Co-Optimization of
Fuels & Engines

Environmental, Economic, and Scalability Consideration of Selected Biomass-Derived Blendstocks for Mixing-Controlled Compression Ignition (MCCI) Engines

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better fuels | better vehicles | sooner

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

Introduction

- **Co-Optimization of Fuels & Engines (Co-Optima)** explores how simultaneous innovations in fuels and engines can boost fuel economy and vehicle performance while reducing emissions.

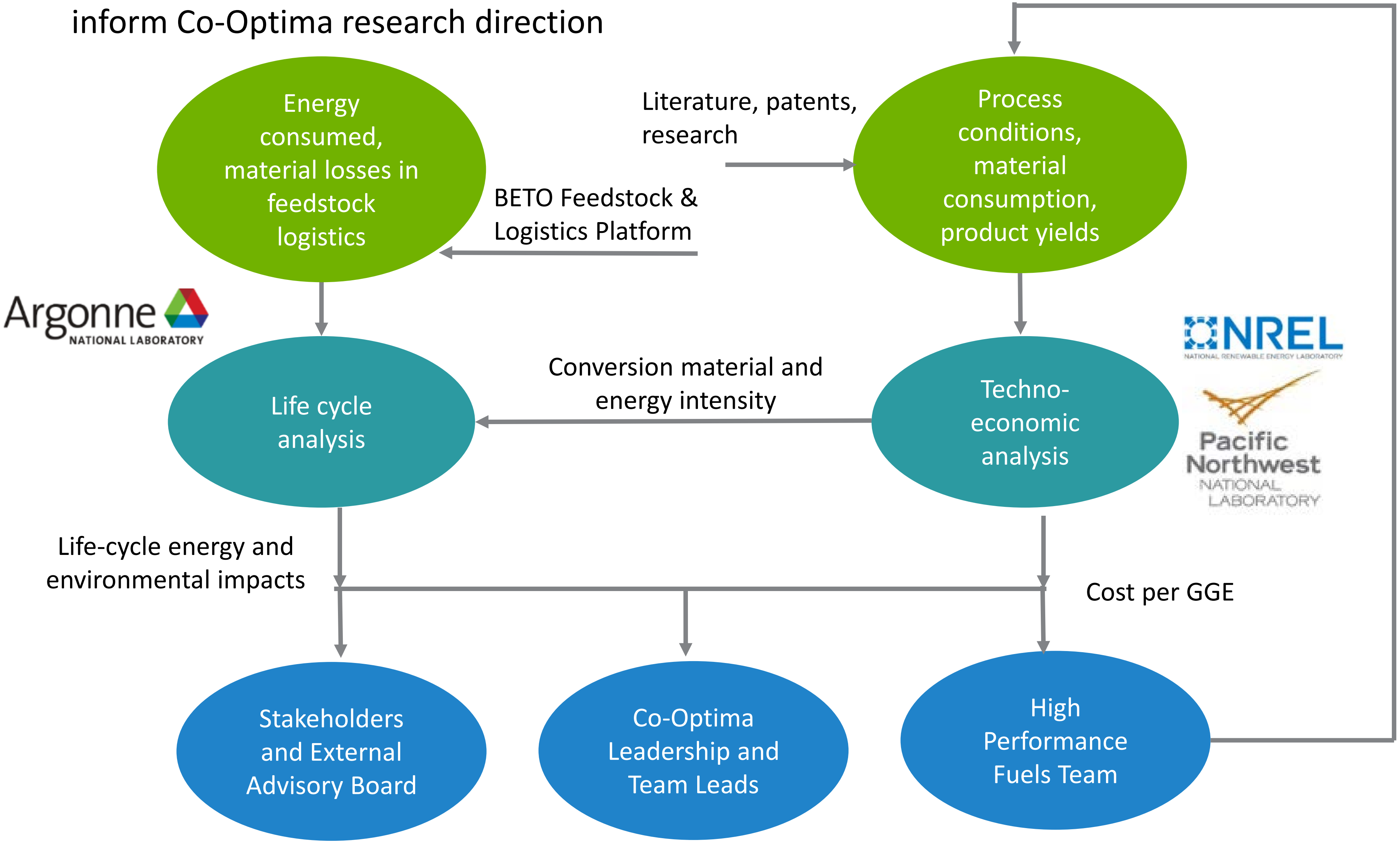
- **Analysis of Sustainability, Scale, Economics, Risk and trade (ASSERT) team** support Co-Optima goals by evaluating environmental and economic drivers and the potential of bio-blendstock candidates and assesses potential benefits or drawbacks of deploying co-optimized fuels and engines in the transportation.

- **This presentation** provide guidance into which Co-Optima bioblendstocks may be most viable economically, environmentally, & from a scalability perspective.

    - Evaluate **economic**, **environmental**, and **scalability** viability metrics of 12 MCCI bioblendstocks (via 14 pathways)
    - Conduct techno-economic and life-cycle analyses selected bioblendstocks with most favorable properties and potential.

TEA/LCA– Approach for Co-Optima

Inter-linked techno-economic and life cycle analysis inform Co-Optima research direction



Energy consumed, material losses in feedstock logistics

Literature, patents, research

Process conditions, material consumption, product yields

BETO Feedstock & Logistics Platform

Life cycle analysis

Conversion material and energy intensity

Techno-economic analysis

Life-cycle energy and environmental impacts

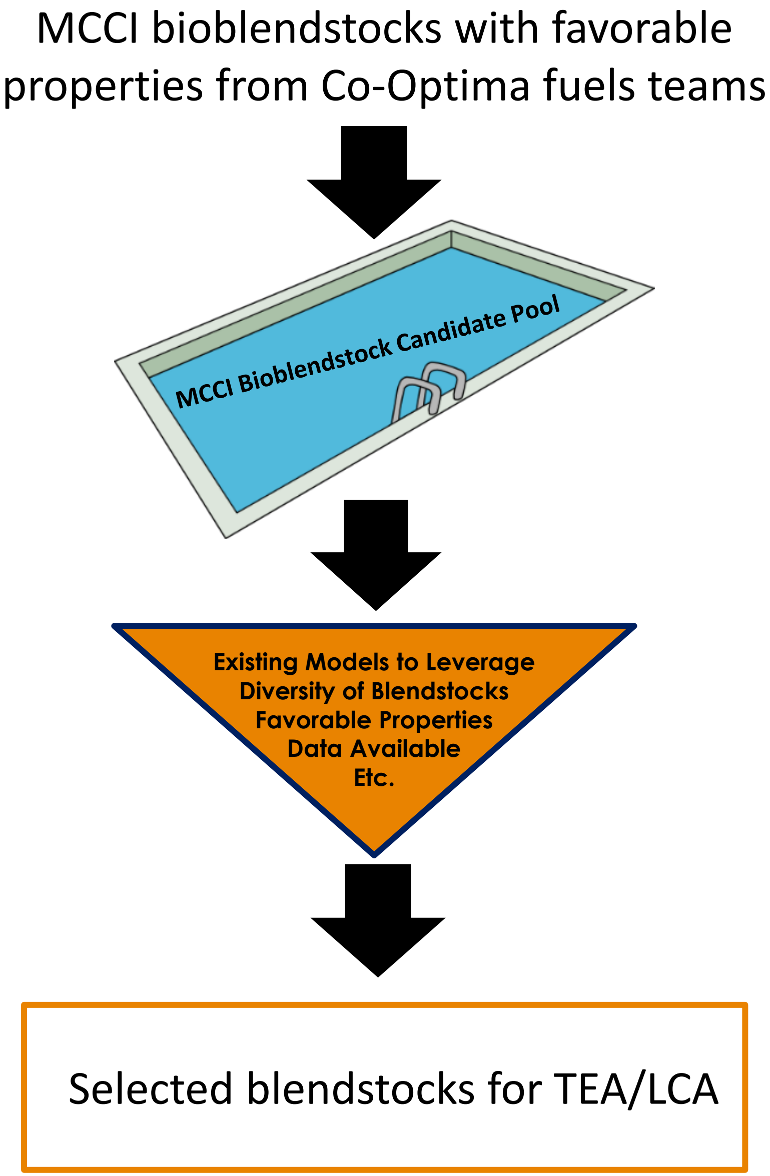
Cost per GGE

Stakeholders and External Advisory Board

Co-Optima Leadership and Team Leads

High Performance Fuels Team

Selection of Candidates



MCCI bioblendstocks with favorable properties from Co-Optima fuels teams

MCCI Bioblendstock Candidate Pool

Existing Models to Leverage
Diversity of Blendstocks
Favorable Properties
Data Available
Etc.

Selected blendstocks for TEA/LCA

- From a list of potential bioblendstocks that meet favorable MCCI fuel properties, the ASSERT team worked with the HPF and FP teams to downselect for TEA/LCA evaluation
- These fuel candidates are diesel-like with typical diesel attributes meeting cold flow, energy density, and viscosity, for example. They should also have good reactivity (cetane number of 40-50 or higher) coupled with reduced soot formation.
- Selected blendstocks were diverse in production methods, chemical structure, and feedstock

List of Evaluated Bioblendstocks

Bioblendstock	Pathways	Feedstock
Long Chain Primary Alcohols	[B] Biochemical fermentation to products	Corn Stover
Long Chain Mixed Alcohols	[B] Biochemical fermentation to ethanol with catalytic upgrading	Corn Stover
Renewable Diesel via HTL of Wet Wastes	[T] Thermochemical via hydrothermal liquefaction with hydrotreating	Wet Waste (Sludge)
Hydroxyalkanoate-Based Ethyl-Esters	[B] Biochemical fermentation to alcohols and lactic acid with catalytic upgrading of intermediates	Corn Stover
One-Step OMEs from Methanol	[T] Thermochemical methanol via syngas with further synthesis to OMEs	Forest Residues
4-Butoxyheptane	[B] Biochemical fermentation to carboxylic acids with catalytic upgrading	Corn Stover
Mixed Dioxolanes	[B] Biochemical fermentation to ethanol and BDO with catalytic upgrading of intermediates	Corn Stover
Fatty Acid Ethers (1)	Catalytic upgrading of biodiesel	60:40 Mix Soybean Oil:Yellow Grease
Fatty Acid Ethers (2)	Catalytic upgrading of biodiesel	100% Yellow Grease
Fatty Acid Ethers (3)	Catalytic upgrading of biodiesel	100% Soybean Oil
5-Ethyl-4-Propyl-Nonane	[B] Biochemical fermentation to carboxylic acids with catalytic upgrading	Corn Stover
4-(Hexyloxyl)Heptane	[B] Biochemical fermentation to carboxylic acids with catalytic upgrading	Corn Stover
Upgraded Pyrolysis Oils	[T] Thermochemical to pyrolysis oils with hydrotreating	Clean Pine
Renewable Diesel via HTL of Whole Algae	[T] Thermochemical via hydrothermal liquefaction with hydrotreating	Algae

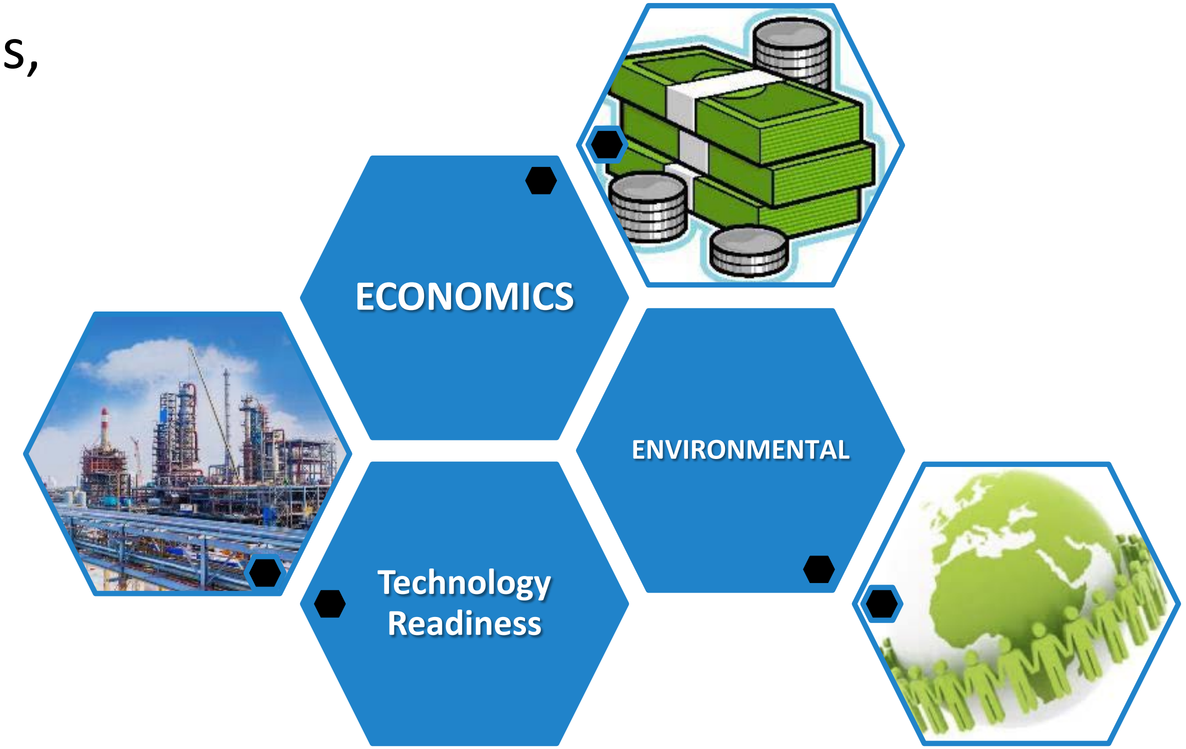
For this analysis, biochemical pathways assume lignin is burned for process heat and not upgraded to valuable co-products.   [B]: Biochemical pathway, [T]: Thermochemical pathway

Methodology

To carry out the screening, the ASSERT team developed economic and environmental metrics, including results for both the current SOT and future target cases.

A set of 19 metrics that fall into 3 categories for each metric:

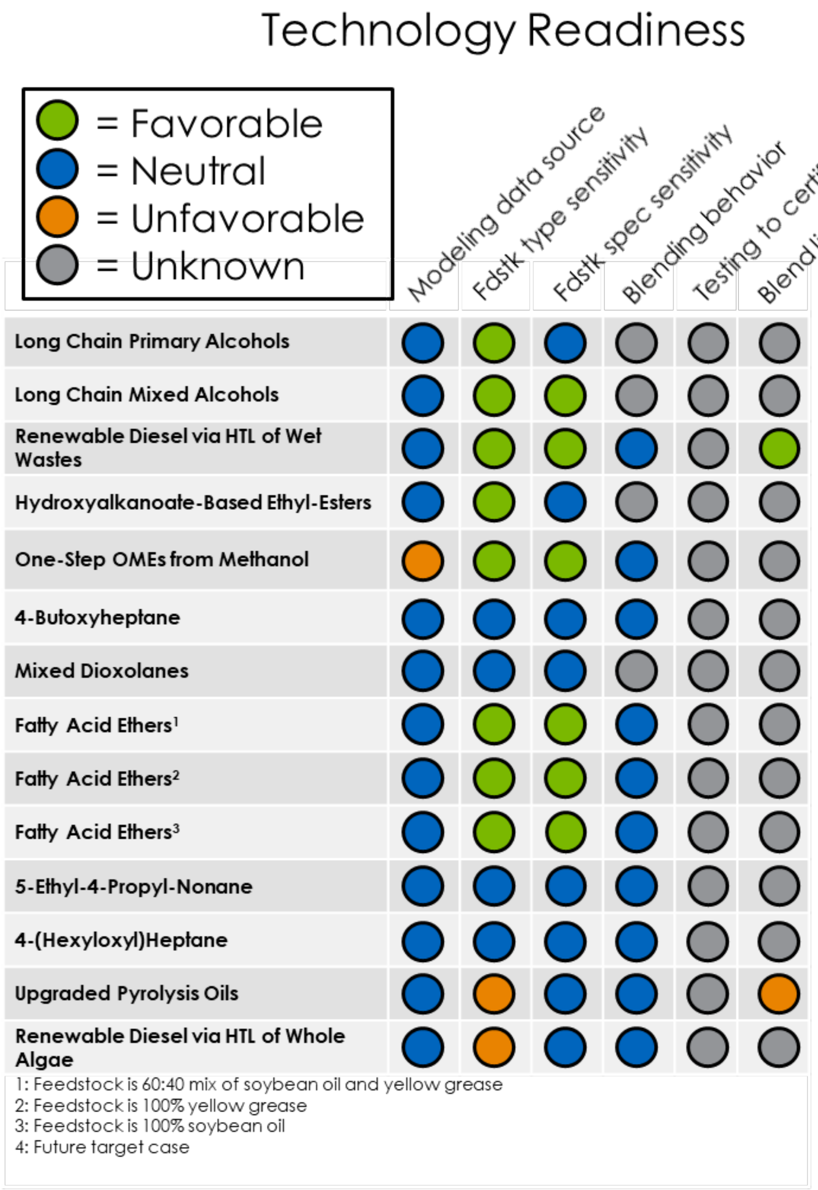
- **Favorable**
- **Neutral**
- **Unfavorable**
- **Unknown** – used in limited cases where lack of information prevents categorization of the bioblendstock for a specific metric



Technology Readiness Metrics

Metric	Favorable (+)	Neutral (0)	Unfavorable (-)
Process modeling data source	Demonstration-scale (or larger) data available, this includes detailed process analysis from literature	Bench-scale data available	Notional, yields and conversion conditions estimated partly from literature
Production process sensitivity to feedstock type	Feedstock changes result in *minor variations* in fuel yield/quality	Feedstock changes result in *some variations* in fuel yield/quality	Feedstock changes can cause *significant variations* in fuel yield/quality
Robustness of process to feedstocks of different specs	Changes in feedstock specifications *minimally* influences yield/quality	Changes in feedstock specifications *moderately* influences yield/quality	Changes in feedstock specifications *greatly* influences yield/quality
Blending behavior of bioblendstock with current fuels for use in vehicles	Current quality good enough for replacement (i.e. drop-in)	Current quality good enough for blend	Current quality in blend not good or unknown
Bioblendstock underwent testing towards certification	Yes	Limited	None
Bioblendstock will be blendable only in limited levels because of current legal limits	No limit	Blendable at high levels	Significant limit (i.e. on aromatics)

Results – Technology Readiness



Technology Readiness

🟢 = Favorable
🔵 = Neutral
🟠 = Unfavorable
⚪ = Unknown

	Modeling data source	Fdstk type sensitivity	Fdstk spec sensitivity	Blending behavior	Testing to certification	Blend limit
Long Chain Primary Alcohols	🔵	🟢	🔵	⚪	⚪	⚪
Long Chain Mixed Alcohols	🔵	🟢	🟢	⚪	⚪	⚪
Renewable Diesel via HTL of Wet Wastes	🔵	🟢	🟢	🔵	⚪	🟢
Hydroxyalkanoate-Based Ethyl-Esters	🔵	🟢	🔵	⚪	⚪	⚪
One-Step OMEs from Methanol	🟠	🟢	🟢	🔵	⚪	⚪
4-Butoxyheptane	🔵	🔵	🔵	🔵	⚪	⚪
Mixed Dioxolanes	🔵	🔵	🔵	⚪	⚪	⚪
Fatty Acid Ethers[1]	🔵	🟢	🟢	🔵	⚪	⚪
Fatty Acid Ethers[2]	🔵	🟢	🟢	🔵	⚪	⚪
Fatty Acid Ethers[3]	🔵	🟢	🟢	🔵	⚪	⚪
5-Ethyl-4-Propyl-Nonane	🔵	🔵	🔵	🔵	⚪	⚪
4-(Hexyloxy)Heptane	🔵	🔵	🔵	🔵	⚪	⚪
Upgraded Pyrolysis Oils	🔵	🟠	🔵	🔵	⚪	🟠
Renewable Diesel via HTL of Whole Algae	🔵	🟠	🔵	🔵	⚪	⚪

1: Feedstock is 60:40 mix of soybean oil and yellow grease
2: Feedstock is 100% yellow grease
3: Feedstock is 100% soybean oil
4: Future target case

- Most of the technology readiness metrics fall in the **neutral or unknown** bin.

- **Feedstock changes** to type and specs typically have little to no impact on the fuel production process and is neutral or favorable for most of the pathways.
  - In biochemical processes, feedstock recalcitrance and sugar content will be important aspects that might influence fuel production.
  - For the upgraded pyrolysis oils and HTL of whole algae pathways, the processes are highly sensitive to feedstock type, limiting flexibility of these pathways.

- Many of the Co-optima MCCI bioblendstocks are at a relatively **low TRL** and are in the early stages of testing for fuel properties and blending behavior.
  - Most modeling data sources were based on bench-scale experiments. One-step OMEs from methanol was based on thermodynamic equilibrium.
  - There is still a lot of uncertainty and lack of information regarding blending metrics, testing, and **legal** limits of these bioblendstocks. Therefore, most of the bioblendstocks fall in the “unknown” category.

Economic Viability Metrics

Metric	Favorable (+)	Neutral (0)	Unfavorable (-)
Co-Optima bioblendstock production SOT cost	Falls in cluster of lowest cost pathways (≤$5/GGE)	Falls in cluster of moderate cost pathways ($5/GGE - $7/GGE)	Falls in cluster of high cost pathways (≥$7/GGE)
Fuel production target cost	Falls in cluster of lowest cost pathways (≤$4/GGE)	Falls in cluster of moderate cost pathways ($4/GGE - $5.5/GGE)	Falls in cluster of high cost pathways (>$5.5/GGE)
Ratio of SOT-to-target cost	<2	2–4	>4
Percentage of product price dependent on co-products (i.e., chemicals, electricity, other bioblendstocks/fuels produced as co-product to Co-Optima fuel)	<30%	30–50%	>50%
Competition for the biomass-derived bioblendstock or its predecessor	Bioblendstock is not produced from, nor is itself, a valuable chemical intermediate	Bioblendstock is produced from, or is itself, a raw chemical intermediate	Bioblendstock is produced from, or is itself, a valuable chemical intermediate
Cost of feedstock (in US$2016)	Cost likely to be at or below target of $84/dry ton delivered at reactor throat	Cost likely to be between $84/dry ton to $120/dry ton delivered at reactor throat	Cost likely to exceed $120/dry ton delivered at reactor throat

Results – Economic Viability

Economic Viability

🟢 = Favorable
🔵 = Neutral
🟠 = Unfavorable
⚪ = Unknown

	Blendstock SOT Cost	Blendstock target cost	SOT:Target cost	Co-prod dependency	Market competition	Fdstk cost[4]
Long Chain Primary Alcohols	🟠	🟠	🟠	🟢	🟢	🟢
Long Chain Mixed Alcohols	🟢	🔵	🟢	🟢	🟢	🟢
Renewable Diesel via HTL of Wet Wastes	🟢	🟢	🟢	🟢	🟢	🟢
Hydroxyalkanoate-Based Ethyl-Esters	🟢	🟢	🟢	🟢	🟢	🟢
One-Step OMEs from Methanol	⚪	🔵	⚪	🟢	🟢	🟢
4-Butoxyheptane	🔵	🟠	🟢	🟢	🟢	🟢
Mixed Dioxolanes	🔵	🟠	🟢	🟢	🟢	🟢
Fatty Acid Ethers[1]	🔵	🔵	🟢	🟢	🟠	🟠
Fatty Acid Ethers[2]	🔵	🟢	🟢	🟢	🟠	🟠
Fatty Acid Ethers[3]	🔵	🔵	🟢	🟢	🟠	🟠
5-Ethyl-4-Propyl-Nonane	🟠	🔵	🟢	🟢	🟢	🟢
4-(Hexyloxyl)Heptane	🟠	🔵	🟢	🟢	🟢	🟢
Upgraded Pyrolysis Oils	🟢	🟢	🟢	🟢	🟢	🔵
Renewable Diesel via HTL of Whole Algae	🟠	🔵	🟢	🟢	🟢	🟠

1: Feedstock is 60:40 mix of soybean oil and yellow grease
2: Feedstock is 100% yellow grease
3: Feedstock is 100% soybean oil
4: Future target case

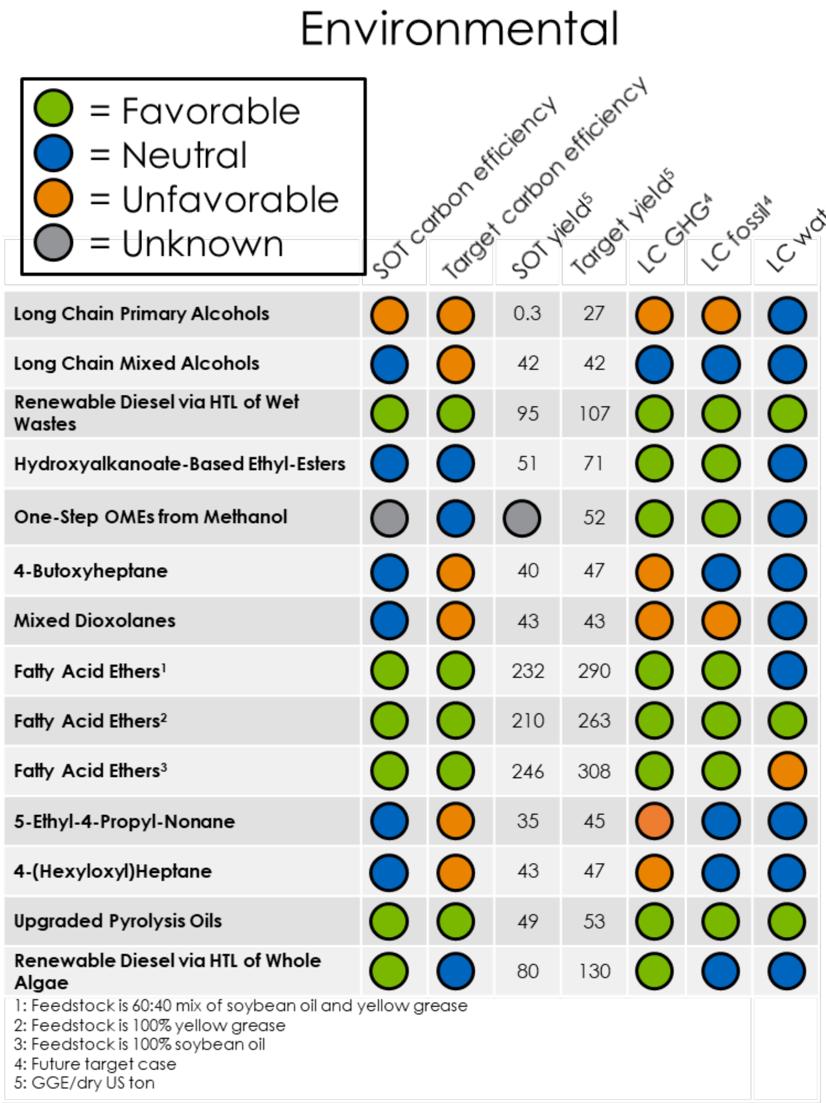
- Most of the economic viability metrics fall in the **favorable** bin.
- Since SOT and target costs were compared relative to each-other, there were ~1/3 in each favorability bin.
  - **Four pathways fell at or below $5/GGE for SOT cases**. Upgraded pyrolysis oils had the lowest SOT cost.
  - Under target case assumptions, **four pathways offer the potential of $4/GGE fuel selling price or less.** Diesel via HTL of wet wastes and hydroxyalkanoate-based ethyl esters offered the lowest potential target costs.
- **SOT:Target cost ratios** were almost all favorable. This indicates lower levels of research and development required to reach target production costs.
- **Co-product dependency** (i.e. on electricity, co-produced fuels, etc.) was low for all pathways.
- Most **market competition** for either the produced fuel or feedstock was low. Fatty acid ethers relied on FOG feedstocks with already established markets.
- A majority of pathways had **feedstock costs** falling at or below $84/dry US ton. Fatty acid ethers and HTL of whole algae had feedstock costs of over $500/dry US ton, but this was made up for in higher energy density or processability.

Environmental Impact Metrics

Metric	Favorable (+)	Neutral (0)	Unfavorable (-)
SOT: Efficiency of input carbon (fossil and biomass-derived) to Co-Optima bioblendstock	>30%	10–30%	<10%
Target: Efficiency of input carbon (fossil and biomass -derived) to Co-Optima bioblendstock	>40%	30–40%	<30%
SOT: Co-Optima bioblendstock yield (GGE/dry ton)*			
Target: Co-Optima bioblendstock yield (GGE/dry ton)*			
Target: Life-cycle GHG emissions	Likely to achieve a greater than 60% reduction in life-cycle GHG emissions as compared to conventional diesel in 2019.	Could achieve a greater than 60% reduction in life-cycle GHG emissions as compared to conventional diesel in 2019.	Unlikely to achieve a greater than 60% reduction in life-cycle GHG emissions as compared to conventional diesel in 2019.
Target: Life-cycle fossil energy consumption	Likely to use less fossil energy on a life-cycle basis than conventional diesel in 2019.	Could use less fossil energy on a life-cycle basis than conventional diesel in 2019.	Unlikely to use less fossil energy on a life-cycle basis than conventional diesel in 2019.
Target: Life-cycle water consumption	Likely to use less water on a life-cycle basis than 3 gal/gge.	Could use less water on a life-cycle basis than 55 gal/gge.	Could use more water on a life-cycle basis than 55 gal/gge.

* SOT and target bioblendstock yields were included for reference, but were not ranked on favorability due to different comparative bases on pathways and feedstocks

Results – Environmental Impact



Environmental

- 🟢 = Favorable
- 🔵 = Neutral
- 🟠 = Unfavorable
- ⚪ = Unknown

	SOT carbon efficiency	Target carbon efficiency	SOT yield[5]	Target yield[5]	LC GHG[4]	LC fossil[4]	LC water[4]
Long Chain Primary Alcohols	🟠	🟠	0.3	27	🟠	🟠	🔵
Long Chain Mixed Alcohols	🔵	🟠	42	42	🔵	🔵	🔵
Renewable Diesel via HTL of Wet Wastes	🟢	🟢	95	107	🟢	🟢	🟢
Hydroxyalkanoate-Based Ethyl-Esters	🔵	🔵	51	71	🟢	🟢	🔵
One-Step OMEs from Methanol	⚪	🔵	⚪	52	🟢	🟢	🔵
4-Butoxyheptane	🔵	🟠	40	47	🟠	🔵	🔵
Mixed Dioxolanes	🔵	🟠	43	43	🟠	🟠	🔵
Fatty Acid Ethers[1]	🟢	🟢	232	290	🟢	🟢	🔵
Fatty Acid Ethers[2]	🟢	🟢	210	263	🟢	🟢	🟢
Fatty Acid Ethers[3]	🟢	🟢	246	308	🟢	🟢	🟠
5-Ethyl-4-Propyl-Nonane	🔵	🟠	35	45	🟠	🔵	🔵
4-(Hexyloxyl)Heptane	🔵	🟠	43	47	🟠	🔵	🔵
Upgraded Pyrolysis Oils	🟢	🟢	49	53	🟢	🟢	🟢
Renewable Diesel via HTL of Whole Algae	🟢	🔵	80	130	🟢	🔵	🔵

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2: Feedstock is 100% yellow grease
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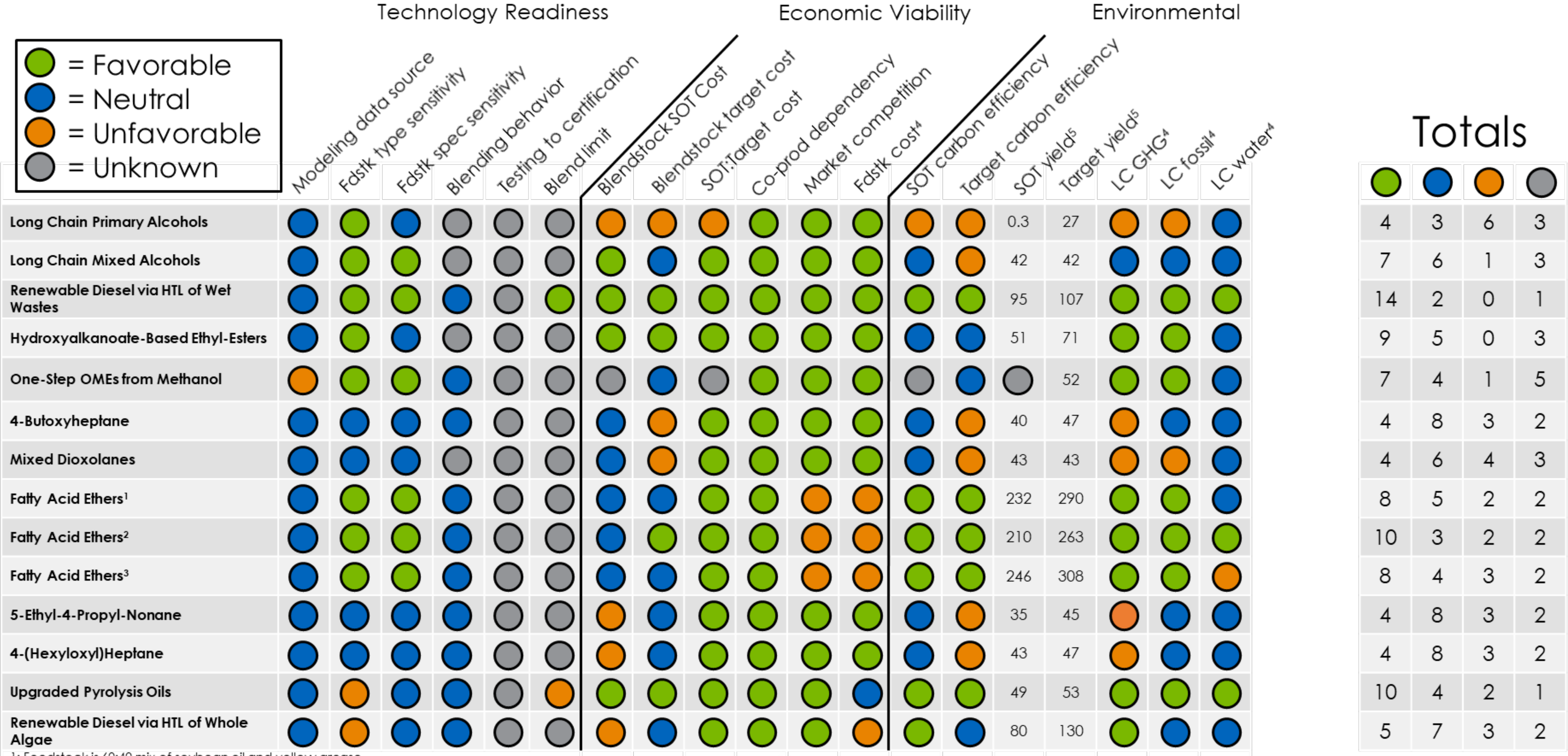
4: Future target case
5: GGE/dry US ton

- Environmental impact metrics were **approximately equally distributed** across the categories.

- **Carbon efficiency** was highest for fatty acid ethers, HTL of wet wastes and upgraded pyrolysis oils among all bioblendstocks.
  - Fatty acid ethers had the highest yields
  - Thermochemical pathways tended to have higher yields than biochemical pathways.
- **Water consumption** was favorable for only three pathways.
  - Fatty acid ethers[3] was the only unfavorable pathway due to its dependency on 100% soybean oil, produced from a water intensive crop.

- **Eight of the twelve pathways show favorable life-cycle greenhouse gas and fossil energy consumption reductions (>60%),** compared to those of conventional diesel fuel (ULSD) diesel.
  - The biggest contributor to GHG emissions is sodium hydroxide, a very GHG intensive chemical.
  - Electricity requirements were also significant contributors to GHG emissions. These were higher for biochemical pathways, with electricity required in mechanical refining step of corn-stover pretreatment.
  - Valorizing lignin has potential to reduce GHG emissions by 50% to 271% relative to petroleum diesel the the case of 4-butoxyheptane, depending on the co-product treatment used (Huq et al., 2019).

Results - Overall



🟢 = Favorable
🔵 = Neutral
🟠 = Unfavorable
⚪ = Unknown

	Technology Readiness						Economic Viability						Environmental							Totals			
	Modeling data source	Fdstk type sensitivity	Fdstk spec sensitivity	Blending behavior	Testing to certification	Blend limit	Blendstock SOT Cost	Blendstock target cost	SOT:Target cost	Co-prod dependency	Market competition	Fdstk cost[4]	SOT carbon efficiency	Target carbon efficiency	SOT yield[5]	Target yield[5]	LC GHG[4]	LC fossil[4]	LC water[4]	🟢	🔵	🟠	⚪
Long Chain Primary Alcohols	🔵	🟢	🔵	⚪	⚪	⚪	🟠	🟠	🟠	🟢	🟢	🟢	🟠	🟠	0.3	27	🟠	🟠	🔵	4	3	6	3
Long Chain Mixed Alcohols	🔵	🟢	🟢	⚪	⚪	⚪	🟢	🔵	🟢	🟢	🟢	🟢	🔵	🟠	42	42	🔵	🔵	🔵	7	6	1	3
Renewable Diesel via HTL of Wet Wastes	🔵	🟢	🟢	🔵	⚪	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🟢	95	107	🟢	🟢	🟢	14	2	0	1
Hydroxyalkanoate-Based Ethyl-Esters	🔵	🟢	🔵	⚪	⚪	⚪	🟢	🟢	🟢	🟢	🟢	🟢	🔵	🔵	51	71	🟢	🟢	🔵	9	5	0	3
One-Step OMEs from Methanol	🟠	🟢	🟢	🔵	⚪	⚪	⚪	🔵	⚪	🟢	🟢	🟢	⚪	🔵	⚪	52	🟢	🟢	🔵	7	4	1	5
4-Butoxyheptane	🔵	🔵	🔵	🔵	⚪	⚪	🔵	🟠	🟢	🟢	🟢	🟢	🔵	🟠	40	47	🟠	🔵	🔵	4	8	3	2
Mixed Dioxolanes	🔵	🔵	🔵	⚪	⚪	⚪	🔵	🟠	🟢	🟢	🟢	🟢	🔵	🟠	43	43	🟠	🟠	🔵	4	6	4	3
Fatty Acid Ethers[1]	🔵	🟢	🟢	🔵	⚪	⚪	🔵	🔵	🟢	🟢	🟠	🟠	🟢	🟢	232	290	🟢	🟢	🔵	8	5	2	2
Fatty Acid Ethers[2]	🔵	🟢	🟢	🔵	⚪	⚪	🔵	🟢	🟢	🟢	🟠	🟠	🟢	🟢	210	263	🟢	🟢	🟢	10	3	2	2
Fatty Acid Ethers[3]	🔵	🟢	🟢	🔵	⚪	⚪	🔵	🔵	🟢	🟢	🟠	🟠	🟢	🟢	246	308	🟢	🟢	🟠	8	4	3	2
5-Ethyl-4-Propyl-Nonane	🔵	🔵	🔵	🔵	⚪	⚪	🟠	🔵	🟢	🟢	🟢	🟢	🔵	🟠	35	45	🟠	🔵	🔵	4	8	3	2
4-(Hexyloxyl)Heptane	🔵	🔵	🔵	🔵	⚪	⚪	🟠	🔵	🟢	🟢	🟢	🟢	🔵	🟠	43	47	🟠	🔵	🔵	4	8	3	2
Upgraded Pyrolysis Oils	🔵	🟠	🔵	🔵	⚪	🟠	🟢	🟢	🟢	🟢	🟢	🔵	🟢	🟢	49	53	🟢	🟢	🟢	10	4	2	1
Renewable Diesel via HTL of Whole Algae	🔵	🟠	🔵	🔵	⚪	⚪	🟠	🔵	🟢	🟢	🟢	🟠	🟢	🔵	80	130	🟢	🔵	🔵	5	7	3	2

1: Feedstock is 60:40 mix of soybean oil and yellow grease
2: Feedstock is 100% yellow grease
3: Feedstock is 100% soybean oil
4: Future target case
5: GGE/dry US ton

Summary

- This process to screen the candidate bioblendstocks against the ASSERT metrics has provided insights into the technology readiness, economic, and environmental impact attributes of the 14 bioblendstocks pathways studied in this report

- Challenges for the evaluated bioblendstocks are in the blending behavior and testing for legal limits as most of the "unknown" classification dominates in this technology readiness metric. Therefore, more analyses and testing on blendability and legal limits are needed for these candidates.

- Most of the conversion technologies are robust and will be minimally affected by the feedstock specifications and variations.

- Favorable classification dominated in economic metrics evaluation for most of the bioblendstocks candidates and further economic and environmental improvements could be realized in biochemical pathways when lignin valorization is included.

- Energy intensive processes and the use of GHG intensive chemicals such as sodium hydroxide contribute significantly to the GHG emissions of pathways.

Researchers

THANK YOU

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Backup Slides

ASSERT overview

ASSERT: Analysis of Sustainability, Scale, Economics, Risk and trade.

The ASSERT team supports Co-Optima goals by:

- Evaluating environmental and economic drivers and the potential of bio-blendstock candidates
- Sharing these key outputs with the teams and stakeholders
- Guiding the Co-Optima's research and development

ASSERT also assesses potential benefits or drawbacks of deploying co-optimized fuels and engines in the transportation sector with respect to:

- Energy consumption, harmful emissions and water consumption
- Job creation
- Development of markets for biomass
- Technology readiness for scale up in the near term
- Economic viability

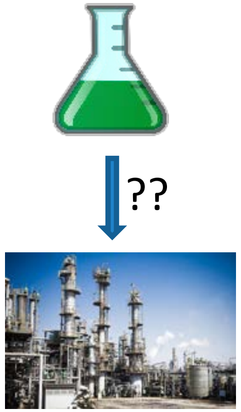
Introduction

- **Overall Objective:** Provide guidance & insights into which Co-Optima bioblendstocks may be most viable economically, environmentally, & from a scalability perspective. Communicate the results of this analysis to Co-Optima leadership, technical teams, & stakeholders.
  - ➢ Insights into the **economic**, **environmental**, and **scalability** viability of 13 MCCI bioblendstocks (via 15 pathways) using metrics developed for HD bio-blendstocks.

- How?
  - Through TEA/LCA to evaluate metrics for selected bioblendstocks with most favorable properties and potential.

Metrics Classification

- Technology Readiness
  - Asks the question: How far along is the blendstock on the path to commercialization and is it scalable?

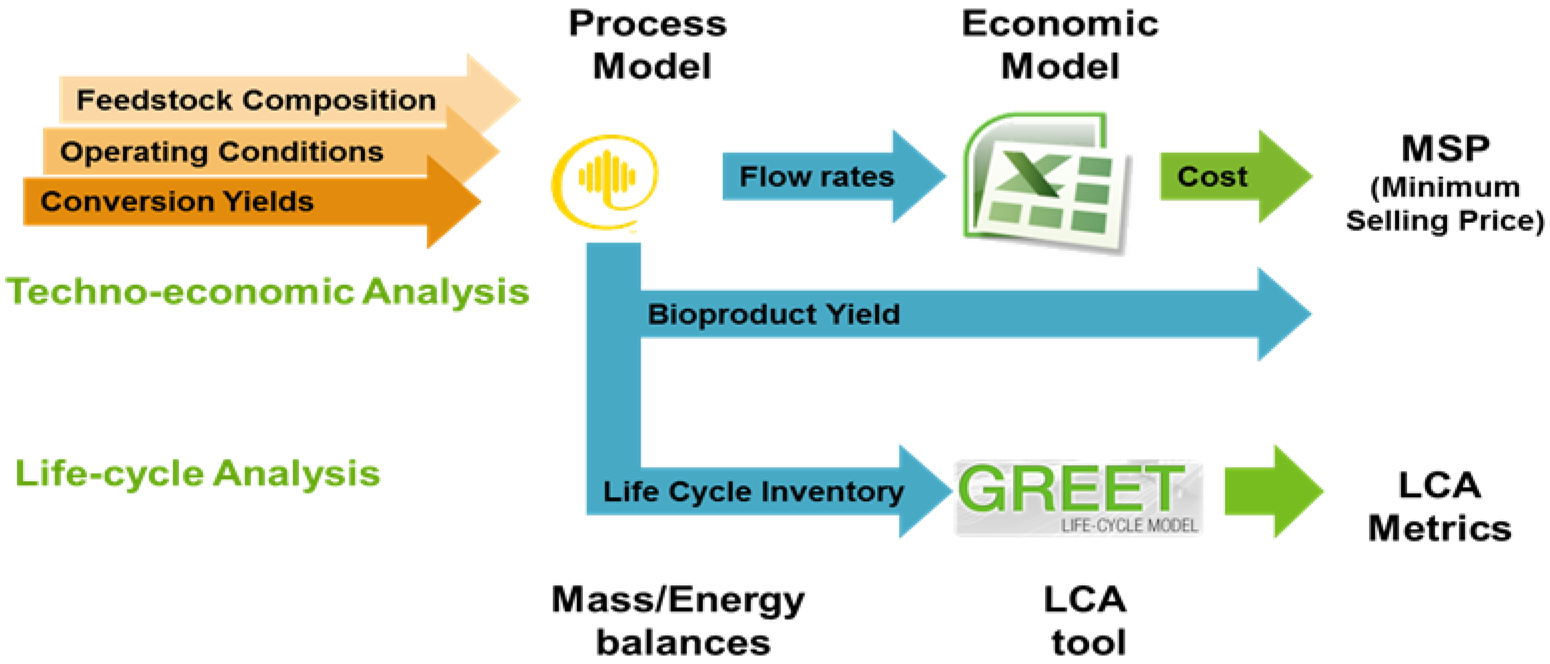


- Economic Viability
  - Asks the question: What’s it going to cost to produce and are the economics favorable?

- Environmental Impact
  - Asks the question: What will be the environmental impacts of blendstock production compared to fossil fuels?

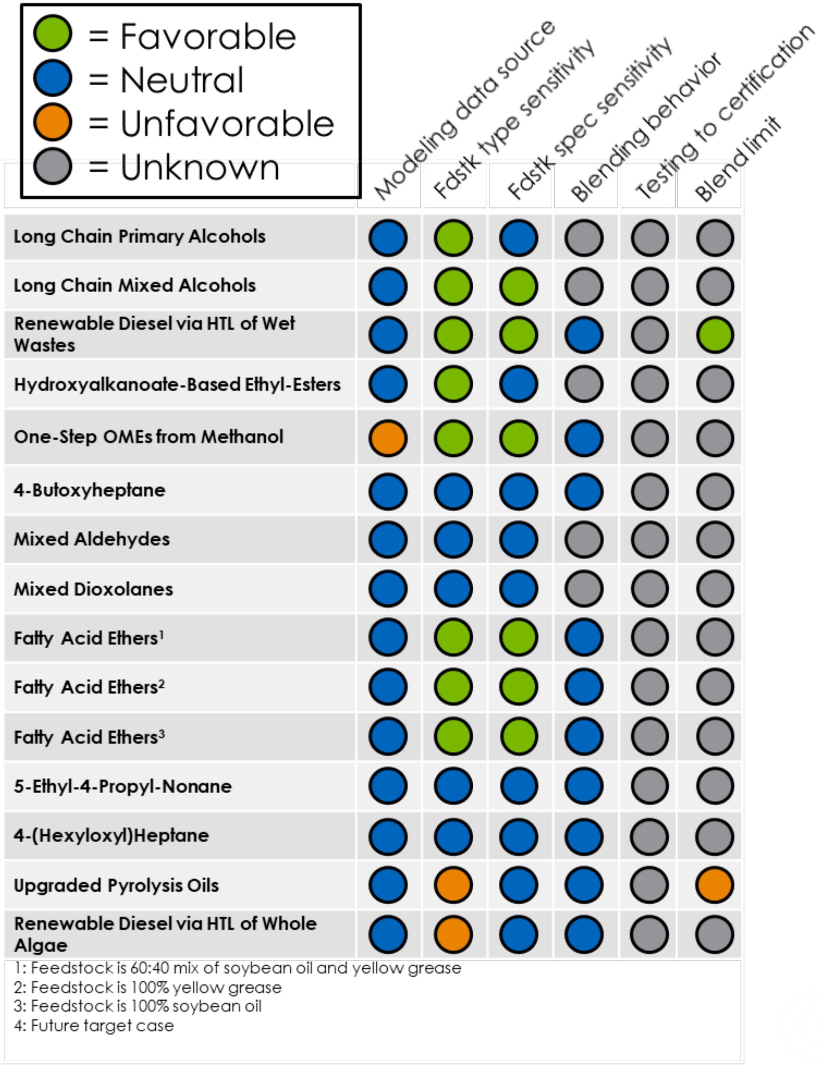
TEA/LCA– Approach for Co-Optima

- Modeling is rigorous and detailed with transparent assumptions
- Assumes nth plant equipment costs
- Typical scale of 2000 dry metric tons/day biomass feed (dependent on feedstock)
- Discounted cash flow calculation includes return on investment, equity payback and taxes
- Identify research targets and measure research progress
- Assess environmental impacts (greenhouse gas emissions, fossil fuel consumption and water consumption)



Results – Technology Readiness

Technology Readiness



🟢 = Favorable
🔵 = Neutral
🟠 = Unfavorable
⚪ = Unknown

	Modeling data source	Fdstk type sensitivity	Fdstk spec sensitivity	Blending behavior	Testing to certification	Blend limit
Long Chain Primary Alcohols	🔵	🟢	🔵	⚪	⚪	⚪
Long Chain Mixed Alcohols	🔵	🟢	🟢	⚪	⚪	⚪
Renewable Diesel via HTL of Wet Wastes	🔵	🟢	🟢	🔵	⚪	🟢
Hydroxyalkanoate-Based Ethyl-Esters	🔵	🟢	🔵	⚪	⚪	⚪
One-Step OMEs from Methanol	🟠	🟢	🟢	🔵	⚪	⚪
4-Butoxyheptane	🔵	🔵	🔵	🔵	⚪	⚪
Mixed Aldehydes	🔵	🔵	🔵	⚪	⚪	⚪
Mixed Dioxolanes	🔵	🔵	🔵	⚪	⚪	⚪
Fatty Acid Ethers[1]	🔵	🟢	🟢	🔵	⚪	⚪
Fatty Acid Ethers[2]	🔵	🟢	🟢	🔵	⚪	⚪
Fatty Acid Ethers[3]	🔵	🟢	🟢	🔵	⚪	⚪
5-Ethyl-4-Propyl-Nonane	🔵	🔵	🔵	🔵	⚪	⚪
4-(Hexyloxyl)Heptane	🔵	🔵	🔵	🔵	⚪	⚪
Upgraded Pyrolysis Oils	🔵	🟠	🔵	🔵	⚪	🟠
Renewable Diesel via HTL of Whole Algae	🔵	🟠	🔵	🔵	⚪	⚪

1: Feedstock is 60:40 mix of soybean oil and yellow grease
2: Feedstock is 100% yellow grease
3: Feedstock is 100% soybean oil
4: Future target case

- Many of the co-optima MCCI bioblendstocks are at a relatively **low TRL** and are in the early stages of testing for fuel properties and blending behavior.
  - Most modeling data sources were based on bench-scale experiments. One-step OMEs from methanol was based on thermodynamic equilibrium.
  - There is still a lot of uncertainty and lack of information regarding blending metrics, testing, and **legal** limits of these bioblendstocks. Therefore, most of the bioblendstocks fall in the "unknown" category.

Results – Economic Viability

Economic Viability

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	Blendstock SOT Cost	Blendstock target cost	SOT:Target cost	Co-prod dependency	Market competition	Fdstk cost[4]
Long Chain Primary Alcohols	🟠	🟠	🟠	🟢	🟢	🟢
Long Chain Mixed Alcohols	🟢	🔵	🟢	🟢	🟢	🟢
Renewable Diesel via HTL of Wet Wastes	🟢	🟢	🟢	🟢	🟢	🟢
Hydroxyalkanoate-Based Ethyl-Esters	🟢	🟢	🟢	🟢	🟢	🟢
One-Step OMEs from Methanol	⚪	🔵	⚪	🟢	🟢	🟢
4-Butoxyheptane	🔵	🟠	🟢	🟢	🟢	🟢
Mixed Aldehydes	🔵	🔵	🟢	🟢	🟢	🟢
Mixed Dioxolanes	🔵	🟠	🟢	🟢	🟢	🟢
Fatty Acid Ethers[1]	🔵	🔵	🟢	🟢	🟠	🟠
Fatty Acid Ethers[2]	🔵	🟢	🟢	🟢	🟠	🟠
Fatty Acid Ethers[3]	🔵	🔵	🟢	🟢	🟠	🟠
5-Ethyl-4-Propyl-Nonane	🟠	🔵	🟢	🟢	🟢	🟢
4-(Hexyloxyl)Heptane	🟠	🔵	🟢	🟢	🟢	🟢
Upgraded Pyrolysis Oils	🟢	🟢	🟢	🟢	🟢	🔵
Renewable Diesel via HTL of Whole Algae	🟠	🔵	🟢	🟢	🟢	🟠

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4: Future target case

*Davis et al. NREL/TP-5100-71949, 2018

- Co-product dependency (i.e. on electricity, co-produced fuels, etc.) was low for all pathways.
    - Biochemically-produced bioblendstocks did not include lignin valorization in their evaluation. Target production costs are likely to be significantly reduced with additional coproduct creation for these pathways.*
- Most market competition for either the produced fuel or feedstock was low. Fatty acid ethers relied on FOG feedstocks with already established markets.
- A majority of pathways had feedstock costs falling at or below $84/dry US ton. Fatty acid ethers and HTL of whole algae had feedstock costs of over $500/dry US ton, but this was made up for in higher energy density or processability.

Results – Environmental Impact

Environmental

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🔵 = Neutral
🟠 = Unfavorable
⚫ = Unknown

	SOT carbon efficiency	Target carbon efficiency	SOT yield[5]	Target yield[5]	LC GHG[4]	LC fossil[4]	LC water[4]
Long Chain Primary Alcohols	🟠	🟠	0.3	27	🟠	🟠	🔵
Long Chain Mixed Alcohols	🔵	🟠	42	42	🔵	🔵	🔵
Renewable Diesel via HTL of Wet Wastes	🟢	🟢	95	107	🟢	🟢	🟢
Hydroxyalkanoate-Based Ethyl-Esters	🔵	🔵	51	71	🟢	🟢	🔵
One-Step OMEs from Methanol	⚫	🔵	⚫	52	🟢	🟢	🔵
4-Butoxyheptane	🔵	🟠	40	47	🟠	🔵	🔵
Mixed Aldehydes	🔵	🟠	44	44	🟠	🔵	🔵
Mixed Dioxolanes	🔵	🟠	43	43	🟠	🟠	🔵
Fatty Acid Ethers[1]	🟢	🟢	232	290	🟢	🟢	🔵
Fatty Acid Ethers[2]	🟢	🟢	210	263	🟢	🟢	🟢
Fatty Acid Ethers[3]	🟢	🟢	246	308	🟢	🟢	🟠
5-Ethyl-4-Propyl-Nonane	🔵	🟠	35	45	🟠	🔵	🔵
4-(Hexyloxyl)Heptane	🔵	🟠	43	47	🟠	🔵	🔵
Upgraded Pyrolysis Oils	🟢	🟢	49	53	🟢	🟢	🟢
Renewable Diesel via HTL of Whole Algae	🟢	🔵	80	130	🟢	🔵	🔵

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5: GGE/dry US ton

- **Eight bioblendstock pathways show significant reduction in GHG emissions and favorable fossil energy consumption reduction** ranging from 63% to 80% and 60% to 81% less GHG emission and fossil fuel consumption, respectively, compared to those of conventional diesel fuel (ULSD) diesel.
  - The biggest contributor to GHG emissions is sodium hydroxide, a very GHG intensive chemical.
  - Electricity requirements were also significant contributors to GHG emissions. These were higher for biochemical pathways, with electricity required in mechanical refining step of corn-stover pretreatment.
  - Valorizing lignin has potential to reduce GHG emissions by 50% to 271% relative to petroleum diesel the the case of 4-butoxyheptane, depending on the co-product treatment used (Huq et al., 2019).