DOE Bioenergy Technologies Office (BETO)  
2023 Project Peer Review

Bio-oil Co-processing with Refinery Streams

April 4\textsuperscript{th}, 2023  
SDI Project Peer Review

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NREL, PNNL, LANL

This presentation does not contain any proprietary, confidential, or otherwise restricted information
Project Overview

**Objective:** Accelerate adoption of co-processing biomass-derived feedstocks with petroleum streams in operating petroleum refineries to produce biogenic-carbon-containing fuels.

**Expand from** co-processing FOGs (resource < 43 M tons/yr\(^1\)) to lignocellulosic and waste feedstocks (forestry, agriculture, algae, wastes) with a resource of > 1,100 M tons/yr.\(^2\)

**Risks:** Bio-oils are difficult to co-process due to their molecular structure and non-hydrocarbon constituents.

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**Leveraging Existing Refining Infrastructure for Biogenic Feedstocks**

**Biomass/Wastes**

Liquefaction (FP, CFP, HTL)*

**Bio-Intermediates**

Bio-oil, Bio-crude

**Co-processing**

Developing bio-oil intermediates for various insertion points

*FP: Fast pyrolysis oil  
CFP: Catalytic fast pyrolysis oil  
HTL: Hydrothermal liquefaction  
FOGs: Fats, Oils, and Greases

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Multi-pronged approach to address BETO goals and innovation

- FCC and HT/HC process development using **refinery compatible reactor systems** of various scales.

- Refinery compatible, **state of the art catalysts** with industrial partners for FCC and HT/HC co-processing pathways.

- **Bio-oil/Bio-crude production** from various feeds with different techniques and composition.

- **Isotope tracking** to determine biogenic carbon in products and online biogenic carbon measurement (refiner ask).

- Detailed analysis of feeds, products, and catalysts to determine the influence of biogenic feeds.

- **Kinetic modeling** of processes such as hydrotreating.

- **Technoeconomic analysis and lifecycle analysis** to assess process cost and GHG impact.

FCC: Fluid Catalytic Cracking; HT: hydrotreating; HC: hydrocracking
Existing Challenges:

- A critical **operability risk** comprising long term process stability around catalyst deactivation and fouling of feed systems and during operation.
- A **regulatory risk** comprising the need to rapidly measure biogenic carbon and oxygenates in process streams and products.
- A **knowledge risk** centered on the lack of co-processing data including feedstock compositions and contaminants, product compositions, reaction kinetics of unique bio-compounds, and associated TEA/LCA.

Mitigation Strategies:

- Quantify biomass contaminant impact to catalyst stability (i.e., K, S, N)
- Track contaminants in bio-oils/bio-crudes
- Develop deployable biogenic carbon tracking
- Reactor model modification to improve prediction
- Process improvements assessed via TEA/LCA and refinery impact analysis
Management Plan – Communication and Collaboration

1 – Approach

Wood, Herbaceous, WWTP Sludge, Algae

5 Tasks across 3 National Labs

1. FP, CFP (NREL) HTL (PNNL)
2. FCC (NREL)
3. HT/HC (PNNL)
4. Biogenic Tracking LANL, PNNL, NREL
5. Process TEA, LCA (PNNL, NREL)

Industrial Advisory Board (IAB)

BASF Kern Energy
BP Parkland Refinery
BTG Phillips 66
CARB Preem
Chevron Suncor
ENSYN U. Brit. Columbia
Exxon Mobil U. Of Calgary
Honeywell/UOP WR Grace
Johnson Matthey

External Partners
- Johnson Matthey
- Grace
- Topsoe
- Utah State U.

Diversity, Equity, and Inclusion
- Trainings on DEI, hiring, partnerships
- Internships for underrepresented students pursued
- Workshops on Partnerships with Minority Serving Inst.
- LDRD-funded Energy Justice analysis

14C Analysis
- Beta Analytic
- LLNL (14C), UC Irvine
- CEC, CARB*

* California Energy Commission California Air Resources Board.

DEI efforts not part of 2021 AOP, but ramped up since 2022.
### Progress for Addressing the Co-Processing Project Goals

#### Feed Quality/Consistency
- Measurements on bio-oil/crude properties and liquid products
- Quantified and tracked contaminants

#### Biogenic C incorporation
- Demonstrate significant incorporation of biogenic C by FCC and HT/HC
- Extended to other feeds, catalysts

#### Impact to refinery process
- Impact of co-processing to FCC and HT/HC chemistry and kinetics (S, N removal and distillate yield; actual feed and model systems)
- Impact to fuel quality
- Determined impact to catalyst (lifetime), $H_2$ consumption, and reactor
- Modified reactor model based on kinetic measurements

#### Biogenic carbon tracking
- Further improved isotope methods ($\delta^{13}C$ and $^{14}C$ LSC) at reduced costs.
- Improved accuracy and relevance to difficult samples

#### Benefit to refinery and bio-refinery
- TEA and refinery impact analysis
- Provided updated yield data and composition for TEA models

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2021 Peer Review
Current
Various CFP Oil Production for Further Co-Processing

**Goal:** Produce/acquire a variety of bio-oils for optimizing the properties for co-processing. Properties include oxygen content, moisture, and viscosity.

DCR (Davison Circulating Riser) for upgrading FP vapors without hydrogen using zeolite-based catalysts produces bio-oils with significantly less oxygen.

Study the impact of different bio-oils on co-processing. Bio-oils with lower O improve storage/transport and compatibility with refinery infrastructure.
Three different bio-oils (5 vol%) were recently co-processed with Vacuum Gas Oil (low-S VGO) in a Davison Circulating Riser.

Oxygen contents of oils were between 20 and 39%.

Two different catalysts were used.

Yields were comparable with VGO-only.

Oxygen in product was 1-2.5%.

Relative biocarbon incorporation was improved by adding JM CP758 catalyst.

The type of bio-oil can be chosen by refiners depending on their configuration and specifications.
High Incorporation of Biogenic C and Tailoring HT/HC for Product Distribution

### Evaluating various feedstocks and HT/HC insertion points

<table>
<thead>
<tr>
<th>Co-processing Unit</th>
<th>Woody FP bio-oil</th>
<th>Woody CFP bio-oil</th>
<th>Sewage Sludge HTL biocrude</th>
</tr>
</thead>
<tbody>
<tr>
<td>SR Diesel HT / VGO mild HC</td>
<td>SR Diesel HT* / VGO mild HC*</td>
<td>SR Diesel HT / VGO HC*</td>
<td></td>
</tr>
</tbody>
</table>

### Bio-C incorporation in fuel products

- 60-80 %
- 80~90%
- >95%

### Challenges

- Instability
- Fuel quality
- Water and oxygen
- Fuel quality
- Instability
- Water and oxygen
- High N
- Inorganics
- Reactive oxygenates

### Mitigation

- Bio-oil stabilization or fractionation
- CFP process modification
- Preconditioning
- HT-pretreatment
- Guard bed

### Sludge HTL biocrude (5%) and VGO co-processing

- at different conditions and catalysts

*Preferred insertion point; SR: straight run; # Bio-carbon yield in 5-20 wt.% blending.

- High biogenic carbon incorporation demonstrated for woody CFP bio-oil and HTL biocrude – including pretreatment to mitigate high nitrogen issues of bio-crude.

- Tuning HT/HC process to enable co-processing various bio-oils/bio-crudes and producing desired fuel products
Mitigating the Impact on Chemistry and Catalyst

Impact on Hydrotreating Chemistry

- Kinetic measurement
- Reactor model

Impact on Catalyst Stability

- Catalytic Activity
- Spent catalysts after >300 h testing

Kinetic-based reactor model for co-processing developed, enabling predictive capability

Mitigation plan identified for catalyst deactivation from co-processing HTL biocrude
LSC $^{14}$C for Tracking Biocarbon in Co-Processing

1. Clear fuels

Jet fuel (0-10% biogenic content) Biodiesel

Optimized data range, counting time, and data interpretation. Achieved +/-0.4 % points relative to ASTM 6866 ($^{14}$C AMS) in the range of 1-10% biocarbon.

2. Lightly colored fuels (diesel)

Decolorization Adsorbents

Decolorized fuels can be analyzed in LSC, but decolorization reduced biogenic carbon.

3. Dark fuels and solids (bio intermediates and feeds)

CO$_2$ Conversion Oxy-combustion

CO$_2$ capture In absorbent/scintillate

LSC $^{14}$C method can be used for quantifying biogenic C in clear and dark fuels from co-processing.
Biocarbon Determination of Solid Biomass and CO$_2$ Gas Samples by LSC

### IAEA-C3 standard cellulose

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Saturation rate</th>
<th>Carbon mass (g)</th>
<th>Bio C%, LSC</th>
<th>Bio C%, AMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>IAEA-1-0809</td>
<td>37.56%</td>
<td>0.238</td>
<td>130.87</td>
<td>129.41</td>
</tr>
</tbody>
</table>

### CO$_2$ standard gas samples

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Tank CO$_2$</th>
<th>Tank 1 CO$_2$ (g)</th>
<th>Tank 2 CO$_2$ (g)</th>
<th>Saturation</th>
<th>Bio C%, LSC</th>
<th>Bio C%, AMS</th>
</tr>
</thead>
<tbody>
<tr>
<td>T1T2-1-0630</td>
<td>Tank 1 &amp; 2 CO$_2$</td>
<td>0.483</td>
<td>1.739</td>
<td>89.22%</td>
<td>76.9</td>
<td>75.9</td>
</tr>
<tr>
<td>T1T2-2-0630</td>
<td>Tank 1 &amp; 2 CO$_2$</td>
<td>1.136</td>
<td>1.035</td>
<td>89.29%</td>
<td>48.1</td>
<td>47.3</td>
</tr>
</tbody>
</table>

CO$_2$ conversion method with LSC enables low-cost biocarbon tracking with good agreement with AMS.

Developing Online Biogenic Carbon Tracking Method Based on Tunable Infrared Laser Direct Absorption Spectroscopy (TILDAS)

TILDAS can be a low-cost, fast, and precise method for biogenic carbon tracking, via $\delta^{13}$C approach, including online measurement.

No statistically significant difference exists between results from TILDAS and IRMS.
3 – Impact

Commercialization Potential of Co-Processing on Biofuels Production

- **Refinery Capacity**
  - Diesel hydrotreaters (diesel mode) 70 BGal/yr
  - Distillate and/or gas oil hydrocrackers (jet mode) 37 BGal/yr
  - Fluid catalytic crackers (fuels and chemicals mode) 85 BGal/yr

Co-processing at 5% would allow > 7.5 BGal/yr bio-fuels from 140 Mt/yr of biomass.

- **Specific to SAF 2030 Goals**
  - HTL of wet waste (sludge, food waste, manure)
    - 77 million dry tons feed; 6.8 BGal fuel; **1.4 BGal SAF** (20% in jet range)
  - Lignocellulosic (forest waste, agricultural residues)
    → Gasification – Fischer-Tropsch synthesis
    - 27 million tons feed; SAF: 0.6 BGal (direct) + **0.3 BGal (wax upgrading)**
    → Pyrolysis (CFP/stabilized FP)
    - 53 million tons feed; **0.6 BGal SAF** (co-processing)

SAF of 2.3 BGal/yr, using currently available feedstocks, through FCC/HT/HC co-processing.
• Project directly supports BETO’s mission of reducing GHGs by transforming biomass into refinery integrable biofuels (jet, diesel, gasoline).

• Addresses a critical need for conversion enabling technology development using the existing refinery infrastructure - limited CAPEX required. CP in existing refineries enables cost reductions.

• Project metrics/technical targets are defined/vetted by TEA and the IAB.

• We work directly with catalyst and instrument manufacturers, refiners.

3 – Impact of Project on Co-Processing Industry

Connection of approach toward significant impact and outcomes

• Refinery compatible FCC, HT/HC bio-oil conversion catalysts developed with industry leaders

• Refinery co-processing conditions for FCC and Co-HT/HC

• CP nozzles that reduce / eliminate plugging

• Accurate biogenic carbon measurement for RINs and GHG reduction

• On-line biogenic carbon and oxygenate measurement for process feedback and control

• Process kinetic models to predict HT/HC performance
3 – Impact Dissemination of Results to Industry and Academic Community

- **Yearly IAB Meetings**
  - Recent meeting at Los Alamos National Laboratory with 60 participants (20 from industry)

- **Ongoing industry Collaborations**
  - CRADA with Johnson Matthey
  - Sharing of samples and results with BTG, Topsoe

- **Publications and presentations**
  - 14 publications since 2021 peer review (see additional slides)

- **Patents**
Summary

**Project Goal**
- Accelerate adoption of co-processing biomass-derived feedstocks with petroleum streams in operating petroleum refineries to produce biogenic-carbon-containing fuels

**Approach**
- Addressing major risks and efficient communication
- Interdisciplinary and collaborative effort with three national labs and industrial partners
- Developing foundational data and offering co-processing strategies
- Combining multiple technologies and unique capabilities
- Progress reviewed and future work vetted by Industrial Advisory Board

**Impact**
- Address critical needs for biomass conversion enabling technology development
- Project deliverables are transferrable to refiners. Refiners are interested in co-processing with active participation in IAB meeting and several of them moving beyond lipids.

**Progress and Outcomes**
- High biogenic C incorporation demonstrated
- Biogenic carbon tracking method improved (incl. dark liquids)
- Different bio-oils successfully co-processed in FCC (up to 10%)
- Hydrotreating of HTL biocrude completed with catalyst deactivation mitigated.
- Process kinetic models to predict HT/HC performance

**Future work**
- Perform detailed analyses of feeds (assays) for refiners
- Continue tracking contaminants in bio-oils/bio-crudes
- Increase olefins and jet fuel as major product from FCC
- Increase biogenic feed percentages including a variety of feeds
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Quad Chart Overview

### Timeline
- **Project start date:** 10/1/2020
- **Project end date:** 9/30/2023

### Project Goal
Accelerate adoption of co-processing (CP) biomass-derived feedstocks with petroleum streams in current petroleum refineries by developing and disseminating foundational data for processing renewable intermediates to SAF and marine fuel by providing CP strategies via FCC and Co-HT/HC.

### End of Project Milestone
Demonstrate at least 100 h of FCC co-processing cleaned FP or CFP with VGO with up to 15 vol% blending level, 75 wt% relative biogenic carbon incorporation into SAF, MFSP approaching $2.50/GGE and 70% GHG reduction; 500 h stable operation of co-hydrotreating HTL bio-crudes with diesel or VGO with 2-10 vol% blending ratio, at least 80% biogenic carbon incorporation into fuel, maintained diesel fuel quality compared to diesel or VGO only, minimal impact on HT/HC catalyst, and less than 10% faster deactivation compared with baseline.

### Funding Mechanism
*Beto SDI Lab Call, 2019.*

### Project Partners
- Johnson Matthey, Chevron, Topsoe, Kern Oil, Ensyn, BTG, Aerodyne

### FY22 Costed Total Award

<table>
<thead>
<tr>
<th>DOE Funding</th>
<th>FY22 Costed</th>
<th>Total Award</th>
</tr>
</thead>
<tbody>
<tr>
<td>NREL</td>
<td>$664.8k</td>
<td>$2,250k</td>
</tr>
<tr>
<td>PNNL</td>
<td>$794.7k</td>
<td>$2,250k</td>
</tr>
<tr>
<td>LANL</td>
<td>$334.8k</td>
<td>$1,125k</td>
</tr>
</tbody>
</table>

### TRL at Project Start: 4
### TRL at Project End: 5
Additional Slides
Project Acronyms and Pathways

AMS: accelerator mass spectrometer
BC: biogenic carbon
CFP: catalytic fast pyrolysis
CP: co-processing
E-Cat: equilibrium FCC refinery catalyst
FCC: fluid catalytic cracking
FP: fast pyrolysis
HC: hydrotreating
HT: hydrocracking
HTL: hydrothermal liquefaction
JM: Johnson Matthey
LSC: liquid scintillation counter
SPO: stabilized pyrolysis oil

Considered Pathways

FCC

Bio-oil - VGO Blends

FCC

Biogenic Fuels

Fuel Composition

BC Measurement

HT/HC

Bio-oil/Crude - VGO Blends

HT/HC
Comment: "This is a great project that is directly addressing knowledge gaps limiting the commercial processing of bio-oils; it has excellent industry participation, has clearly identified challenges and a research approach to address them, and has plans for a published database to disseminate information post-project."

Response
We thank the reviewers for their positive comments about this co-processing project including their support of the knowledge gaps the project is addressing, database development and industry participation through the project's industrial advisory board.
Comment: "Good, but need more refinery insight and ops experience. Is HT/HC and FCC possible in one refinery? Need to clearly understand value (advanced opt needed) Why is biogenic C tracking needed? Shouldn't a simple C accounting balance be enough? Value of added bio-oils, value created. How was TEA performed? LP should be calculating cost of external (bio) stream to achieve fuel costs. A different way to look at it."

Response
We agree that increased refinery insight and operations experience is needed, and we are expanding refiner participation in the next 3 years of this project. We did not mention in the review that we are currently performing FCC co-processing tests for two major refiners using NREL's DCR system with their specific feedstocks and catalysts to define process parameters. Additionally, biogenic carbon tracking is an ask of our industrial advisory board: to understand where biogenic carbon is reporting both during co-processing and in the final product. Note that California is requiring 14C analysis of biogenic C containing fuels for RINs. Finally, TEA was performed using an Aspen refinery model and project generated co-processing data.
Comment: "The tasks of the refineries was not clear. It would appear that they were involved at an advisor role only. It would be of benefit if NREL could entice these entities into a greater participatory role. It would be beneficial to know what refineries have told BETO regarding the willingness to adopt a new catalyst recipe. Refinery buy-in is absolutely critical for this path and it isn’t clear if refiners are being brought in to monitor the progress of this technology. The project is aware of the further challenges in refinery adoption but there aren’t any further plans to do this work at a pilot scale. 8% displacement is massive in industry even if it is a small number. The corn ethanol industry displaces 10% of petroleum and supports thousands of jobs and billions of dollars in GDP. Would be good to understand the non-RIN value of the blend vs. the standard FCC output (Slide 12). The project has done a good job of providing tasks to each of the known risks of this technology blend and is clearly working towards eliminating roadblocks to the development of bio-oil and FCC blending. Project discusses the long term catalyst stability risk but the presentation is not clear on how this is being measured experimentally. Reviewers would like to know how the project has assessed performance, how frequently it has regenerated its catalyst and how it projects performance. Potassium and Sulfur are mentioned as elements under study for catalyst deactivation - however the impact of other more minor elements, or those that are known to easily be resolved through regeneration do not appear to be under study. If the catalyst needs to be regenerated more frequently, that too would have a serious impact on the refinery. The metrics of the demonstration of FCC/HTC fuel production were not provided. Without these metrics it is hard to evaluate whether this project has successfully impacted the state of biofuel production. "Linked to FCIC database" is unclear. The interface should be a singular consistent UI, not a conglomeration of different programs merged together. Not clear whether the development of the instrument is on-going or is considered complete. The fidelity of the carbon monitoring device is critical on equipment that is pumping millions of gallons a day. The presentation noted it could measure down to a percent, but this does not provide sufficient information to determine its benefit."
Response

The Johnson Matthey catalysts used in the FCC co-processing work are HZSM-5 catalysts modified to enhance bio-oil conversion while retaining their original ability to convert vacuum gas oil. Catalyst characteristics have to be maintained for FCC operation and the modifications adhere to this requirement - thus refiners should not have issues using these catalysts in their FCC systems. Project plans in years 2-3 will address catalyst lifetime and potential deactivation from fugitive contaminants as will regeneration requirements for both FCC and HTC co-processing. The bio-oil database can be linked to the FCIC feedstock database as both are using LabKey as the platform; this approach leverages the information in both databases for researchers and refiners. The biogenic C measurement systems under development are slated for ease of use and ruggedness in a refining environment.
Comment: "This is a solid project overall. Good Management and Risk Mitigation Plan, excellent outreach to catalyst vendors and refiners, effective plan to target the right feedstocks for the right processes and to acquire data, both primary (conversion to products) and secondary (catalyst life, operational issues, etc.). Progress so far has been good, and success vs. the stated Objectives seems likely. The one major concern is that by targeting low-level blending, the project may be a tactical success but a strategic dead end. We don't need 5-10% bio content in a couple of process units, we need refineries that are processing 75%-plus renewable feedstocks. If this is clearly a step along that path, fine, but it wasn't clear from the material presented that was so. The BETO Vision for existing petroleum refineries should be that they will process mostly renewable feedstocks or they will go out of business."

Response
We agree that the more bio content in fuels the better! However, refiners have told us that for FCC co-processing, 10wt% bio-oil blend is the upper limit to that can be current co-processing in FCC units. Greater than 10wt% upsets downstream processes. Also consider that biomass resources may limit how much bio-oil is available for co-processing."
Comment: "This is an excellent project that is achieving good results. I am amazed at the complexity of the project and how the objectives are being met in spite of this complexity. The team may want to review its objectives to ensure that they are not over stretched and are able to continue to function at a high level. It is well managed with excellent industrial involvement. As with other projects I really like that they are looking at co-processing, and co-processing in numerous unit operations. This reviewer also likes that they are tracking and documenting the feed quality and consistency, a deficiency of other projects. Great project and great team"

Response
We thank the last reviewer for their positive comments - very much appreciated. We believe tracking feed quality and consistency is a critical process parameter that must be understood if co-processing is to be successfully adopted by refiners.
Publications (2021-2023)

- Charles Doll, Andrew Plymale, Matthew O'Hara, Christopher Thompson, Alan Cooper, Huamin Wang, Mariefel Olarte, Demonstration of low-level biogenic fuel content using quench curve and direct liquid scintillation counting (LSC) methods, Fuel, 2023, 334, 126468.
- Edwin Yik, Huamin Wang, Enrique Iglesia, Hydrogenation and C-S bond activation pathways in thiophene and tetrahydrothiophene reactions on sulfur-passivated surfaces of Ru, Pt, and Re nanoparticles, Applied Catalysis B, 2021, 291, 119797
Publications, Patents, Presentations, Awards, and Commercialization

Presentations (2021-2023)

- Reinhard Seiser, Jessica Olstad, Braden Peterson, Rebecca Jackson, Earl Christensen, Kim Magrini; Robert Baldwin, “Biocarbon Tracking in FCC Co-processing of Biogenic Feedstocks”, oral presentation, TCBIomass 2022, Denver.
Publications, Patents, Presentations, Awards, and Commercialization

Patents


Commercialization

NREL/Johnson Matthey CRADA to develop refinery compatible biomass conversion catalysts

3-Phase project with Chevron to assess co-processing with their feedstocks and catalysts (200K)

MOU-19-523: K. Magrini and D. Chiaramonte, Memorandum of Understanding finalized with the University of Florence, Florence, IT for developing products from biomass pyrolysis streams. Hosted Stefano Dell’Orco from February-July 2020 for doctoral work in thermochemical biomass conversion.
DEI Plan

The three national labs have increased their participation in diversity, equity and inclusion programs:

• Support a diverse workforce and promote the interviewing of candidates with a wide variety of backgrounds.
• Applied to hiring interns from MSIs through Research Participant Program (RPP) internship – demand was larger than supply.
• Participated in workshops on different internship programs and fellowships such as GEM (Graduate Education for Minorities).
• Participated in LDRD-sponsored Energy Justice analysis:
  • Evaluate impact of research on disadvantaged communities – positively by renewable industry programs and negatively by emissions and waste generation.
  • Broaden publication research to other regional areas
  • Dissemination of research results in global, open access journals
• Participated in workshops on partnering with MSI institutions. Administration compiled a list of MSIs with contacts.
• Participated in Justice Equity Diversity and Inclusion (JEDI) group’s programs and seminars inviting speakers and visitors from MSIs.
The objective of this three-laboratory project is to accelerate adoption of co-processing biomass-derived feedstocks with petroleum streams in current refineries by developing and broadly disseminating foundational data for processing renewable intermediates and offering co-processing strategies. It will enable utilizing U.S. refineries which in 2020 have 8.8 million barrels/day capacity for hydrotreating and 5.6 million barrels/day capacity for FCC. Three critical challenges were identified by the project’s industrial advisory board (IAB): 1) A critical operability risk comprising process stability around catalyst deactivation. 2) A regulatory risk comprising the need to rapidly measure biogenic carbon and oxygenates in processed streams. 3) A significant knowledge risk centered on the lack of co-processing data including feedstock compositions and contaminants, product compositions, the reaction kinetics of unique bio-compounds, and associated TEA/LCA. Outcomes of addressing the three challenges are: 1) Preventing catalyst deactivation by reducing alkali species through hot-gas filtering (FCC) and reducing nitrogen compounds by pre-treatment (HT/HC). 2) Developed methods for inexpensive/rapid biocarbon analysis through 14C and delta 13C analysis methods. 3) Provided detailed compositions on bio-oil feeds and co-processing products, including contaminants, operational data including biocarbon yields, an improved kinetic reactor model for HT, and associated TEA/LCA.