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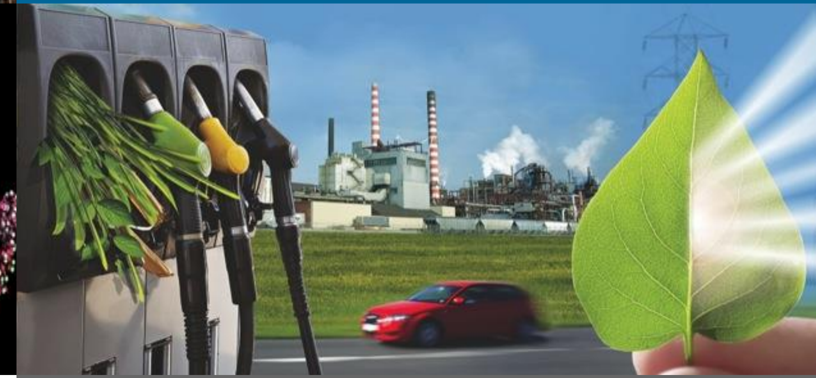

Integrated Analysis in Support of the Separations Consortium

Bioenergy Technologies Office Peer Review

March 4, 2019

Denver, Colorado

BIOPROCESSING SEPARATIONS CONSORTIUM

Consortium Analysis Team:

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Goal Statement

Goal: Provide an analysis-based foundation to support and guide the research strategies being pursued under the Separations Consortium

Outcome:

- A baseline comparison of the strategies being pursued by Separation Consortium compared to commercially relevant off the shelf technologies
- A series of TEAs and LCAs to identify technical targets to improve both economics and sustainability of the proposed projects and guide R&D
- Publications that utilize analysis results to motivate the various strategies developed under the Separations Consortium

Relevance: *Ensure that the proposed processes being developed under the Separations Consortium are economically viable, improve sustainability, and are scalable.*

Quad Chart Overview

Timeline

Start Date: 10/1/2016
End Date: 9/30/2019
Completion: 75%

	Total Costs Pre FY17	FY 17 Costs	FY 18 Costs	Total Planned Funding (FY 19-Project End Date)
DOE Funded	$500,000	$400,000	$175,000	$115,000
Partners		ANL: 13% LBL: 15% NREL: 38% PNNL: 38%	ANL: 20% NREL: 57% PNNL: 23%	ANL: 13% NREL: 39% PNNL: 48%

Barriers Addressed

Ot-B: Cost of Production. Advanced and robust separations and molecular efficiency are required to reduce the up to 50% share of separations costs in bioprocesses.

Objective

Develop cost-effective, high-performing separations technologies through coordinated separations research that targets challenges relevant to industry and BETO.

End of Project Goal

Demonstrate the consortium's value to BETO and the biofuel and bioproduct communities through documentation of technical advances, influence on process economics, and potential industrial applications of consortium technologies.

Project Overview

History:

- At the consortium's beginning, the analysis team reviewed current separations strategies utilized in design cases of BETO.
- Utilized this information to identify key cost and sustainability drivers in current design cases as areas to target R&D.

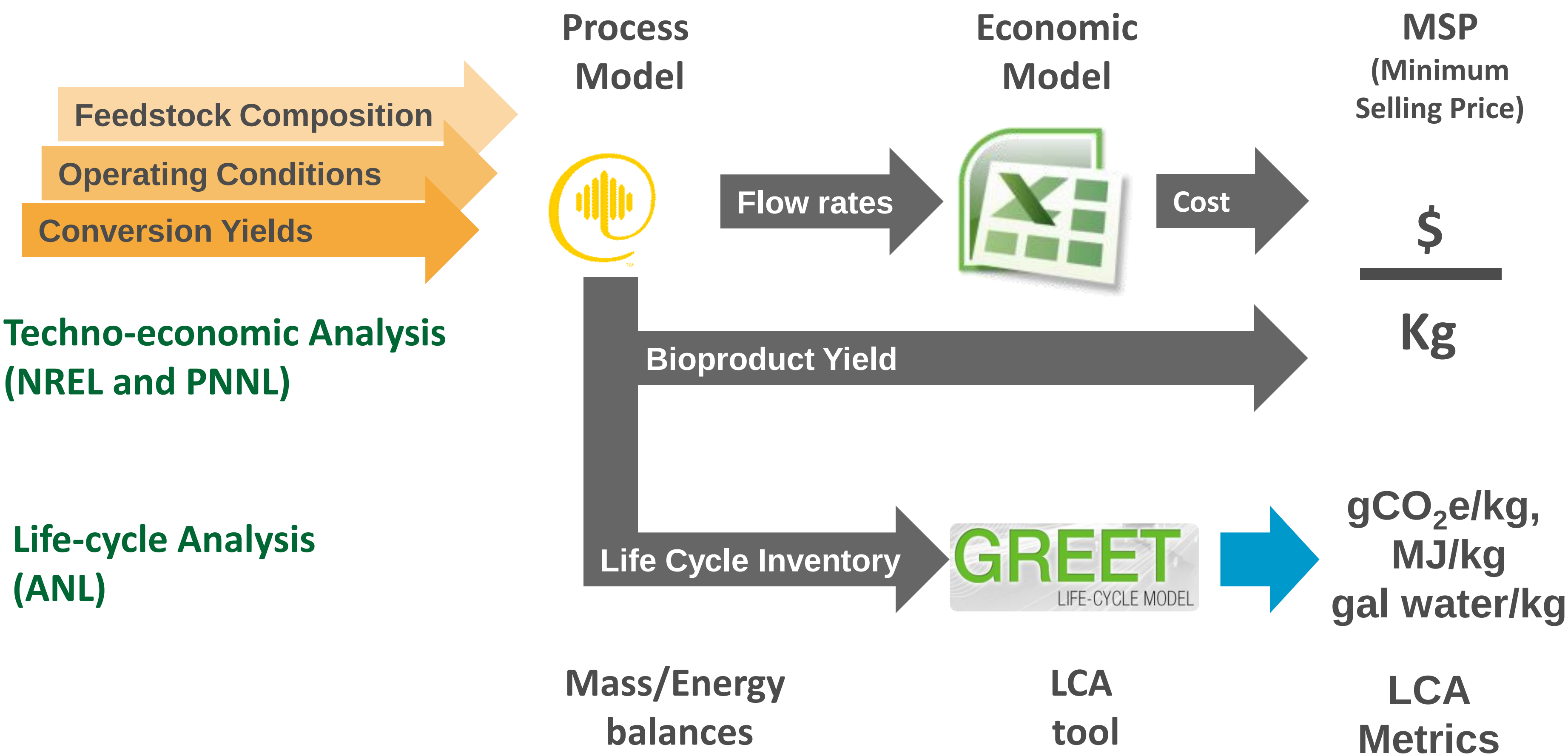
Motivation:

- Many separation options are available; which solutions best address the problem economically and sustainably?
- Provide feedback and guidance to help to bound problems and verify a path towards economic viability and sustainability
- Consider risk and help to define the research space to establish and implement a consortium research portfolio that is relevant at a commercial biorefinery scale

Integrated Analysis Technical Approach

Assess technical, economic, & environmental feasibility of bioproduct/biofuel conversion processes:

- *Detailed process analysis with rigorous mass and energy balances*
- *Identified data needs and further R&D need to improve overall cost and efficiency*
- *Assess environmental impacts (greenhouse gas emissions, fossil fuel and water consumption)*
- *Approach is consistent with other DOE BETO sponsored analyses*



GREET[TM]: Greenhouse gases, Regulated Emissions and Energy use in Transportation

Integrated Analysis Technical Approach

Assess technical, economic, & environmental feasibility of bioproduct/biofuel conversion processes:

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- *Identified data needs and further R&D need to improve overall cost and efficiency*
- *Assess environmental impacts (greenhouse gas emissions, fossil fuel and water consumption)*
- *Approach is consistent with other DOE BETO sponsored analyses*

Challenges:

- Data availability and quality
- Uncertainty of capital cost for new and novel technologies
- Ensuring rigor of separations process modeling – particularly when considering scale-up

Critical Success Factors:

- Techno-economic and life-cycle analyses that have been vetted by stakeholders and that supports all of the Separations Consortium
- Identification of R&D needs to enable improved performance of separation strategies

Integrated Analysis Management Approach

Example data input for TEA:
Raw Material Flowrates
Recovery Efficiency
Regeneration Requirements

Example data feedback from TEA/LCA:
Cost and Sustainability Drivers
Key Data Gaps For Further R&D Needs
Technical Targets/Approach To Reduce Costs and Improve Sustainability

- Participate in monthly calls with entire consortia and BETO
- Participate in IAB meetings (every 6 months) including presenting latest results
- Analysis task QPMs are aligned with specific research areas
- Go/No-Go support for specific research and analysis contributes to decision metrics
- Analysis team has supported a yearly milestone in FY17 and FY18

Integrated Analysis Management Approach

Sample of input sheets provided to R&D team to Obtain key data for TEAs and LCAs

Data Used for Modeling

Key Process Step	Brief Design Description	Based on Biomass Feedstock/Model Compounds/Other?	Experimental Scale (lab/bench/pilot/literature)	Experiment Consistent with Design (yes/no), explanation

				Key process parameters			Key results		
Mass Closure (%)	Carbon Balance (%)	Number of times experiment repeated	Time on stream (hrs)	Temp (°C)	Press (psi)	Residence Time (hr)	Efficiency(wt%)	Selectivity (wt%)	Yield (g/g)

- Work closely with R&D team to obtain data needed to effectively model proposed separations technology
- Work with industrial advisory board to review TEA and LCA approach and outcome
- Adopt guidance from industrial advisory board to refine analyses
- Analysts participate in the regular calls with BC and TC experimentalists
- Meetings between analysts and experimentalists for data exchange to discuss enabled by open lines of communication among consortium PIs

Accomplishments:
Review of separations included in recent design cases

Where we started

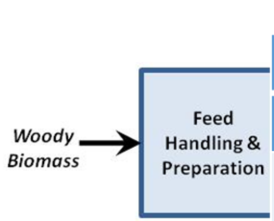
Review of 8 different biomass design cases to:

- Document the basis and cost/sustainability associated with current separations in designs
- Evaluate the impact of any assumptions on costs for separations technologies
- Highlight potential improvement and associated costs that separations could contribute to the design
- Presented and provided to R&D team -- help the development of R&D strategies

  - Fast Pyrolysis
  - Ex Situ Catalytic Pyrolysis
  - Indirect Liquefaction
  - Algae Dewatering
  - Algae CAP process
  - Algae - Hydrothermal liquefaction
  - Biochemical biological conversion
  - Catalytic Conversion of Sugars

Accomplishments:
Review of separations included in recent design cases

Sample of data collected for ex situ CFP (more details provided in back-up slides):



1. Tw
r

The outlined process converts
ex situ catalytic conversion. A
further deoxygenated in a hy
of diesel and gasoline-range h
recycled to the distillation col

1. Two condenser/absorber
streams: non-condensable gases, liquid pyrol

2. Product recovery utilizes standard comme
drums. There is limited potential for improve

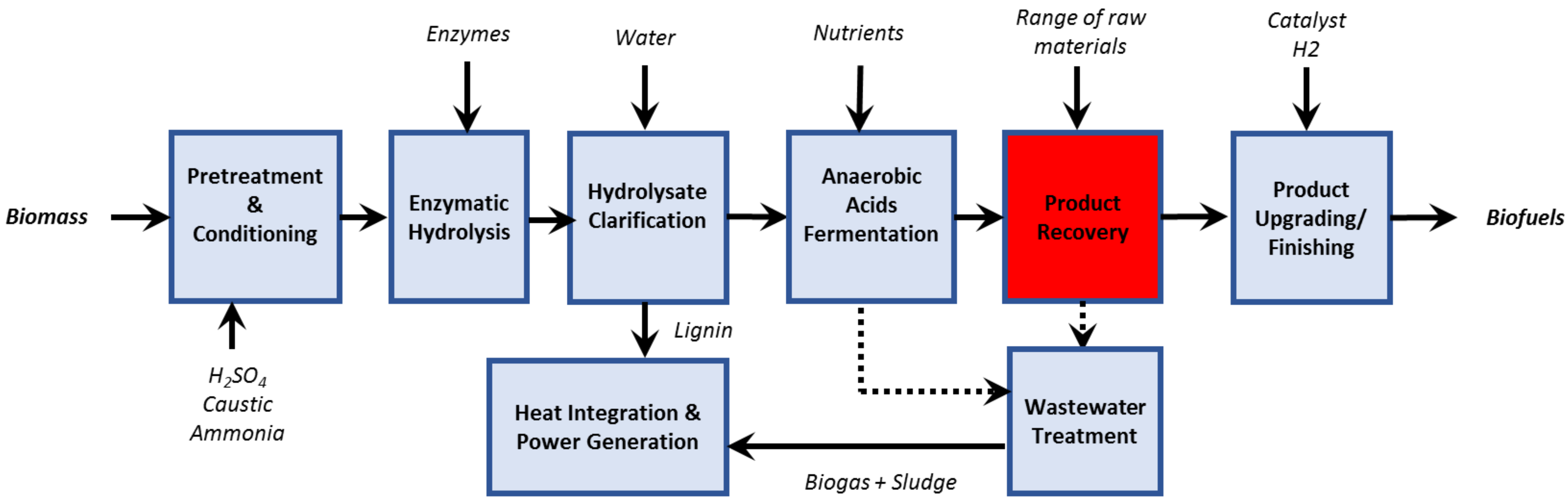
What are th
What is the ba values?
What is the cu known)?
What are assu associated wit targets (cost in

What are the p
What is the basis values?
What is the curren known)?
What are assumpt associated with m targets (cost impa

Additional separations processes that could be included in the design base	
Additional separation strategies to be considered.	Advanced membrane technologies, suc Performance Architecture Surface Selec could be utilized for the vapor quench s efficiency of carbon recovery.
Alternative strategies that might be required to mitigate risk	Hot gas filtration (as discussed in the de needed for the Ex Situ case if additional product stream. This hot gas filter will b upgrading reactor is a fixed bed. Vapor-phase HiPAS membranes have th equipment fouling concerns from heavy
Alternative strategies that might help improve conversion costs -- Use of waste streams/lost carbon for additional production.	Reducing carbon losses to the aqueous the economics of the process. Liquid-p can be used to recover carbon lost to th Process integration/intensification by c a hot gas filter and catalytic upgrading p membrane, could reduce the capital co process. Condenser/absorbers and decanters ar inexpensive, and simple to operate and alternative separation process will most if it reduces carbon losses to the aqueo downstream cleanup equipment.

Accomplishments:
Developing Analyses for Separations Consortium Strategies

Biochemical Example: Anaerobic production of biofuels are routes towards low cost hydrocarbons however separations is a key driver for both cost and sustainability.



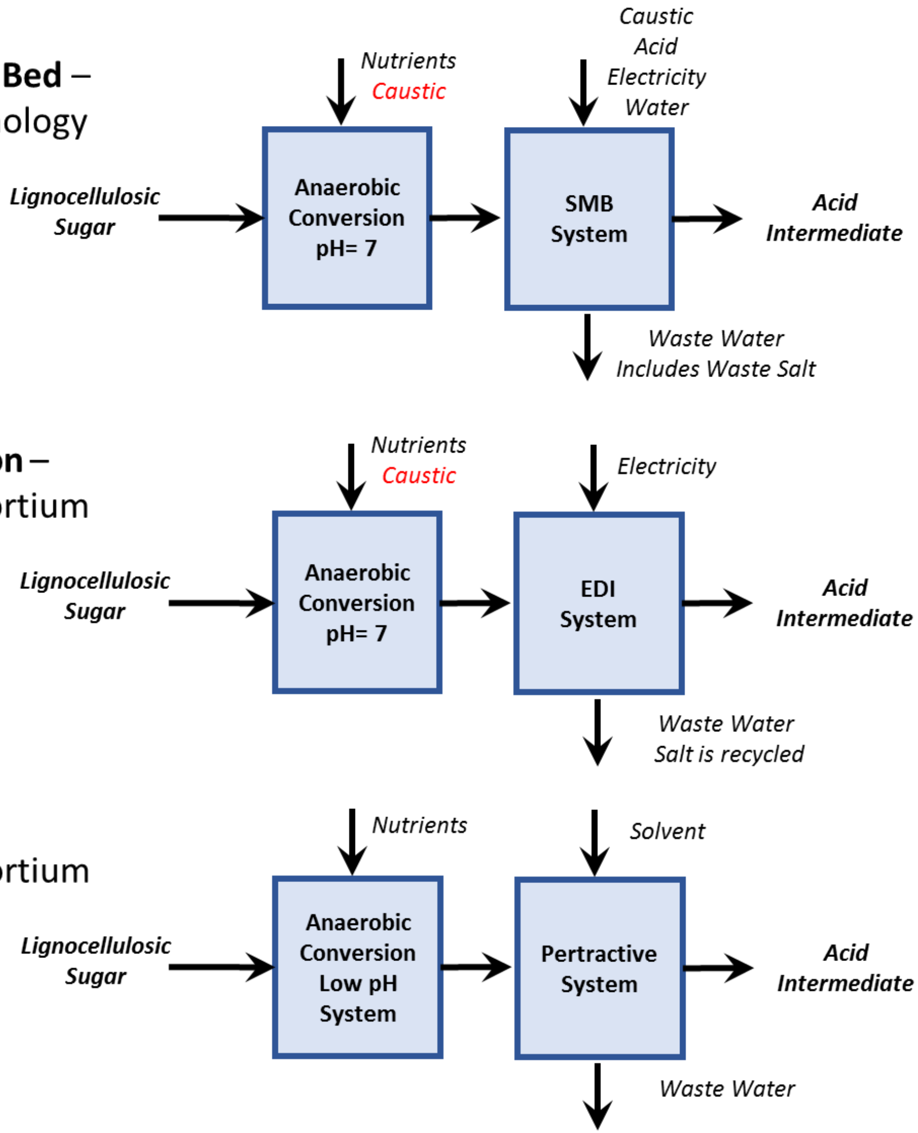
Focus of this analysis is on recovery strategy for acid intermediates

Accomplishments:
Developing Analyses for Separations Consortium Strategies

Simulated Moving Bed – Off the Shelf Technology

Electrodeionization – Separations Consortium Technology

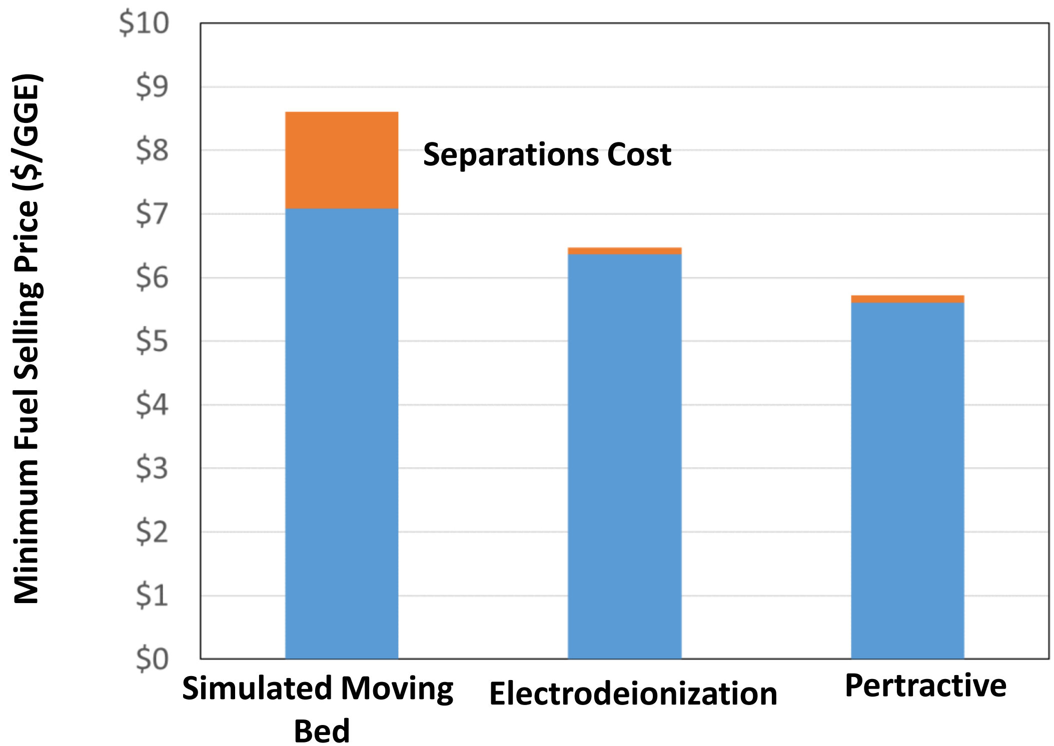
Pertractive – Separations Consortium Technology



Simplified block flow diagrams of technologies considered

- **Simulated Moving Bed** *considered as baseline to compare Separations Consortium Technologies*
- **Electrodeionization** *is linked with pH 7 fermentation in this study and future work will consider low pH case*
- **Pertractive** *separation is integrated with low pH fermentation*
- Designs based on variation of Q3 BC design case (burned lignin and modified enzyme production)

Accomplishments:
Preliminary TEA Results – Biochemical Pathway



Compared to baseline technology -- *Strategies being developed under separations consortium have the potential to lower separations costs as illustrated in the above graph (in orange)*

NOTE: Designs have higher MFSP since lignin upgrading, not considered

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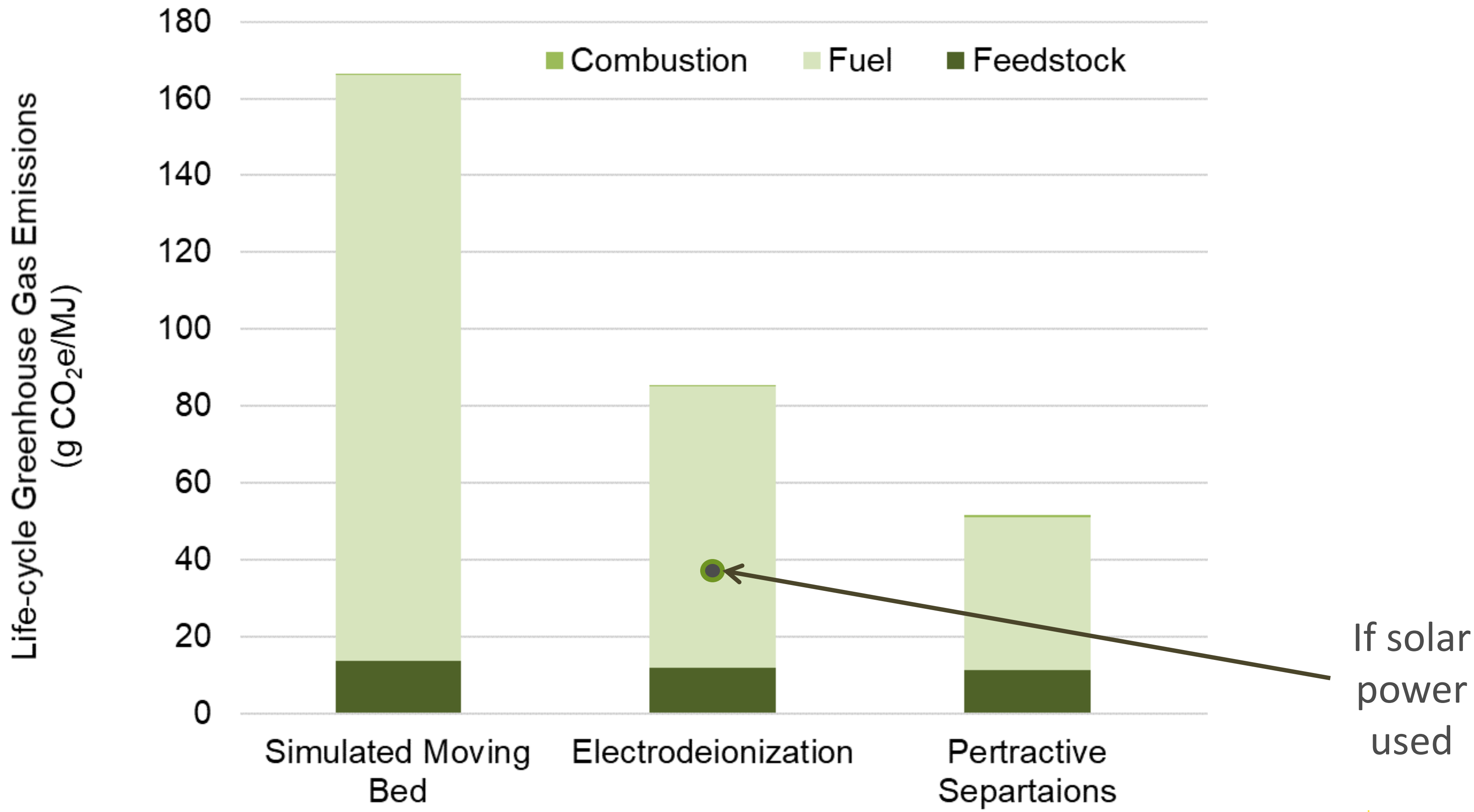
Accomplishments:
Greenhouse gas emissions estimated with LCA

- Compared to the off-the-shelf SMB technology, EDI and pertractive separations exhibit lower life-cycle GHG emissions of the renewable diesel produced in the process.
- One key driver of the fuel stage, which includes the conversion step, is NaOH consumption.



Low Sulfur Diesel baseline: 94 g CO_2e/MJ

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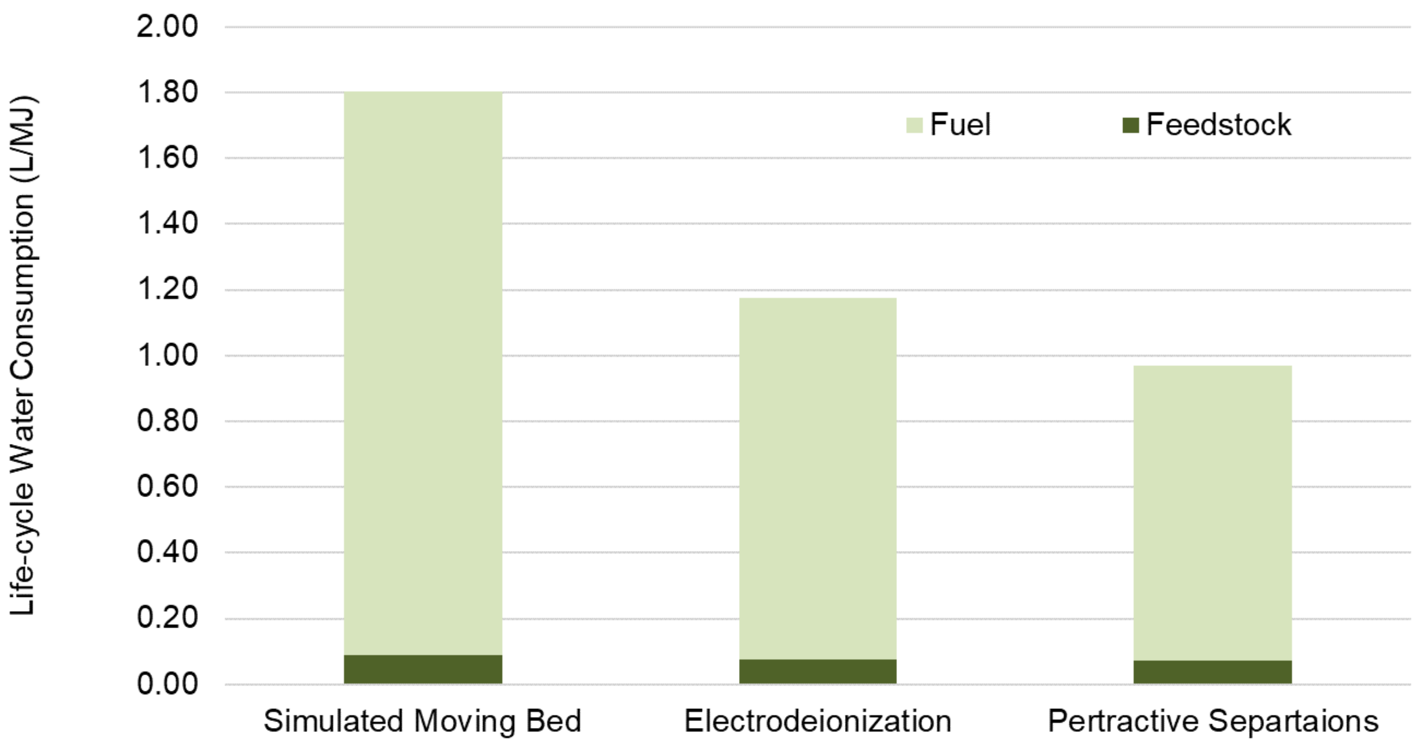
Accomplishments:
Preliminary LCA results – Biochemical Pathway

Water consumption lower through pertractive approach



Note: water consumption not optimized in process modeling.

Petroleum baseline is 0.06 L/MJ. If use solar energy, EDI becomes ~1 L/MJ.

Accomplishments:
Summary of Results and Impacts – Biochemical Pathway

- **Understanding key drivers:**
  - Pertractive technologies shows the lowest overall MFSP and improved sustainability parameters, due to higher targeted yields (at 100%) and low raw material make-up (low pH fermentation and limited electricity demand)
  - The Electrodeionization approach has a higher MFSP than pertractive approach primarily due to lower targeted yields (at 95%) and raw material imports (which account for ~$0.03/GGE). Since EDI does not require low pH fermentation, this is a mitigation strategy for the anaerobic acids pathway
- **Results reviewed by industrial advisory board and compared to expectations on costs**
- **Both technologies are highlighted in the recent update to the Biochemical design report (recently published)**
- Initial analyses began in FY17 and supported a Q4 milestone for this project.
- These results supported an FY18 Q4 milestone for the projects as well as an inter-project Go/No-Go in FY18Q2.

Accomplishments:
Developing Analyses for Separations Consortium Strategies

Thermochemical Example: *Sludge Hydrothermal Liquefaction to Renewable Diesel*

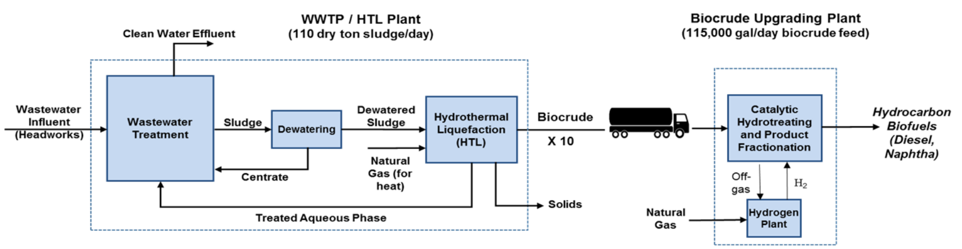
BASELINE:

- for WWT plants with nitrogen restrictions, ammonia is stripped out of the water stream (plus a small amount of non-condensable organics), neutralized, and thermally oxidized
- carboxylic acids are unrecovered

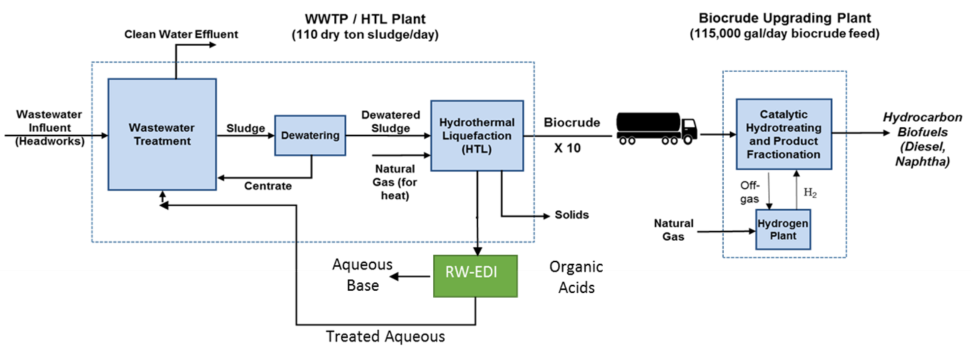
SEPARATIONS CONSORTIUM:

- ammonia recovered as an aqueous product
- low molecular carboxylic acids recovered (treated as acetic acid in LCA)

BASELINE CASE

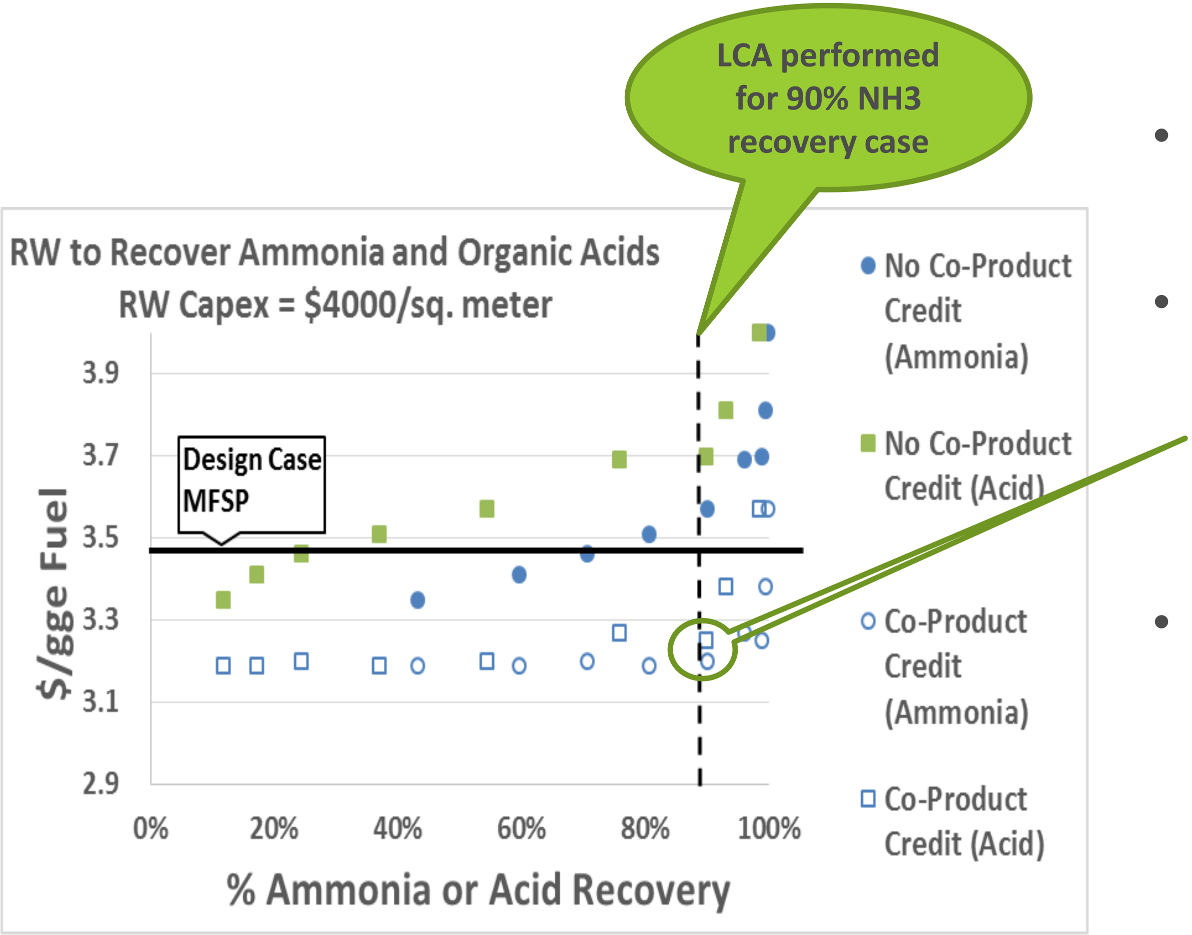


SEPARATIONS CONSORTIUM CASE



Accomplishments:

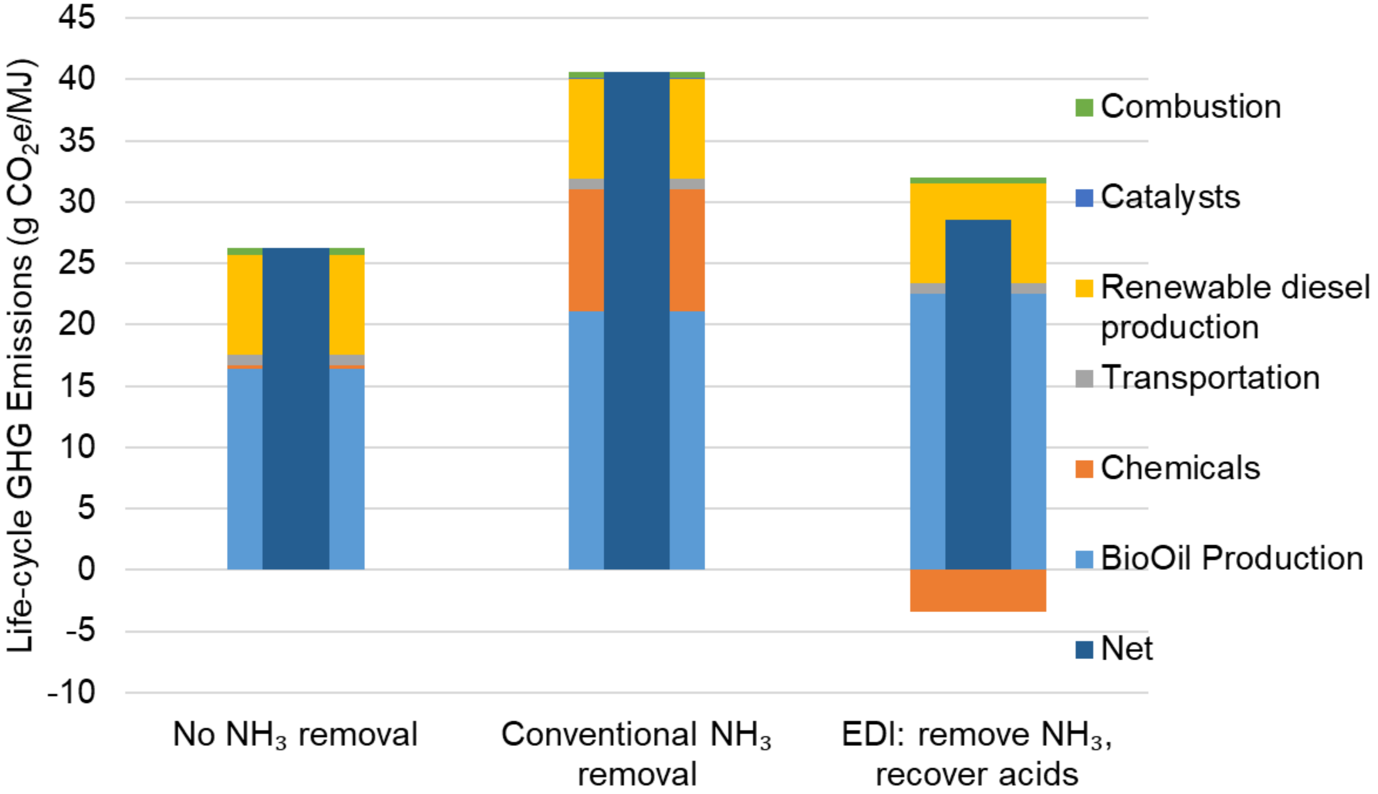
Preliminary TEA Results – Thermochemical Pathway



- Case shown uses the conservative Resin-Wafer (RW) EDI capex
- At 90% ammonia recovery, selling the aqueous ammonia reduces the MSFP below the design case target
- For the optimistic RW-EDI capex case ($2000/sq. meter, not shown), ammonia recovery reduces the MFSP even at zero sales value for aqueous ammonia

Preliminary LCA Results – Thermochemical Pathway

EDI pathway offers lower GHG emissions and fossil fuel consumption than conventional NH_3 removal



NH_3 and acids are co-products. In case of acids, this is a best case estimate of displacement credit because acids are in aqueous stream and need additional separation. Fossil consumption also calculated (not shown, but has similar trend)

Accomplishments:
Summary of Results and Impacts

- Separations consortium technologies offer improvements in cost, fossil energy consumption, GHG emissions, and water consumption over baseline cases per analysis to-date
- Once analysis finalized, a journal article will be prepared to highlight role of TEA and LCA in the consortium
- Initial analyses began in FY17 – with a Q4 milestone for this project.
- These results supported an FY18 Q4 milestone for the projects as well as an inter-project Go/No-Go in FY18Q2.

Relevance

- **Goal:** Provide an analysis-based foundation to support and guide the research strategies being pursued under the Separations Consortium
- **Outcome:**
  - Develop baseline costs for comparison with research improvements
  - Complete TEA and LCA to guide R&D towards cost-effective solutions
  - Publish results for use by stakeholders
  - Identify data gaps for future research
- **Relevance to MYPP Platform Goals**:

Advanced Separations are a Key Focus: Conversion R&D is working to "enable high-performance separations technologies to increase product yields and decrease cost." (MYPP)

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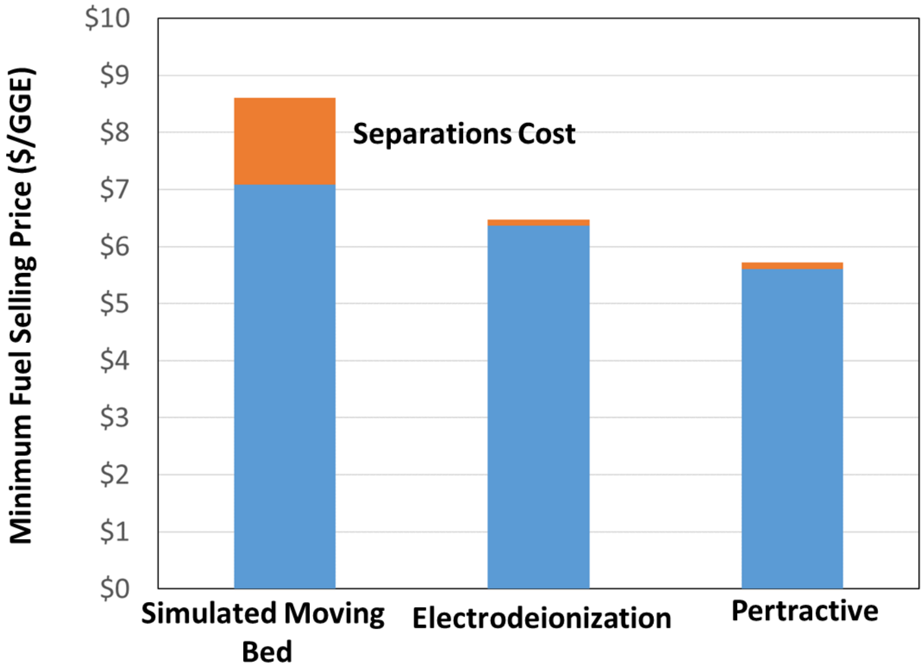
Integrated Analysis is working "to provide context and justification for decisions at all levels by establishing the basis of quantitative metrics, tracking progress toward goals, and informing portfolio planning and management" (MYPP)

Relevance to Bioenergy Industry

<u>Industry Review Undertaken</u>

Example at right: BC separations

- Results presented to IAB board to ensure meaningful analysis
- Cost comparison results reviewed by IAB and compared to expectations for costs

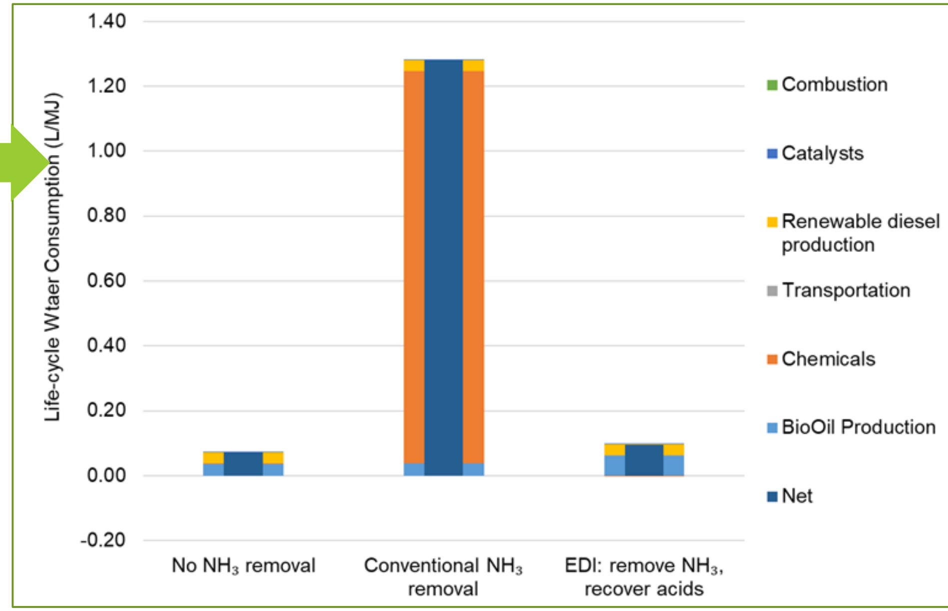


IAB recommendations incorporated into practice (see Future Plans)

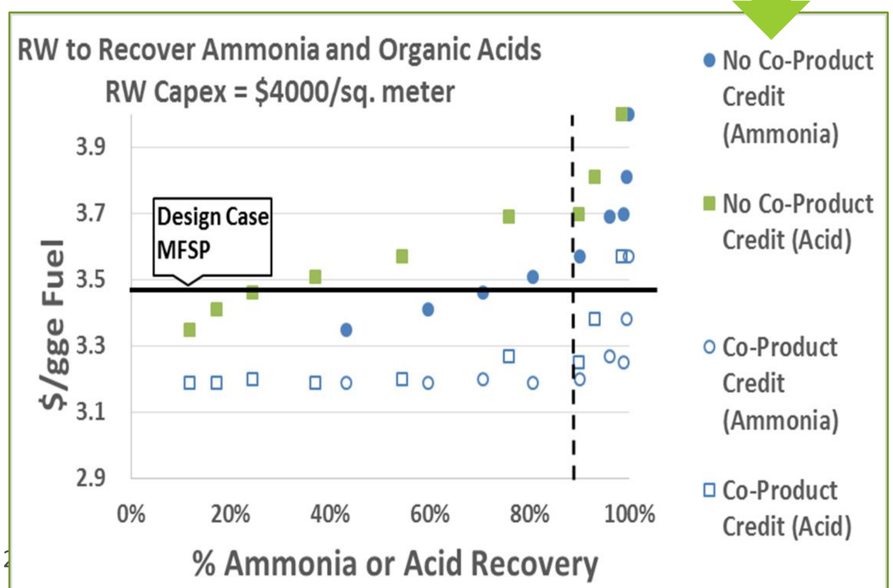
Relevance to Advancing the State of Technology

Enable focused research on key separations issues: TC Example for NH3 recovery from HTL aqueous:

- Identified significant sustainability drivers for recovery of NH_3 from HTL aqueous stream
- Identified operating envelope for further research that will result in reduce cost of fuel production



Quick lime (CaO) consumption in conventional removal case prompts large water consumption



Future Work:
Near Term

- Continue to support TEA/LCA needs of consortium
  - Expand beyond design case separation issues by further integration to assist R&D and other consortiums, including
    - Agile Biofoundry
    - Co-Optima
    - ChemCatBio
    - Performance Advantaged Bioproducts
- Support overall consortium goal and provide data needed for public report (Q4 milestone)
  - Document technical advances from each consortium team and their influence on process economics.
  - Review industry-relevant applications of the technologies under investigation
  - Summarize feedback received from the advisory board on the consortium's progress and impact.

Summary

Overview	Provide an analysis-based foundation to support and guide the research strategies being pursued under the Separations Consortium
Approach	• Detailed process analysis with rigorous mass and energy balances • Identified data needs and further R&D need to improve overall cost and efficiency • Assess environmental impacts (greenhouse emissions, fossil fuel consumption and water consumption) • Approach is consistent with other DOE BETO sponsored analyses
Technical Progress	• **Review of design cases –** Document current separation technologies utilized in design reports and additional separation needs to improve process performance • **TEA of BC and TC pathways-** Developed initial TEAs and LCAs for BC and TC pathways. Compared designs to current off-the shelf technologies. Identified key R&D drivers to improve cost and sustainability.
Relevance	**Ensure that the proposed processes being developed under the Separations Consortium are economically viable, improve sustainability, and are scalable.**
Future Work	• Continue to support TEA/LCA of Separation Consortium strategies • Document technical advances from each consortium team and their influence on process economics.

Thank You!

Responses to Previous Reviewers' Comments

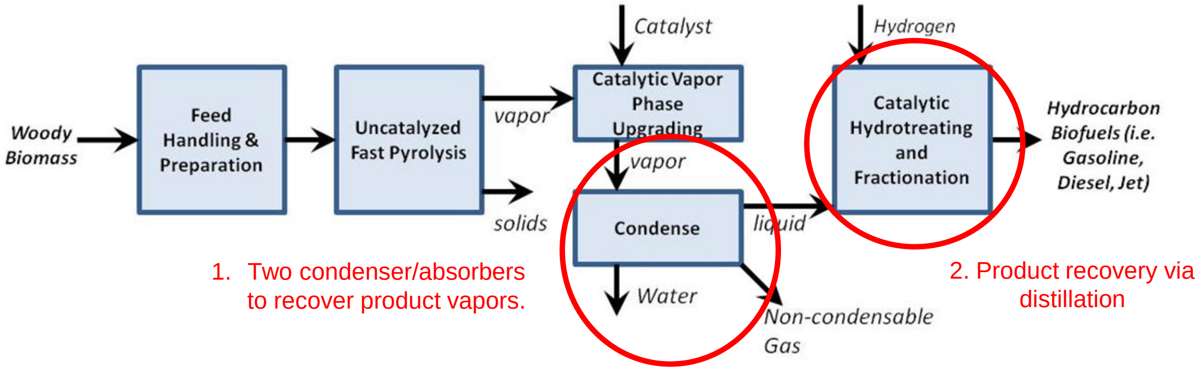
- This project was not reviewed in FY17

Publications, Patents, Presentations, Awards, and Commercialization

- None

Backup: Sample from review of information from design cases

Sample of data collected for ex situ CFP (more details provided in back-up slides):

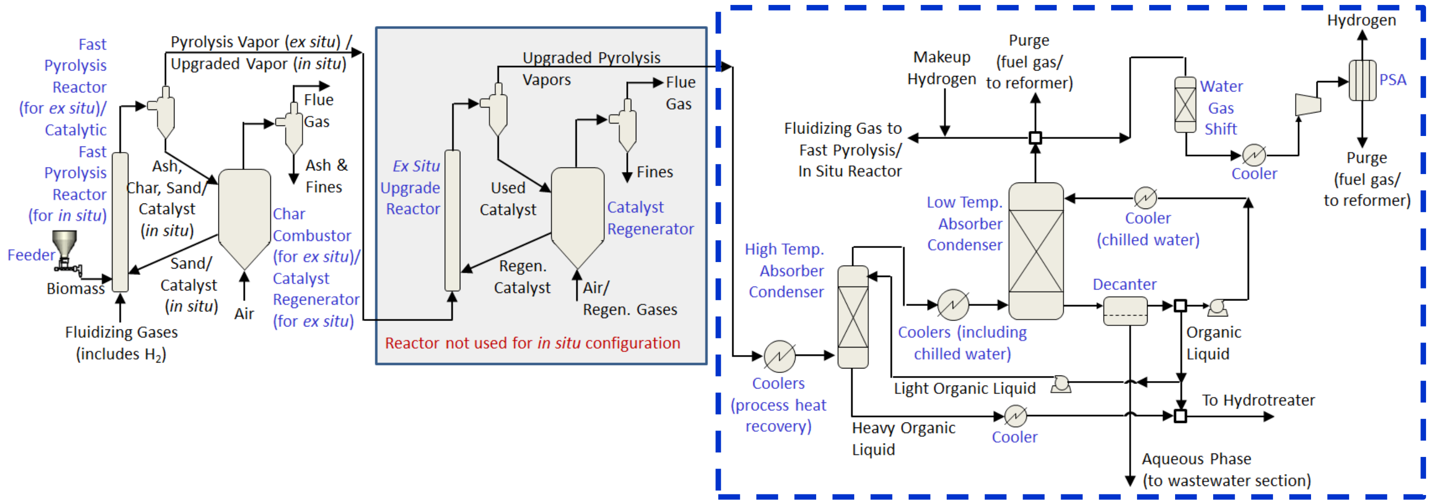


The outlined process converts lignocellulosic biomass to pyrolysis vapors, which are then upgraded via *ex situ* catalytic conversion. After condensation and water removal, the upgraded pyrolysis liquid is further deoxygenated in a hydrotreater and fractionated in two distillation columns to produce a blend of diesel and gasoline-range hydrocarbons; heavier products are sent to a hydrocracker before being recycled to the distillation columns. The primary separations required for the process include:

1. Two condenser/absorbers in series, followed by a decanter; they separate the pyrolysis vapor into three streams: non-condensable gases, liquid pyrolysis oil, and wastewater.

2. Product recovery utilizes standard commercially-relevant processes such as distillation columns and flash drums. There is limited potential for improvement in these processes and thus are not reviewed in this effort.

Pyrolysis Vapor Quench



Pyrolysis vapor quench design summary

- The first stage is a high-temperature absorber/condenser that condenses heavy organics using light organics from the low-temperature absorber/condenser as the condensing agent. Using condenser/absorbers, rather than indirect heat exchange, to condense heavy organics helps mitigate fouling concerns.
- Non-condensable gas stream is split to the pyrolysis reactor and to H_2 production/recovery.
- The aqueous fraction, which contains water-soluble organics, is sent to the wastewater management area, where most is boiled to produce process steam, while the remaining concentrated stream with carbon is combusted in a regenerative thermal oxidizer.

Backup: Sample from review of information from design cases

Describe the separations designs in the baseline design cases.		
	Vapor Quench	Fuel recovery
What is the basis for these designs?	Two-stage condenser/absorber system that utilizes varying temperatures (low/high). Separates organic fraction from non-condensable gases and an aqueous phase.	Distillation columns
Where are the costs derived from?	Estimated from Aspen Icarus – standard equipment, off the shelf equipment	Aspen Icarus estimates
Where did key assumptions/targets come from?	Based on Aspen projections	Aspen simulation projections and literature
What cost impacts does the separations have on the MFSP?	Will show cost breakout in later slides	
Are there sustainability implications around this proposed design (high electricity use or large amounts of chemicals required)?	Yes – Some electricity demand for chiller that could impact LCA. Higher carbon losses to wastewater will result in lower fuel yields impacting both TEA and LCA.	No

Backup: Sample from review of information from design cases

What are the R&D targets?		
	Vapor Quench	Fuel Recovery
What is the basis of these values?	Aspen model predictions Targeting 1.3wt% carbon loss to aqueous	No targets Identified
What is the current SOT (if known)?	Current SOT is 2.9wt% based on experimental data (2015)	
What are assumptions/risks associated with meeting these targets (cost impacts?)?	Higher losses of carbon could increase MFSP and impact LCA due to lower fuel yields.	

Backup: Sample from review of information from design cases

What are the process design assumptions?		
	Vapor Quench	Fuel Recovery
What is the basis of these values?	Design is standard equipment – cost based on Aspen Icarus estimates Heat and electricity requirements based on Aspen estimates	Aspen modeling results Design is standard equipment – cost based on Aspen Icarus estimates Heat and electricity requirements based on Aspen estimates
What is the current SOT (if known)?		
What are assumptions/risks associated with meeting these targets (cost impacts?)?	Lower yields because of lower carbon recovery.	Lower fuel recovery could result in higher costs