigate ways for our TEA/LCA, done in support of FCIC research, to be used as guidance to researchers on key areas of concern and cost drivers in the value chain. We appreciate your input on the comprehensive review of individual projects and will work on providing a more generalized vision of how TEA can be consistently applied across multiple platforms. We agree that considering the volumetric impact and total costs of processing different fractions is important in evaluating economic impacts. We will ensure that we provide a more comprehensive assessment in future case studies. We also acknowledge the need for a clearer path for engaging industry and will explore more proactive ways to directly engage with biorefineries and equipment manufacturers. We will seek assistance in formulating a valuable DEI component to our research.

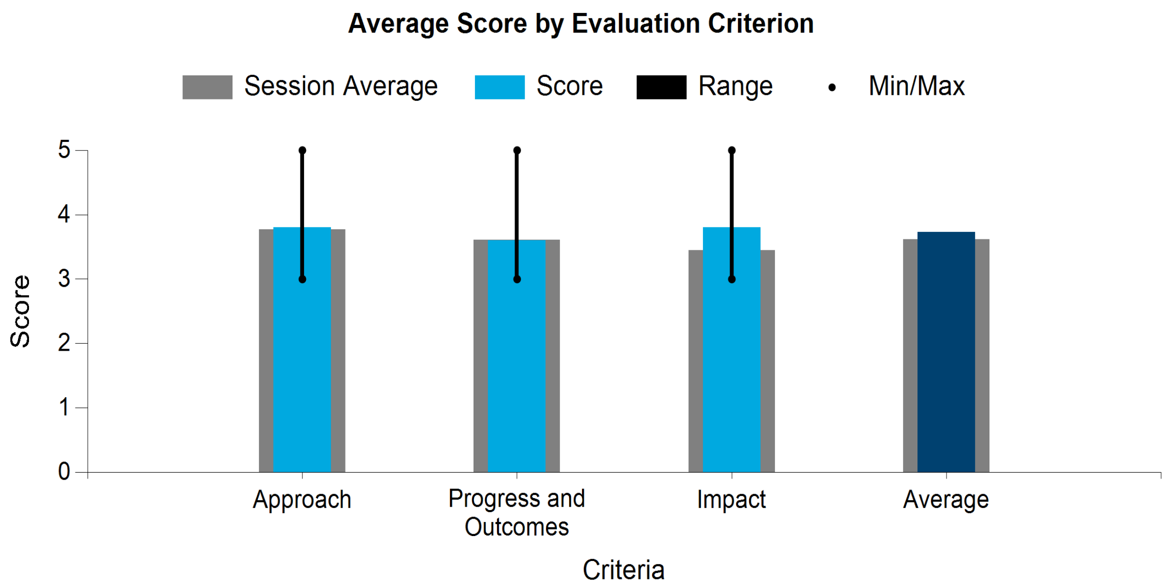
TASK 9 - FAILURE MODES AND EFFECTS ANALYSIS

Feedstock-Conversion Interface Consortium

PROJECT DESCRIPTION

WBS:	Task 9
Presenter(s):	Rachel Emerson
Project Start Date:	10/01/2021
Planned Project End Date:	09/30/2024
Total Funding:	$450,000.

The objectives of this FCIC task are to (1) implement QbD approaches by applying a systematic criticality assessment methodology using failure mode and effect analysis (FMEA), a robust and well-accepted quantitative risk analysis approach, to evaluate preprocessing and conversion unit operations and systems, and (2) develop a framework to track and quantify the criticality of critical material attributes (CMAs), critical process parameters (CPPs), and critical quality attributes (CQAs). This approach will use subject matter experts (SMEs) from Task 5 (Preprocessing), Task 6 (High-Temperature Conversion), Task 7 (Low-Temperature Conversion), Task 8 (Crosscutting Analysis), and industry for FMEA interviews. A semiquantitative scoring system based on the generation of risk priority numbers is used to assess the CMAs, CPPs, and CQAs for key unit operations within the technology configuration pathways of FCIC. The impacts of this research are (1) the development of a systematic methodology for biorefinery risk assessment using a QbD approach, and (2) generation of a database for risk assessment of future simulated system configurations.



COMMENTS

- I appreciate the effort to utilize not only a consistent but also an industry-accepted framework. The task will need to continue to ensure industry input throughout the assessments. This task seems to be right on point in the way it transforms semiqualitative input into a clearly prioritized and actionable list of risks. A strength of this task is engaging with and obtaining information from subject matter industry experts. The downside that there could be bias is a given that is likely outweighed by the collective analyses and insights gained by industry. This task appears to be much more engaged with industry stakeholders than the other tasks, which is much needed. This excellent industry engagement will generate synergies far beyond the scope of this project. This task seems to be a much better investment and return for federal funding than many other tasks.

- Failure Modes and Effects Analysis (FEMA) is well-known to suffer from decision bias from preformed opinions or evaluation conflicts. It is a practiced risk-assessment tool that is continually looking for ways of improving the method. The value of a FMEA depends not only on the SMEs, but also on how well the system being analyzed is defined and the skills of the data collection individual. A postanalysis review is needed to see whether the guidance provided by the FMEA was useful. I was unable to determine whether such a postanalysis was done. Because FMEA is highly dependent on a very specific operation, clear progress to commercialization is not highly transferable, in my opinion.
- The team has developed an excellent survey process for gathering CMAs, CPPs, and CQAs using SMEs for the material and preprocessing operations. They have demonstrated how to use this information to generate a risk priority number to the preprocessing system (material/preprocessing unit operations). They have developed preprocessing system risk priority numbers for pine residue and corn stover using SMEs from the national labs. They are adding SMEs from industry as they expand the FMEA tool to MSW. The abstract for this task and the project goal in the quad chart call for developing a FMEA analysis of preprocessing, high-temperature conversion, and low-temperature conversion. However, the end-of-project milestone calls for completing FMEA on 90% of the material/preprocessing operations. The end-of-project milestone should include the conversion systems as well. Moving forward with the risk-assessment survey for biorefineries is needed to complete the project goal. A specific metric tracking the percent of operations with currently completed FMEA evaluations is needed to track the progress of this task in meeting its end-of-project goal.

PI RESPONSE TO REVIEWER COMMENTS

- We appreciate the reviewers' positive feedback on the use of FMEA as a standardized methodology providing a framework for capturing operation- and system-based risks and their associated critical properties. The concerns regarding potential bias of FMEA and dependence on the knowledge of the SMEs are completely accurate. We acknowledge these as risks and challenges of using this approach and identify these risks within our presentation. We are addressing these risks by using multiple SMEs for each unit operation and/or system and incorporating SMEs from national lab researchers and industry to reduce bias input. We agree with the reviewers that industry engagement is an important and necessary component of this work that we will continue to incorporate into our project. One reviewer identified that our end-of-project goals focus only on completing FMEA analyses on operations and systems in feedstock preprocessing. We acknowledge that conversion should be included in our efforts along with preprocessing. Currently, we have completed FMEA interviews on a select number of conversion area unit operations, and we plan to incorporate more conversion-focused FMEA interviews in the next potential funding cycle.