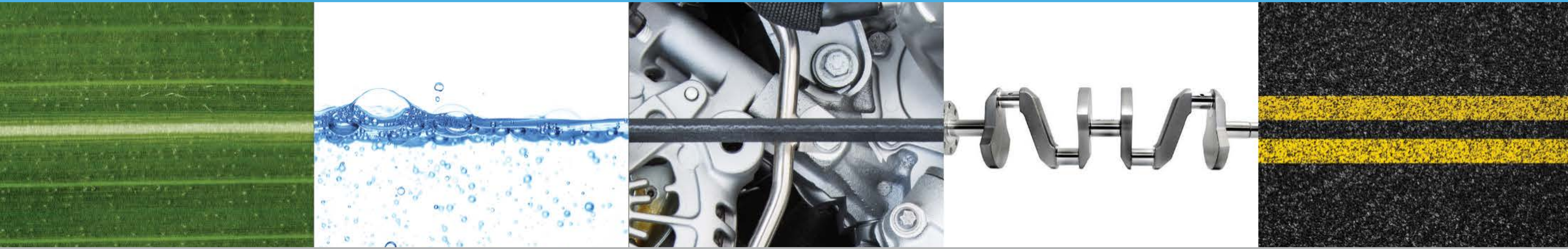
DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

Co-Optima Program: Potential Impact at Scale

Avantika Singh
National Renewable Energy Laboratory
(on behalf of the Analysis Team)
March 15, 2021

CO-OPTIMIZATION OF
FUELS & ENGINES

better fuels | better vehicles | sooner



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Project Overview

What we do within Co-Optima for impact and refinery integration analysis

Goal

Estimate the potential benefits of Co-Optima technologies if adopted at scale

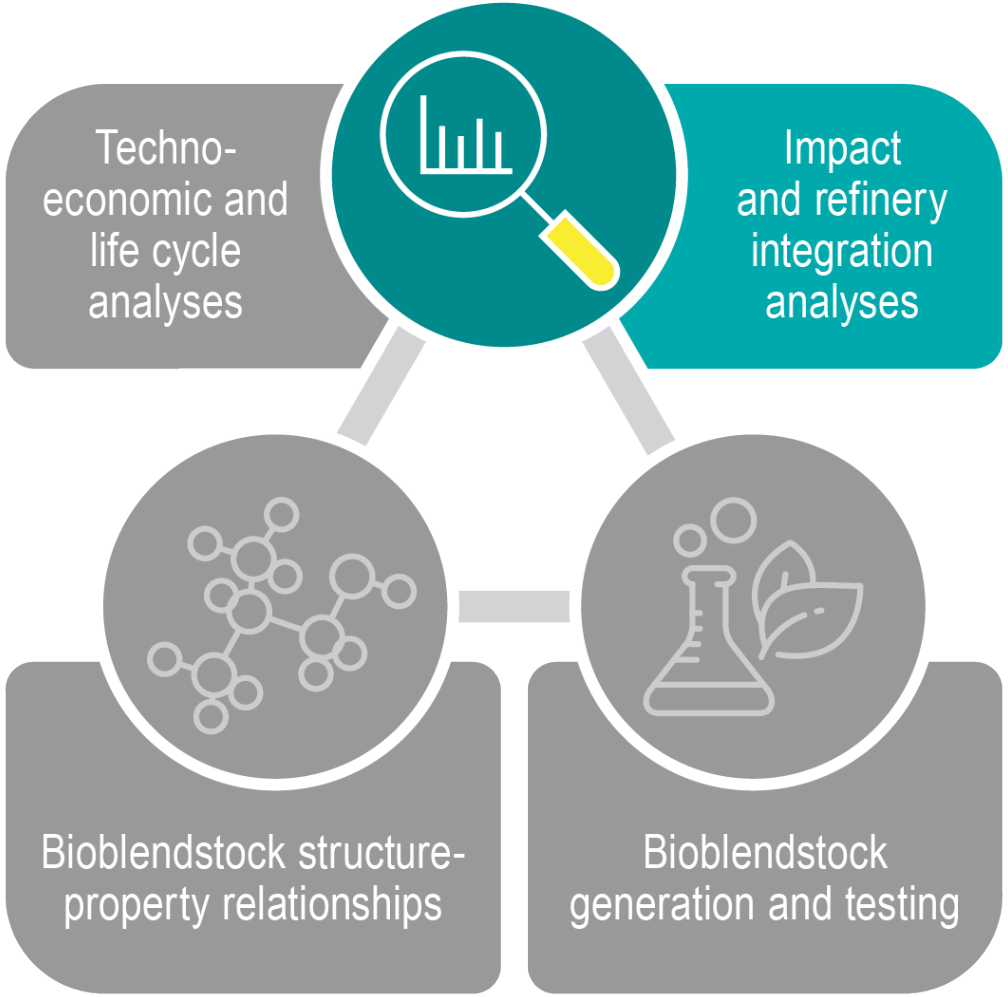
Approach

Deploy state-of-the-art integrated modeling tools using informed inputs from Co-Optima research

Relevance

Addresses BETO Goals to:

1. Quantify economy-wide benefits from the deployment of Co-optimized fuels/engines in the light- and heavy- duty sectors
2. Identify value of performance advantaged biofuels to the refiners
3. Measure environmental and socio-economic benefits to the community



1- Management

1. Management

Analysis team interacts with every Co-Optima team and guidance from leadership team

Advanced Engine Development

Provides engine efficiency & emissions data for fuels/combustion strategies

Toolkit Development

Provides estimated engine performance prior to engine testing

Techno-economic and life cycle analyses

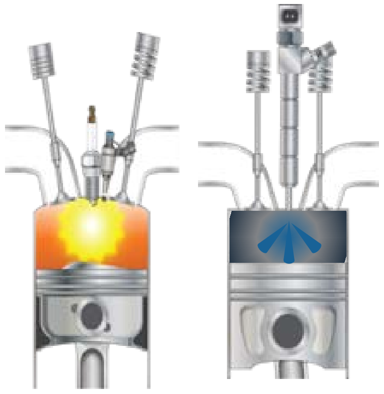
Impact and refinery integration analyses

Refinery Impact Analysis

Vehicle Adoption

Economy-wide Benefits

Considering both LD and HD modes



Light Duty Gasoline Fuels

Heavy Duty Diesel Fuels

High Performance Fuels

Identify bioblendstock pathways & provide conversion data

Fuel Properties

Inputs on relevant fuel properties and their blending with conventional fuels

Analysis team estimates economic and sustainability implications

1. Management

Analysis experts representing core capabilities from different national labs

Troy Hawkins (Lead)

Avantika Singh (Deputy Lead)

Andre Avelino

Aaron Brooker

Hao Cai

Nick Carlson

Scott Curran

Jennifer Dunn

Yuan Jiang

Shuyun Li

Doug Longman

Emily Newes

Doris Oke

Longwen Ou

Lauren Sittler

Scott Sluder

Mike Talmadge

Magdelena Ramirez

Ram Vijayagopal

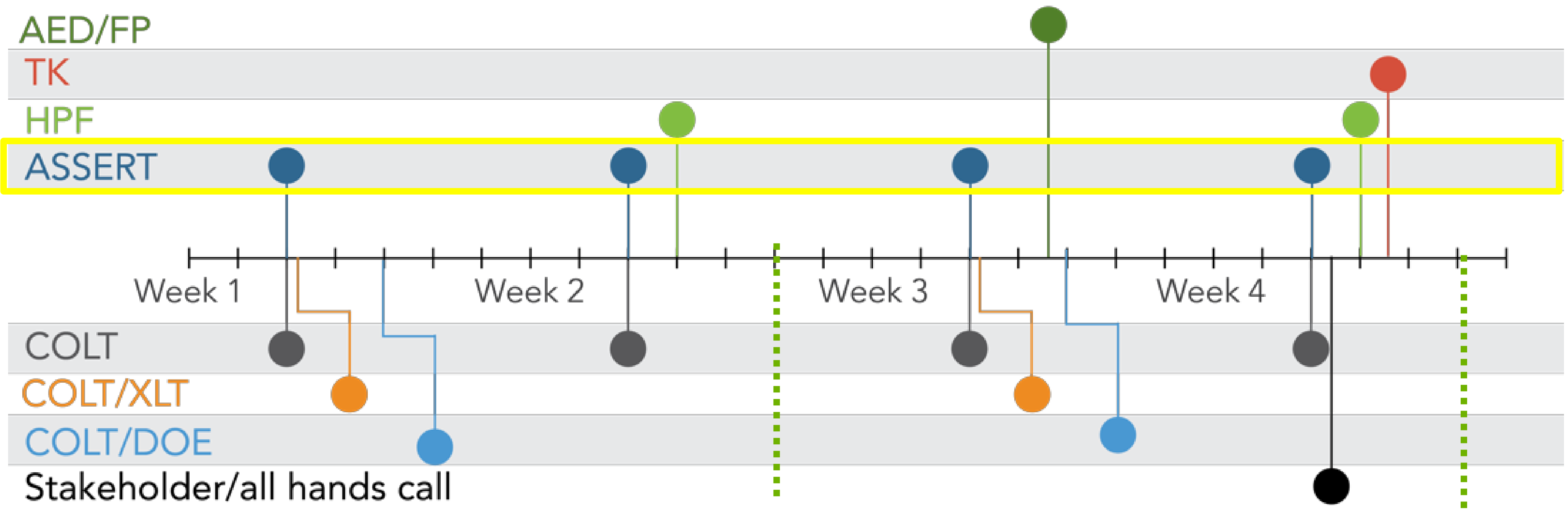
Yimin Zhang

Greg Zaimes

1. Management

Coordination, Collaboration, and Communication

Co-Optima regularly scheduled meetings



Coordination & update meeting between analysis tasks

Monthly updates to Co-Optima teams and stakeholders

External Stakeholders

Quarterly External Advisory Board Meetings

Conference Presentations and Posters

Upcoming Co-Optima Capstone Webinars

1. Management

Data availability and delays in data/results handoffs are risks for the analysis team

Analysis Major Risk Factors	Risk Mitigation Strategy
Lack of complete bioblendstock properties or their blending data with conventional fuels at the time of measurements	Work with fuel properties **Co-Optima Fuel Property** team for additional measurements or perform estimates using process modeling tools
Delays or disruption in the timeline for data flow, such as engine efficiency tests, which inform vehicle adoption models	Engage **Advanced Engine Development** team and **industry partners** to explore a range of key parameters and perform sensitivity analysis

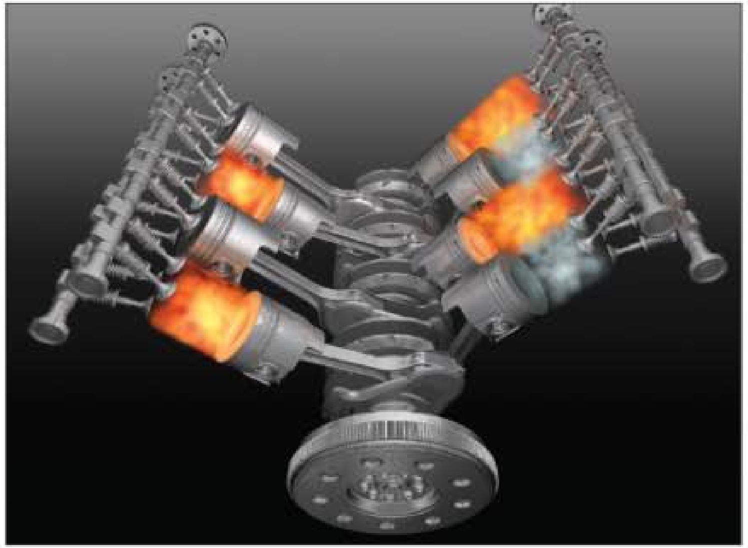
Critical path managed closely with internal and external milestones

2- Approach

2. Approach

Foundational technical questions frame approach

What fuels do engines *really* want?

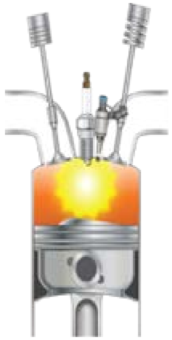


What fuel options work best?

What will work in the real world?

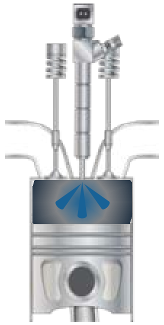
2. Approach

Integrated modeling tools for measuring potential impact of light- and heavy-duty modes



Light Duty
RON / MON / S
Energy Density
Flash / Boil / Freeze
RVP / HOV
Sooting

Light-Duty and Heavy-Duty Fuels and Combustion Modes



Heavy Duty
Cetane
Energy Density
Flash / Boil / Freeze
Water Sol
Sooting

Refinery Benefits
What is the value of Co-Optima bioblendstocks to the refining industry?

Vehicle Adoption
How would Co-Optima fuels and vehicles technology penetrate the market?

Economy-wide Benefits
Any socio-economic benefits of Co-Optima fuels/vehicle adoption?

2. Approach: Refinery Impact Analysis

Quantifies potential bio-blendstock value to refiners using linear programming tools

Refinery Benefits

What is the value of Co-Optima bio-blendstocks to the refining industry?

Techno-Economic Analysis
Quantifies production cost for bio-blendstocks

Refinery Impact Analysis
Quantifies bio-blendstock value to refiners

Benchmarking against a business-as-usual case, quantify the

- refinery-wide cost of blending biofuels
- environmental performance of refinery products

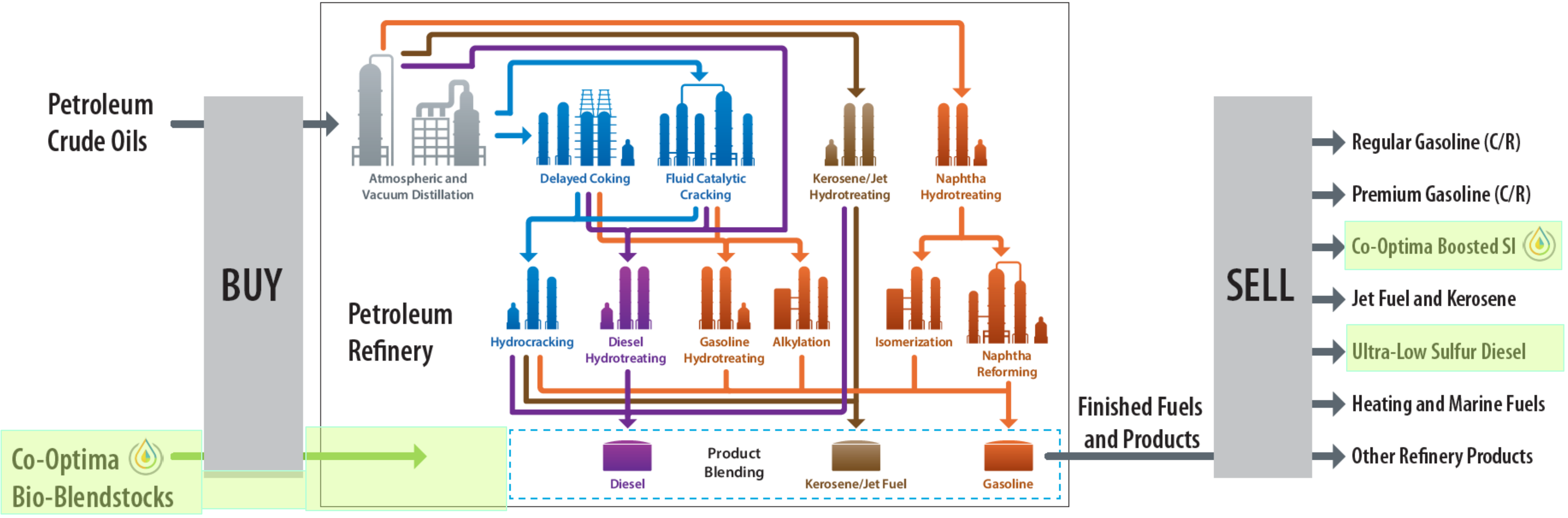
Relevance: Identify fuel properties that would generate **market pull from refiners,** and their **cost and sustainability implications.**

2. Approach: Refinery Impact Analysis

Evaluate impact of blending Co-Optima bio-blendstocks to produce finished products

Overview of Commercial Refinery Modeling Scope in Aspen PIMS

Crude oil quality data (assays)	**Pricing models** for crude oils as functions of quality	**Quality specifications** for finished fuels	**Pricing models** for finished fuels and co-products



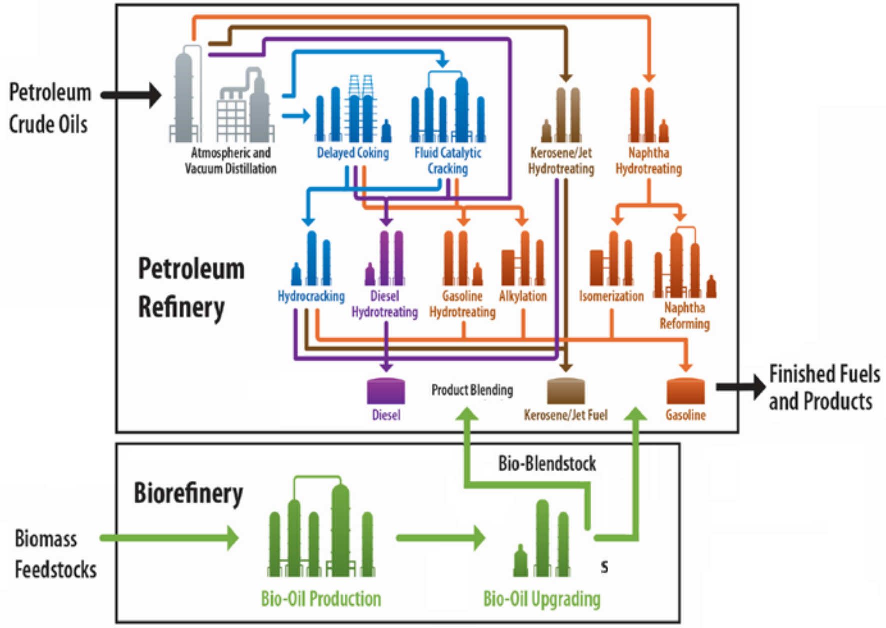
2. Approach: Refinery Impact Analysis

Co-Optima scenario basis are market relevant that inform the linear programming tools

- Refinery configuration and unit capacity basis from EIA.
- Bio-blendstock costs and blending properties from ASSERT and FP.
- ASTM finished fuel specifications are consistent with industry.
- Crude and product pricing data from OPIS by IHS Market.
- Fuel market projections from EIA, OPIS, and ADOPT.

Optimizable Refinery Models

Aspen PIMS
By AspenTech

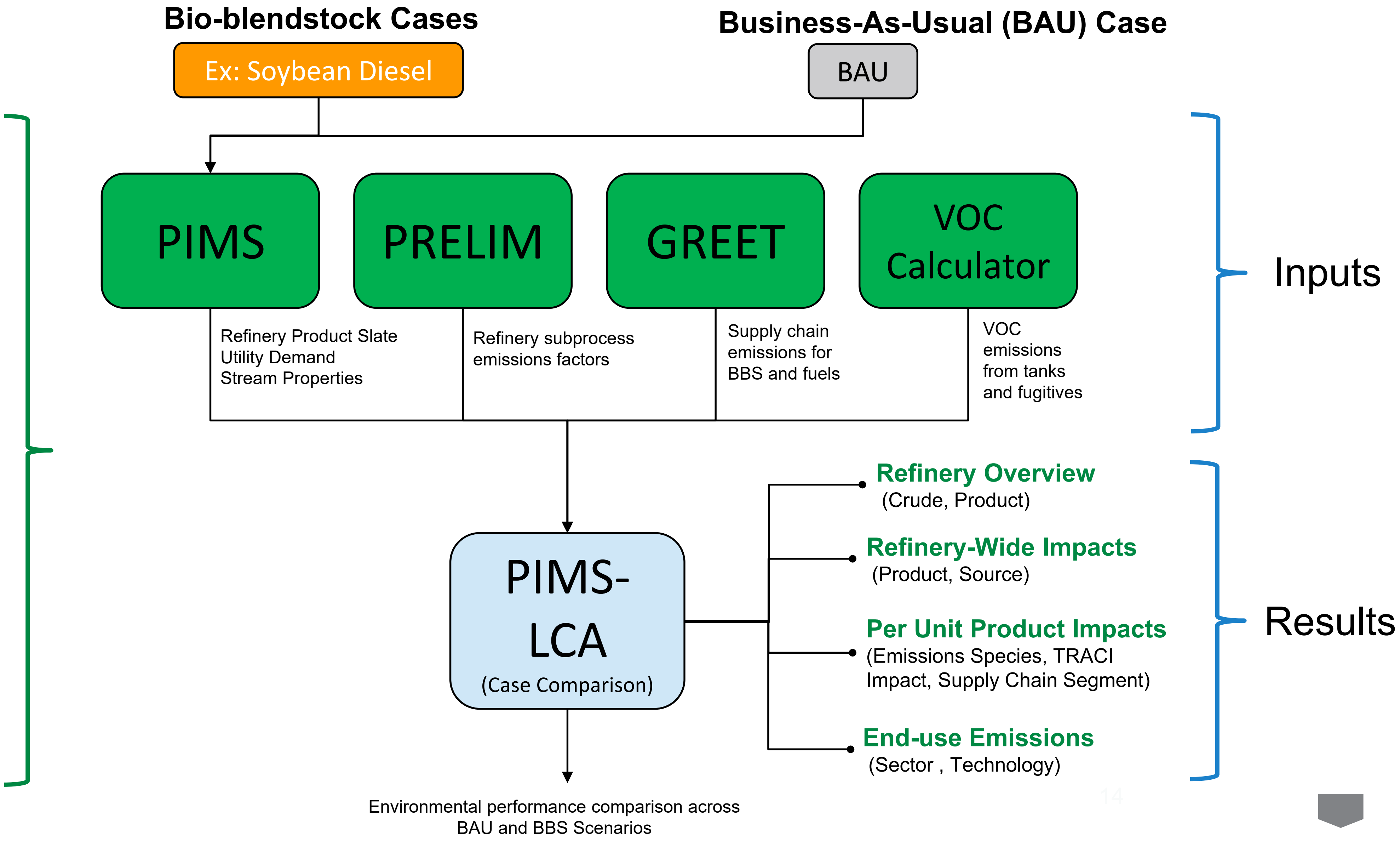


Life Cycle Analysis

2. Approach: Refinery Impact Analysis

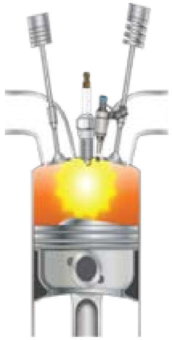
Developed LCA tool coupled with refinery models to measure environmental benefits

Excel based tool to inform carbon intensity of refinery emissions



2. Approach

Integrated modeling tools for measuring potential impact of light and heavy-duty modes



Light Duty

RON / MON / S

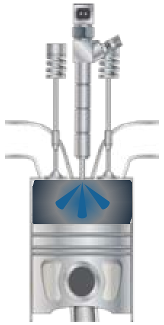
Energy Density

Flash / Boil / Freeze

RVP / HOV

Sooting

Light-Duty and Heavy-Duty Fuels and Combustion Modes



Heavy Duty

Cetane

Energy Density

Flash / Boil / Freeze

Water Sol

Sooting

Refinery Benefits

What is the value of Co-Optima bioblendstocks to the refining industry?

Vehicle Adoption

How would Co-Optima fuels and vehicles technology penetrate the market?

Economy-wide Benefits

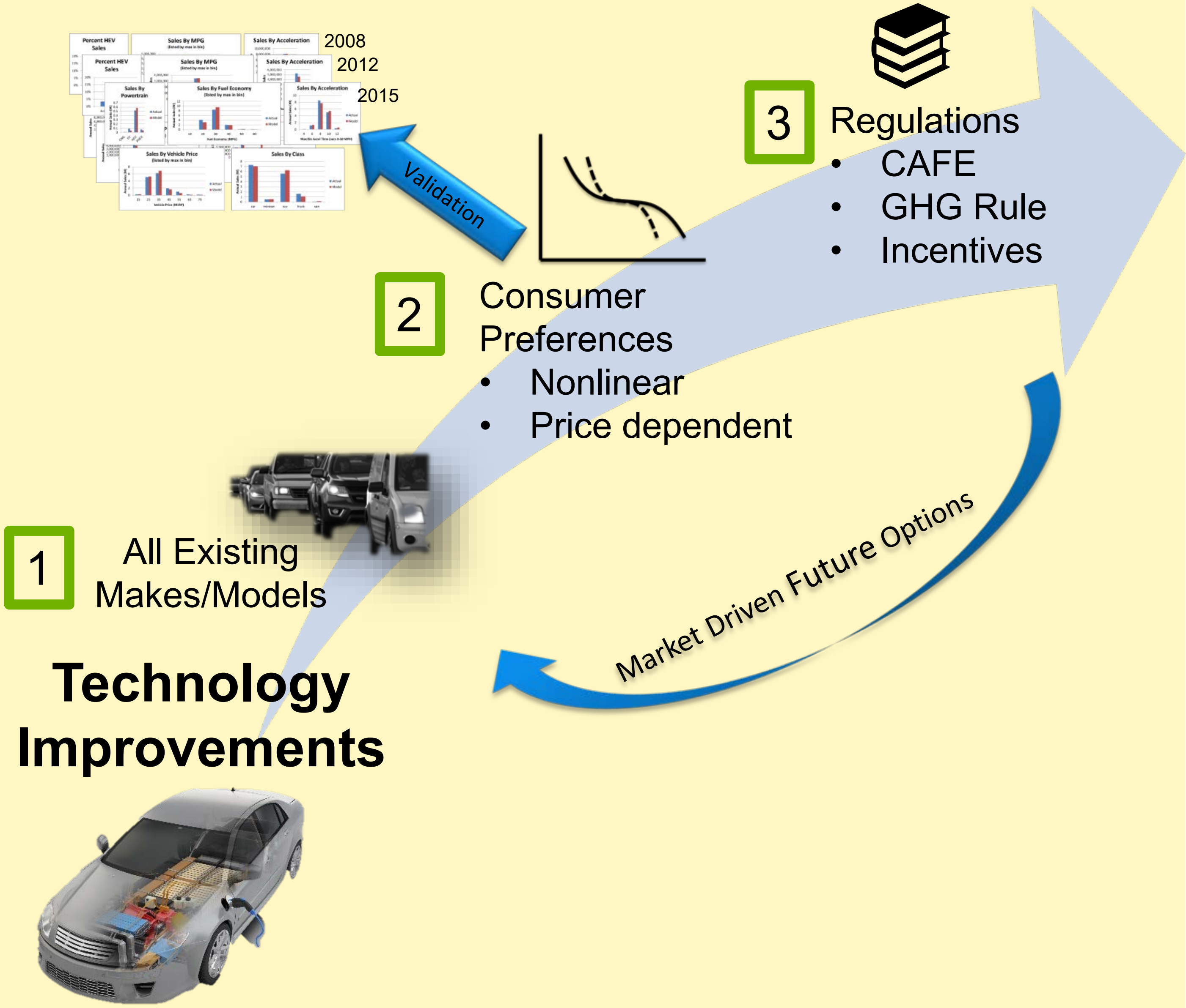
Any socio-economic benefits of Co-Optima fuels/vehicle adoption?

2. Approach: Vehicle Adoption

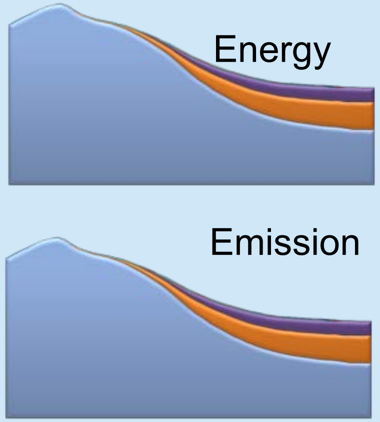
Market factors considered in evolution of Co-Optima vehicles in the automobile fleet

Vehicle Adoption

How would the Co-Optima fuels and vehicles technology penetrate the market?



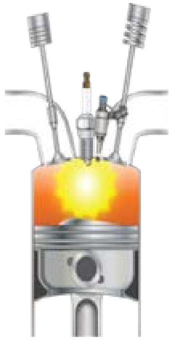
Benefits



Benefits offered by Co-Optima technology

2. Approach

Integrated modeling tools for measuring potential impact of light and heavy-duty modes



Light Duty (LD)

RON / MON / S

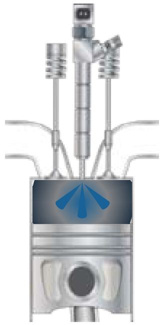
Energy Density

Flash / Boil / Freeze

RVP / HOV

Sooting

Light-Duty and Heavy-Duty Fuels and Combustion Modes



Heavy Duty (HD)

Cetane

Energy Density

Flash / Boil / Freeze

Water Sol

Sooting

Refinery Benefits

What is the value of Co-Optima bioblendstocks to the refining industry?

Vehicle Adoption

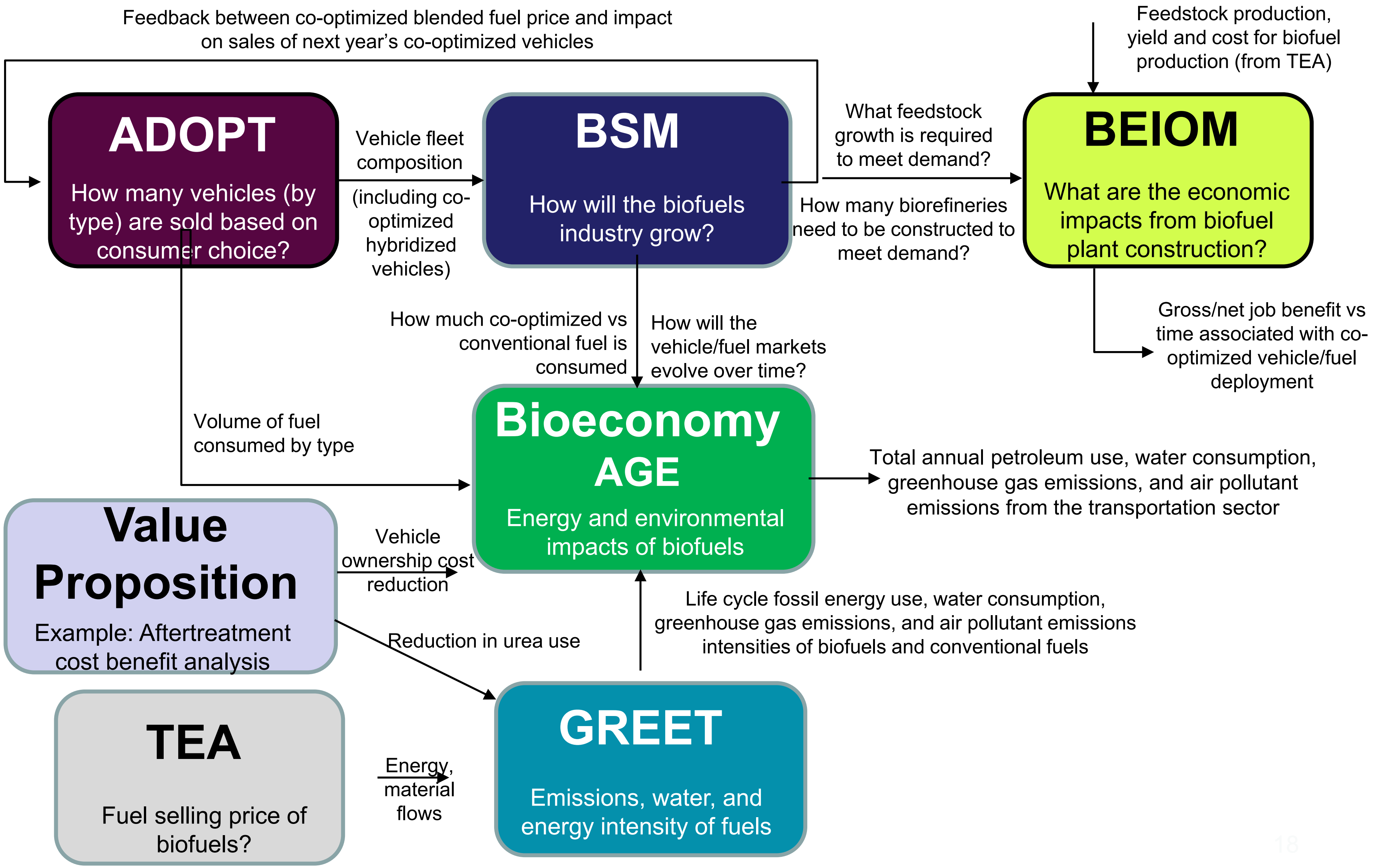
How would Co-Optima fuels and vehicles technology penetrate the market?

Economy-wide Benefits

Any socio-economic benefits of Co-Optima fuels/vehicle adoption?

2. Approach: Economy-wide Benefits

Integrated benefits analysis framework for measuring sector-wide impacts



Economy-wide Benefits

Any socio-economic benefits of Co-Optima fuels/vehicle adoption?

3- Impact

3. Impact

Co-Optima connects with stakeholders, and the broader BETO and VTO programs

VTO Program Interactions

- Advanced Combustion
- Fuel Effects
- Aftertreatment
- Modeling

Inputs and Engagement

- Industry (biofuels, energy companies, OEMs)
- EAB
- Regulatory (EPA, CARB)
- Other stakeholders
- Co-Optima Fuel Properties, Toolkit and Adv Engine Dev

Co-Optima

- Techno-economic and life cycle analysis
- Impacts analysis
- Bioblendstock generation and testing
- Structure-property relationships

BETO Program Interactions

- Analysis
- Sustainability
- Feedstocks
- Conversion
- Scale-Up

Data and Outputs

- Fuel Property Database
- SPR tools
- Techno-economic and lifecycle analysis outputs
- Performance-advantaged bioblendstock candidate lists

3. Impact

Leveraging and interacting with other BETO efforts and disseminates results

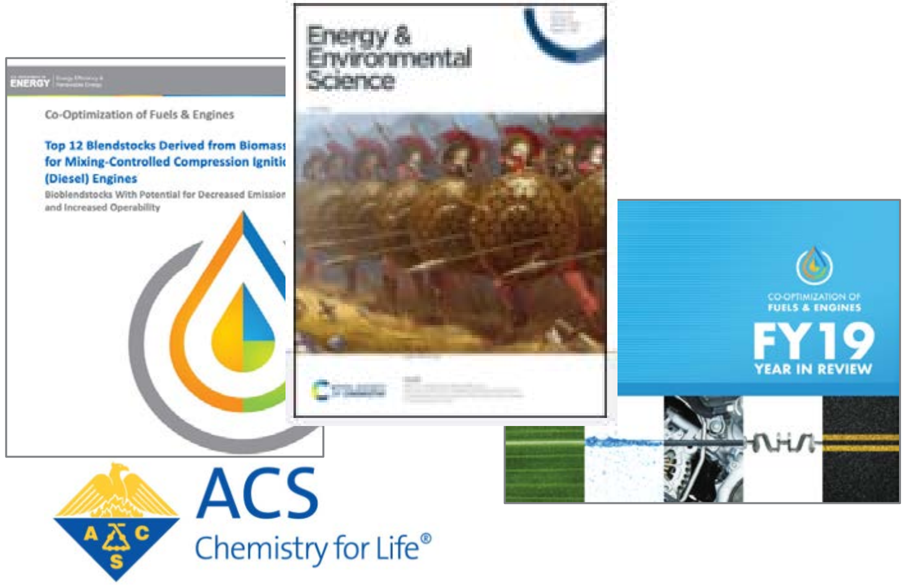
Furthering BETO Goals

Advance public knowledge by sharing state of technology, identifying opportunities & barriers for biofuels scaleup/adoption

Inform BETO program of promising bioblendstocks from refiners' perspective for gasoline, diesel, jet, and marine fuels, including co-processing strategies

Insights from system-wide modeling (including feedstock assessments) inform potential socio-economic benefits of advancing the bioeconomy

Engagements & Disseminating Results



Inform public and key stakeholders in peer-reviewed journals, Co-Optima reports, public databases, conferences, and industry engagements, such as interactions with American Petroleum Institute, Environmental Protection Agency, National Biodiesel Board, etc.

3. Impact

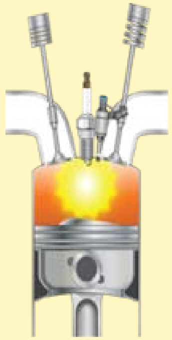
Share insights for a Sustainable Transportation Strategy

Outcome & Impact	Stakeholder Engagement	Disseminating Results
Outcome: Information on scalability, economic viability, and environmental/socio-economic benefits of low carbon bioblendstocks **Impact:** Estimated potential impact of Co-Optima technology adoption at scale, with demonstrated **engine efficiency improvements, emission reductions,** & domestic **job growth**	✓ Attend Co-Optima quarterly **External Advisory Board** meetings ✓ Share results and receive feedback from **leadership team** and the **Board of Directors** ✓ Present research findings at the monthly **Co-Optima stakeholder** calls	✓ Journal Articles (3 published, 9 in preparation) and several conference presentations ✓ Annual Co-Optima Year in Review and other reports collating major findings ✓ Co-Optima Capstone webinars scheduled on LD and HD sector benefits

4- Progress and Outcomes

4. Progress and Outcomes: Light Duty Sector

Integrated modeling tools for measuring potential impact of light- and heavy-duty modes



Light Duty

RON / MON / S

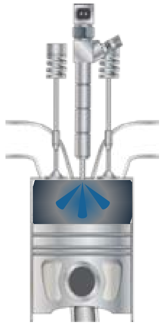
Energy Density

Flash / Boil / Freeze

RVP / HOV

Sooting

Light-Duty and Heavy-Duty Fuels and Combustion Modes



Heavy Duty

Cetane

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Water Sol

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Refinery Benefits

What is the value of Co-Optima bioblendstocks to the refining industry?

Vehicle Adoption

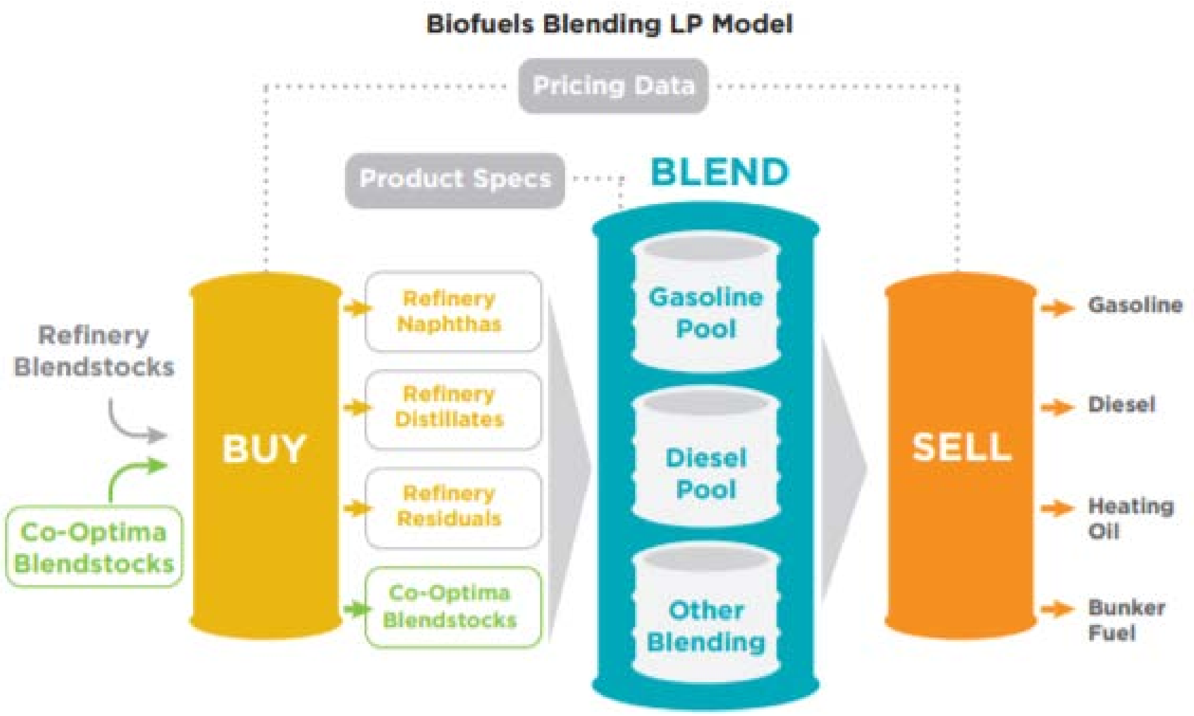
How would Co-Optima fuels and vehicles technology penetrate the market?

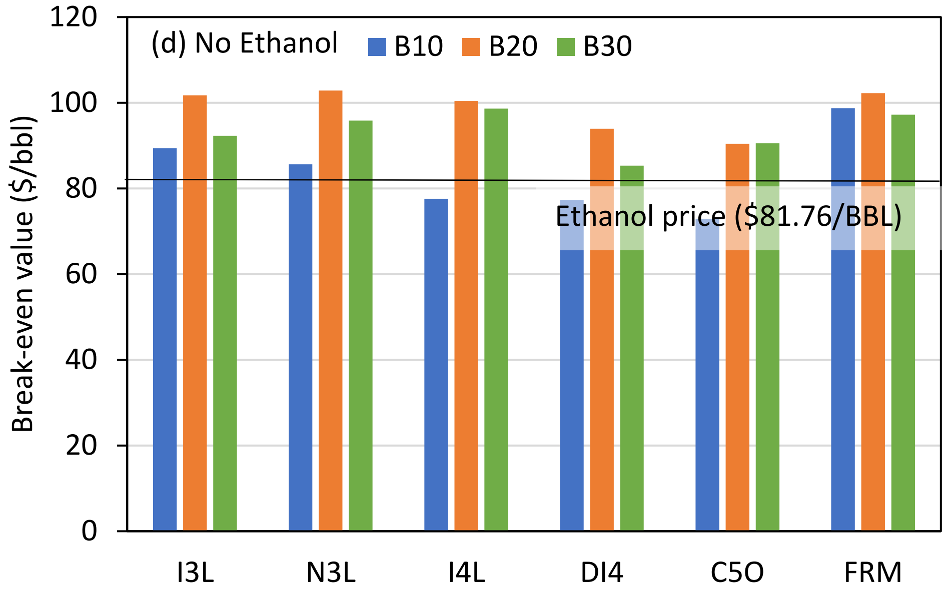
Economy-wide Benefits

Any socio-economic benefits of Co-Optima fuels/vehicle adoption?

4. Progress and Outcomes: Refinery Impacts (LD)

Blending optimization estimated economic value of Co-Optima bioblendstocks





I3L=i-propanol; N3L=n-propanol; I4L=i-butanol; DI4=diisobutylene; C5O=cyclopentanone; FRM=furans mix

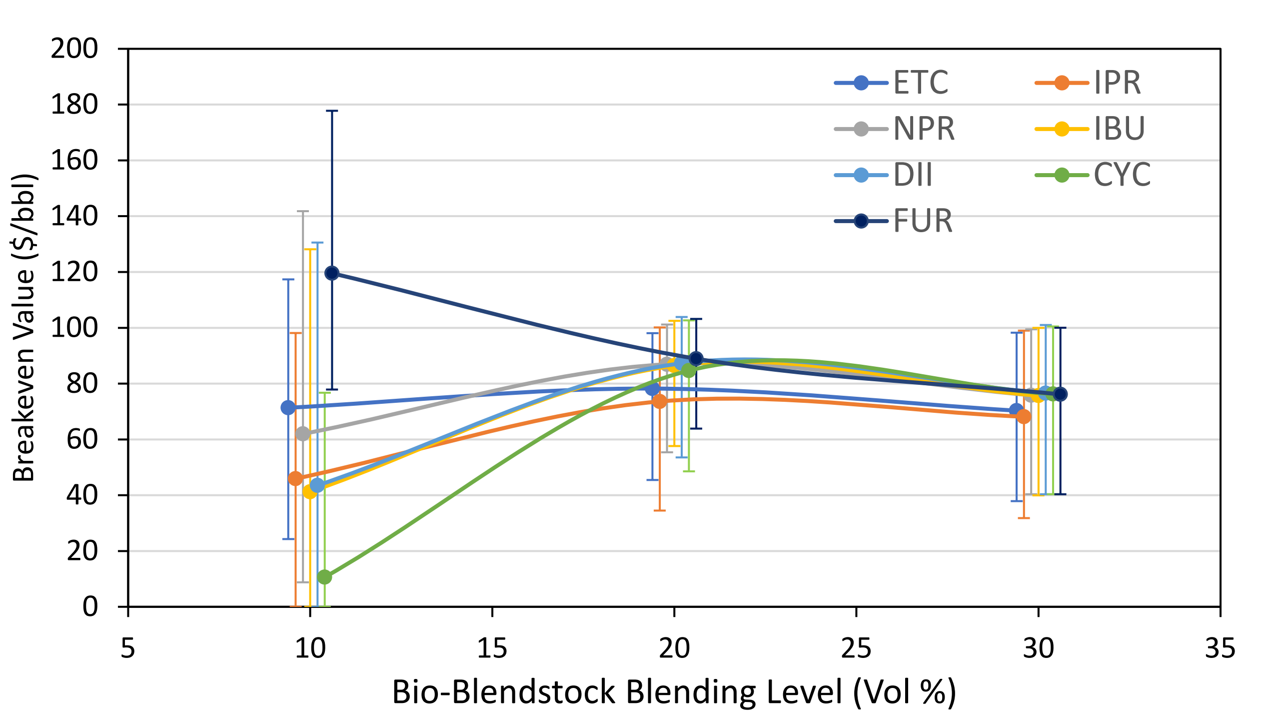
Key Outcome:

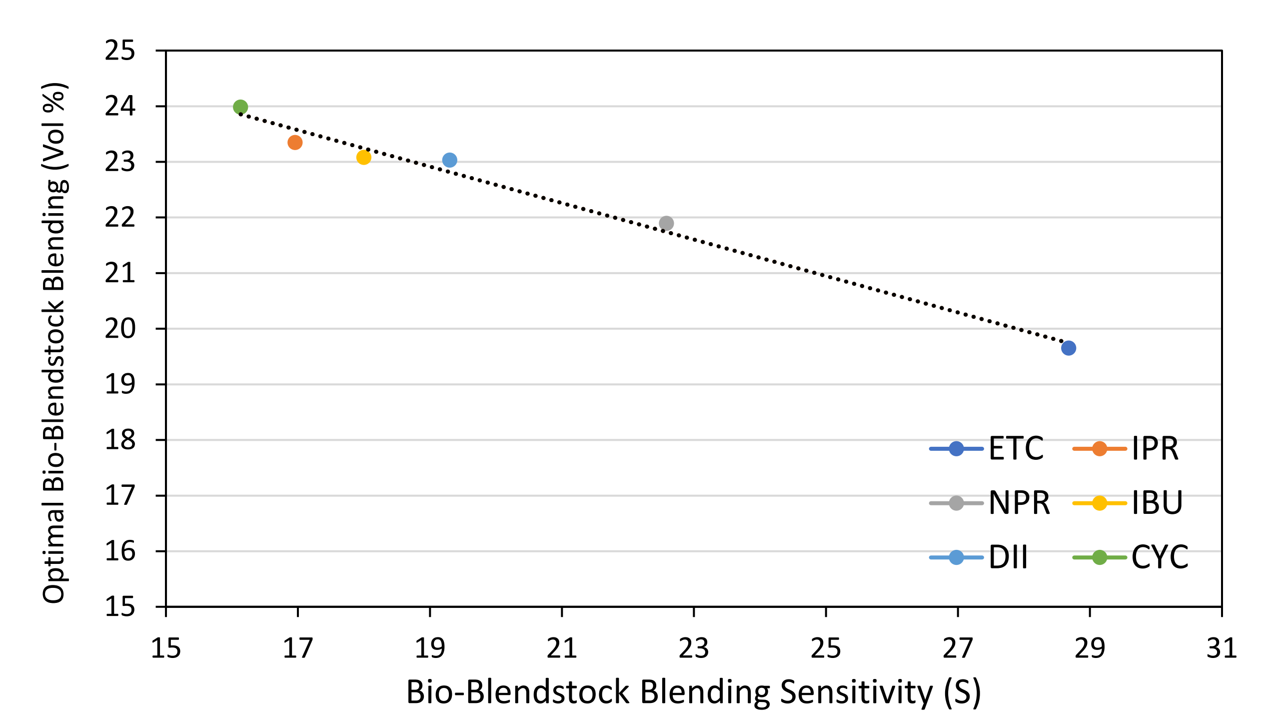
Co-Optima selected **gasoline-range bioblendstocks (high RON, low RVP)** demonstrate similar advantages as ethanol and can be combined with different refinery naphtha streams to produce **premium gasoline**

Jiang, Philips, Singh, Gaspar et al. (2021) in revision

4. Progress and Outcomes: Refinery Impacts (LD)

Fuel characteristics (RON and S) of Co-Optima biofuels drive economic benefits to refiners





ETC= ethanol; IPR=i-propanol; NPR=n-propanol; IBU=i-butanol; DII=diisobutylene; CYC=cyclopentanone; FUR=furans mix

Key Outcomes:

(1) Potential value of bio-blendstocks to refiners depends on the **fuel characteristics (RON and S)** and **varies with biofuel blending** levels

(2) Optimal blending ratio that maximized profitability for each bio-blendstock strongly correlated with the **fuel sensitivity**

Carlson, Singh, Talmadge, Jiang et al. (2021) in preparation

4. Progress and Outcomes: Vehicle Adoption (LD)

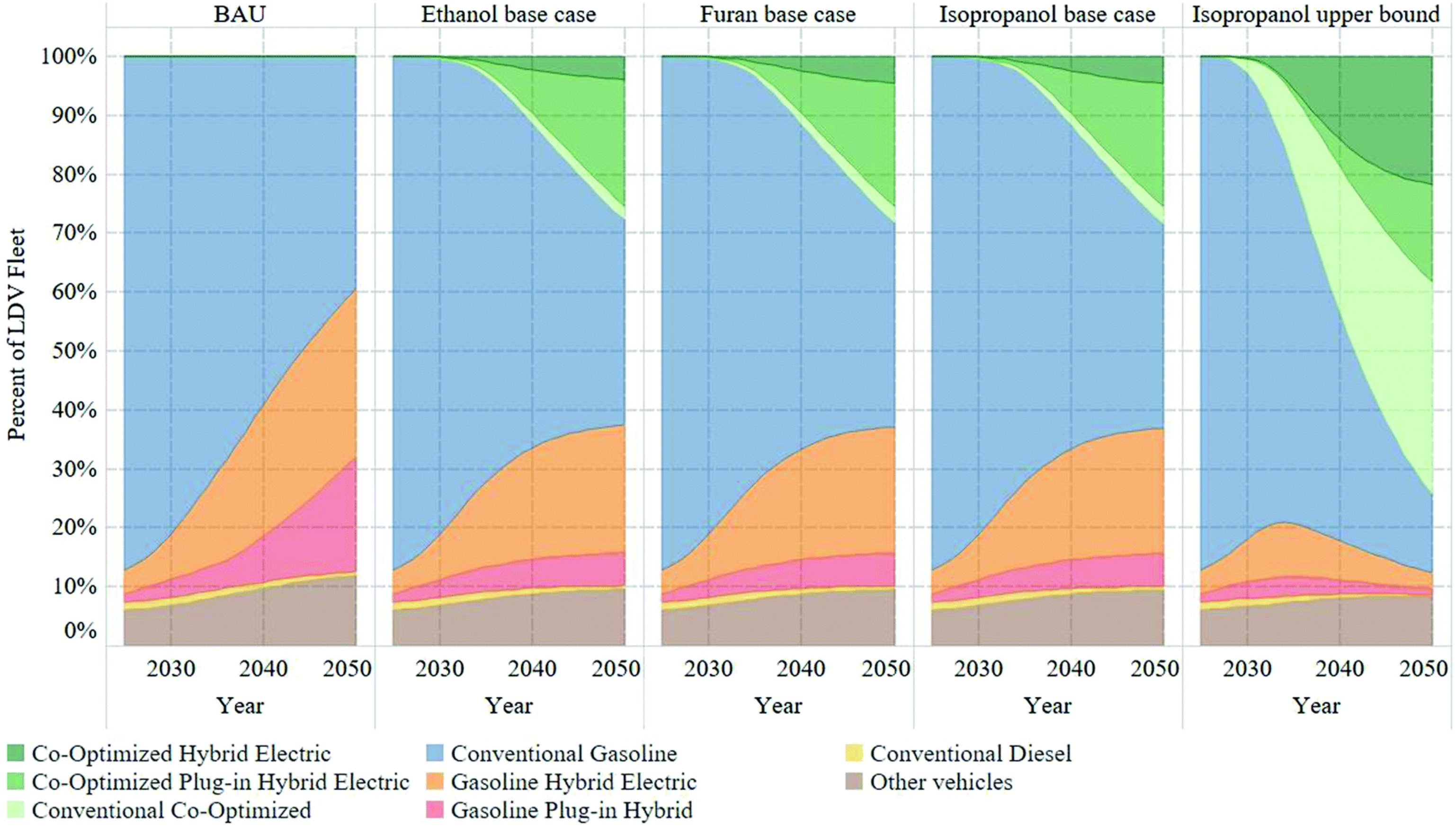
Vehicle choice model predicts penetration of Co-Optima engines in the market

Vehicle Adoption

How would the Co-Optima fuels and vehicles technology penetrate the market?

Key Outcome:

Co-optimized vehicles become the best-selling vehicle after 2035 because they combine - **better performance** and - **lower fuel cost per mile** compared to the best-selling conventional gasoline and gasoline PHEV vehicles.

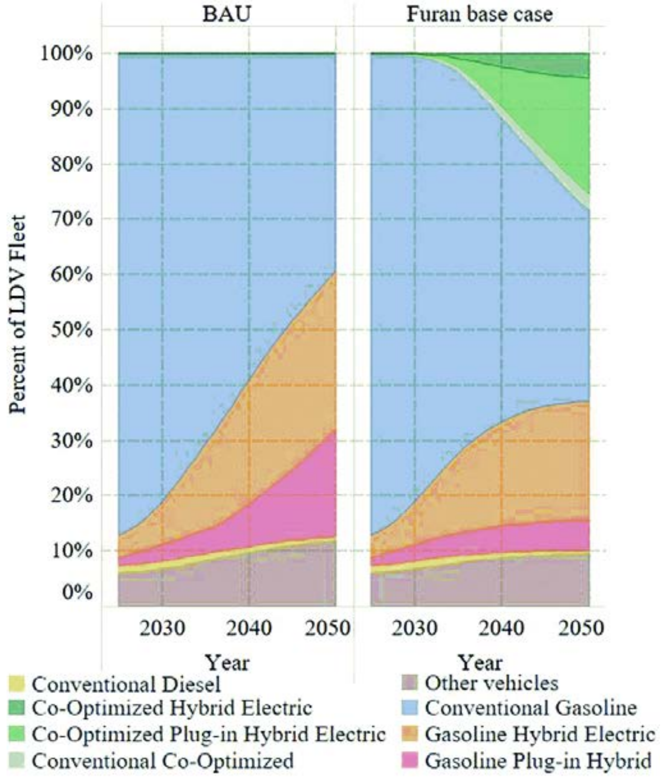


Dunn, Newes, Cai et al. (2020) Energy & Environmental Science

4. Progress and Outcomes: Economy-wide Benefits (LD)

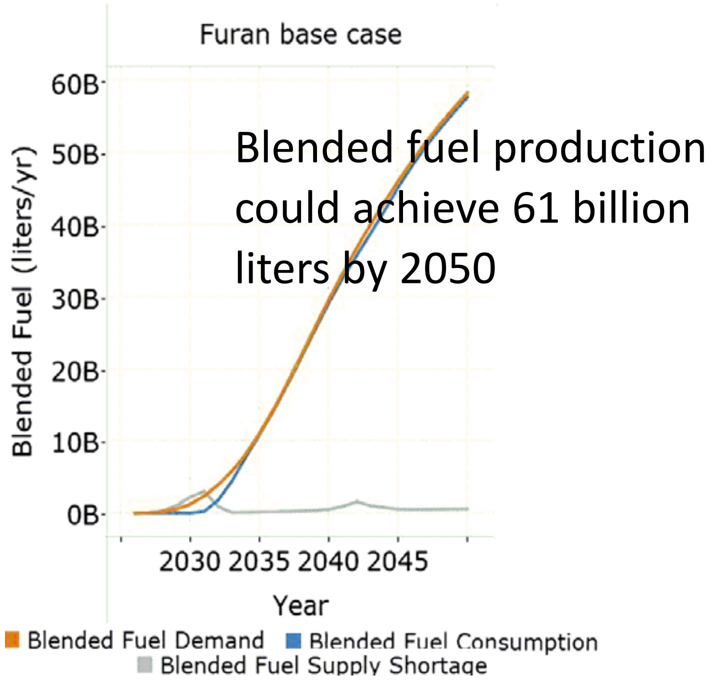
Co-Optimized fuels and vehicle technology lead to significant emissions reductions

Key Outcomes:



Vehicle Adoption

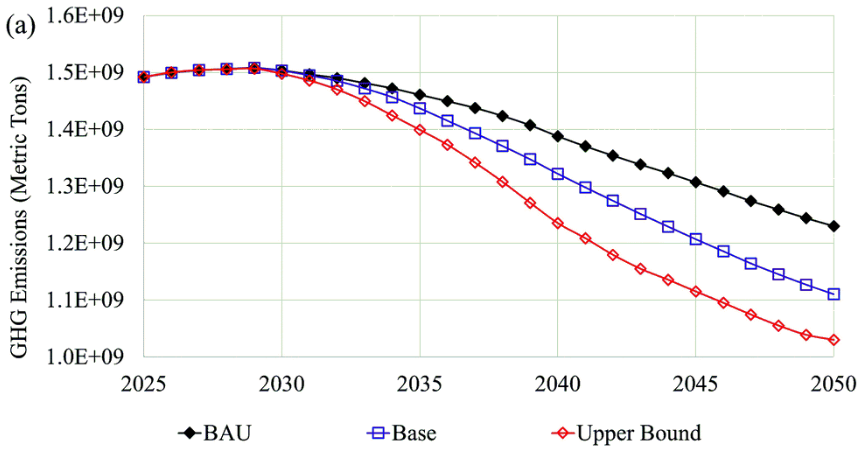
Co-optima fuels/engines could achieve 10% efficiency gains compared to E10



Biofuels Production, Jobs

Diversifying the fuel resource base leads to significant job creation, esp. in rural areas

GHGs reduction (1.3 billion metric tons)



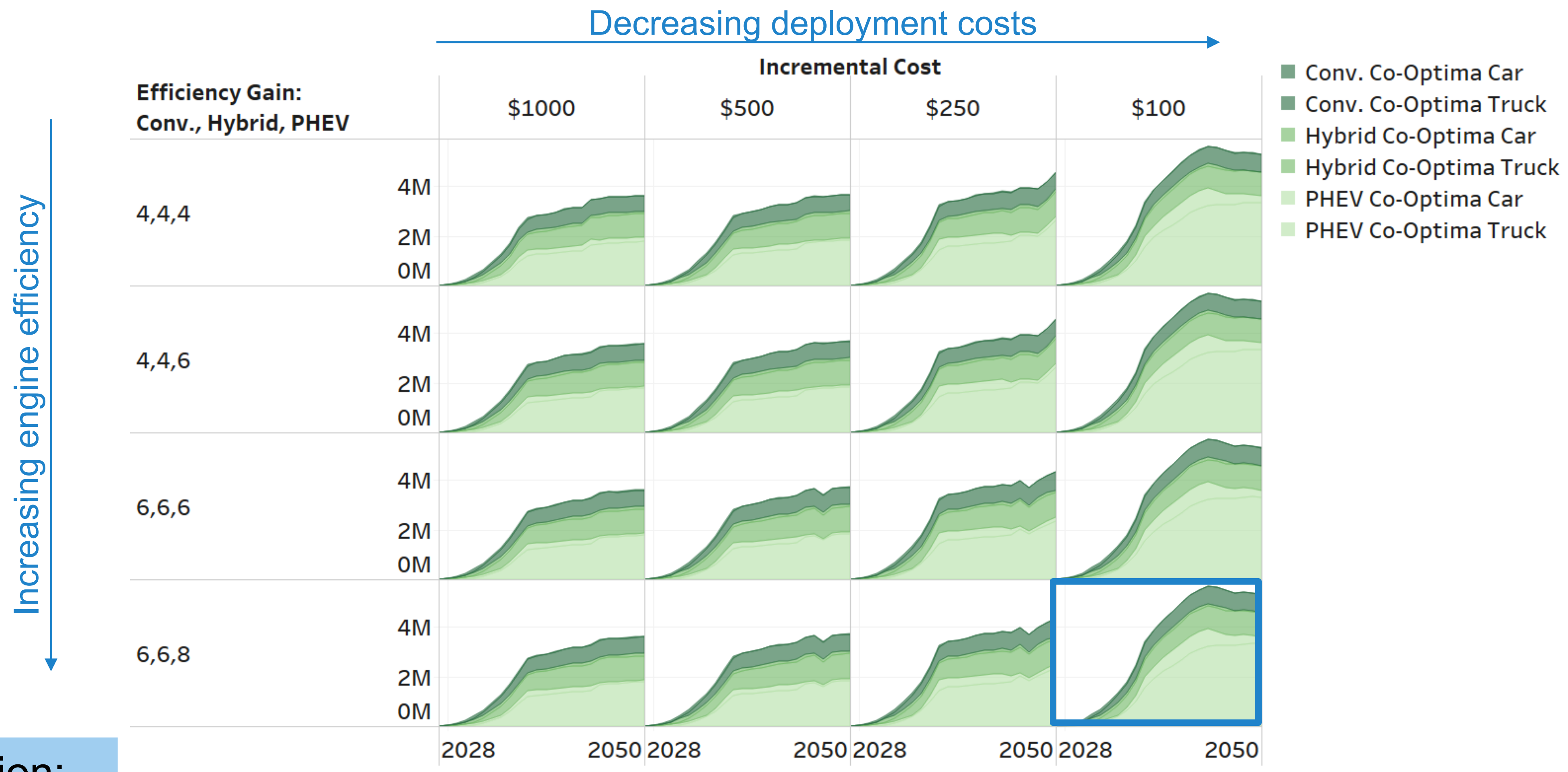
Reduction in GHGs, Criteria Pollutants

Significant reductions in GHG and PM2.5 over 2025-2050

Dunn, Newes, Cai et al. (2020) Energy & Environmental Science

4. Progress and Outcomes: Vehicle Adoption (LD)

Vehicles with hybridized power trains could experience a synergistic efficiency increase



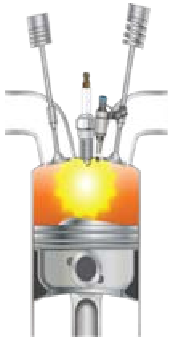
Key Question:

What tradeoffs between the engine efficiency gains vs. the incremental vehicle cost influence adoption of co-optimized vehicles with hybridized power trains?

Sittler, Zaimes, Brooker, Longman et al. (2021) in preparation

4. Progress and Outcomes: Heavy Duty Sector

Integrated modeling tools for measuring potential impact of light- and heavy-duty modes



Light Duty

RON / MON / S

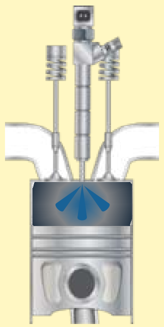
Energy Density

Flash / Boil / Freeze

RVP / HOV

Sooting

Light-Duty and Heavy-Duty Fuels and Combustion Modes



Heavy Duty

Cetane

Energy Density

Flash / Boil / Freeze

Water Sol

Sooting

Refinery Benefits

What is the value of Co-Optima bioblendstocks to the refining industry?

Vehicle Adoption

How would Co-Optima fuels and vehicles technology penetrate the market?

Economy-wide Benefits

Any socio-economic benefits of Co-Optima fuels/vehicle adoption?

4. Progress and Outcomes: Vehicle Adoption (HD)

Understanding the heavy-duty value proposition – reduced aftertreatment costs

Environmental Science & Technology

Article

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pubs.acs.org/est

Co-optimization of Heavy-Duty Fuels and Engines: Cost Benefit Analysis and Implications

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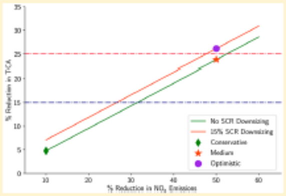
Supporting Information

ABSTRACT: Heavy-duty vehicles require expensive aftertreatment systems for control of emissions such as particulate matter (PM) and nitrogen oxides (NO_x) to comply with stringent emission standards. Reduced engine-out emissions could potentially alleviate the emission control burden, and thus bring about reductions in the cost associated with aftertreatment systems, which translates into savings in vehicle ownership. This study evaluates potential reductions in manufacturing and operating costs of redesigned emission aftertreatment systems of line-haul heavy-duty diesel vehicles (HDDVs) with reduced engine-out emissions brought about by co-optimized fuel and engine technologies. Three emissions reduction cases representing conservative, medium, and optimistic engine-out emission reduction benefits are analyzed, compared to a reference case: the total costs of aftertreatment systems (TCA) of the three cases are reduced to $11,400 (1.63 ¢/km), $9,100 (1.30 ¢/km), and $8,800 (1.26 ¢/km), respectively, compared to $12,000 (1.71 ¢/km) for the reference case. The largest potential reductions result from reduced diesel exhaust fluid (DEF) usage due to lower NO_x emissions. Downsizing aftertreatment devices is not likely, because the sizes of devices are dependent on not only engine-out emissions, but also other factors such as engine displacement. Sensitivity analysis indicates that the price and usage of DEF have the largest impacts on TCA reduction.



INTRODUCTION

Emissions of criteria pollutants such as oxides of nitrogen (NO_x), particulate matter (PM), unburned hydrocarbons (HC), and carbon monoxide (CO) from mixing-controlled compression-ignition (MCCI) (or diesel) engines raise health and air quality concerns. Heavy-duty diesel vehicles (HDDVs) accounted for 43% of NO_x and 47% of PM emissions from all on-road vehicles in the US in 2014.[1] Emission standards for HDDVs, which began in the late 1980s, have resulted in increasingly stringent limits on pollutant emissions from new HDDVs and have promoted progress in emission control technologies. Since 2010, all domestic HDDVs have been equipped with both in-cylinder emission control strategies such as exhaust gas recirculation (EGR), and a series of aftertreatment devices, which typically include diesel oxidation catalysts (DOC), diesel particulate filters (DPF), and urea selective catalytic reduction (SCR) for NO_x emissions control. These devices cooperate with each other for improved efficiency of emission control and maximized durability. For instance, DOC not only oxidizes part of the NO to NO_2, which is critical for effective operations of DPF and SCR, but also generates heat for active regeneration of DPF by oxidation of injected fuel. Details of these devices are discussed in the Supporting Information (SI). Stringent emission regulations have driven up emission control costs for HDDVs, with aftertreatment systems being the major cost driver.[2]

Both engine operating conditions and fuel properties can affect exhaust emissions.[3] For instance, the effects of fuel properties on NO_x emissions depend on factors such as (a) how physical properties of a fuel affect its evaporation, mixing processes, and peak combustion temperature; and (b) the effects of fuel properties on the initial fuel-rich flame-ignition event.[4−6] Several diesel fuel properties, including fuel cetane number,

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Environ. Sci. Technol. 2019, 53, 12904−12913

Ou, Cai, et al. (2019) Environmental Science & Technology

Key Questions:

What is the potential for adoption of Co-Optima technologies by Class 8 Heavy-Duty Trucks?

- Reduced cost of aftertreatment by 5-26% over the lifetime of the vehicle

How do the potential benefits* from Co-Optima technologies compare with those from other technologies?

- Electrification
- Renewable diesel
- Co-Opima technologies in conjunction

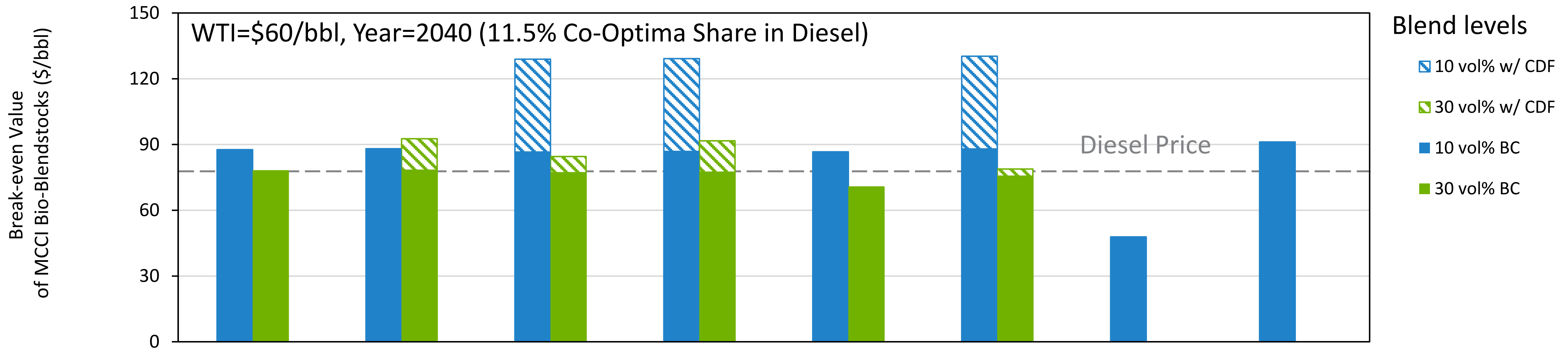
These findings are currently being incorporated into economy-wide benefits analysis

*Key metrics: GHGs, CAPs, water use, energy use, total cost of ownership, jobs

Sittler, Cai, Zaimes, Brooker, et al. (2021) in preparation

4. Progress and Outcomes: Refinery Impacts (HD)

MCCI bio-blendstocks reduce the extent of hydrotreatment necessary to meet sulfur specs



Properties	2-Nonanol	Methyl decanoate	Dipentyl ether	4-butoxy heptane	5-ethyl-4-propyl-nonane	Soy biodiesel	HTL diesel	OMEs	ULSD Spec	CDF Spec
Cetane number	38-41	46-52	91-96	57-65	48	54-55	65.8	93	>40	>53

Property criterion: Greatly Exceeds, Exceeds Criteria, Meets Criteria.

OMEs = oxymethylene ethers, ULSD = ultra-low sulfur diesel, CDF = California diesel fuel, MCCI = Mixing Controlled Compression Ignition, WTI= West Texas Intermediate, BC = base case

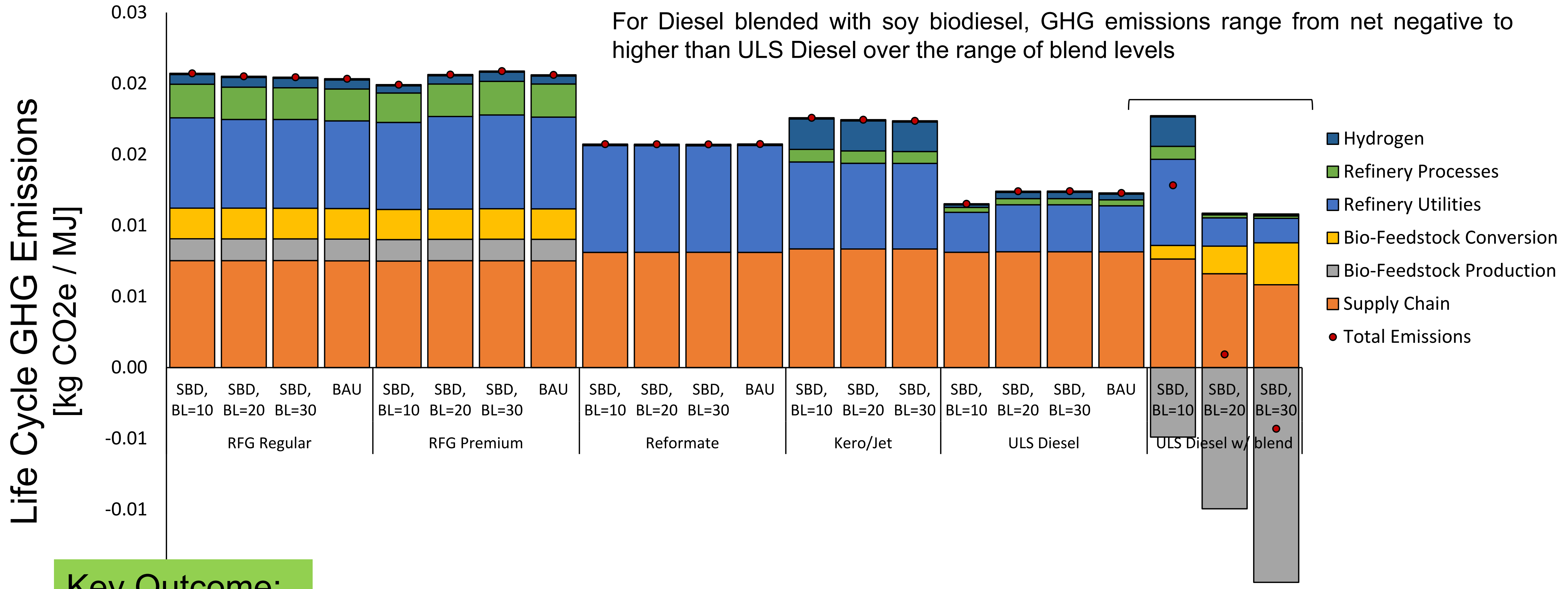
Key Outcomes:

- High-Cetane Number (CN) Bioblendstock will create extra value, if demand for high-CN diesel increases
- BBS properties that help refinery constraints are the most important such as sulfur reduction, followed by CN & density

Jiang, Carlson, Singh, et al. (2021) in preparation

4. Progress and Outcomes: Refinery Impacts (HD)

Significant GHG reduction from cradle-to-refinery gate analysis of Soy Biodiesel



For Diesel blended with soy biodiesel, GHG emissions range from net negative to higher than ULS Diesel over the range of blend levels

Key Outcome:

Biofuel blending levels can have non-linear impacts on the refinery's environmental performance

Zaimes, Hawkins, Jiang, Carlson, et al. (2021) in preparation

Summary

Co-Optima Project: Accomplishments

Provide technology options to increase sustainability of transportation

Light Duty

- 10% fuel economy gain over 2015 baseline

Medium- and Heavy-Duty

- Lower-cost path to reduced engine-out criteria emissions
- Up to 4% fuel economy gain

Biofuels

- Diversify resource base (identified biofuel pathways from terrestrial, waste, and algae biomass)
- Provide economic options to fuel providers to adapt to changing demands/sustainability needs
- Increase market opportunities for performance-advantaged biofuels

Crosscutting Goals

- Reduce greenhouse gas emissions by at least 20% (demonstrated by a 30% biofuel blend)
- Increase clean energy options and decrease petroleum imports
- Stimulate domestic economy and add new bio-economy jobs

Summary

Overview	Analysis supports Co-Optima's goal to identify low carbon fuel-engine combinations that increase fuel economy and reduce emissions by assessing bioblendstocks across economic, environmental, and scalability metrics. We evaluate refinery impacts of blending Co-Optima bioblendstocks into finished fuels as well as economy-wide environmental and socio-economic benefits of Co-Optima technology adoption.
Management	▪ Analysis Tasks are well-organized, tracked by milestones (internal/external), undergo multi-level quality checks. ▪ Regular interactions with other Co-Optima Teams and coordinate with other BETO analysis efforts. ▪ Regular meetings with External Advisory Board and stakeholders. ▪ Disseminate results through articles, reports, and conference presentations.
Approach	▪ Identify biofuel fuel properties that would generate market pull from refiners, and their cost and sustainability implications. ▪ Vehicle adoption models indicate the penetration of co-optimized vehicles, which serves as the basis for integrated analysis informs overall environmental and socio-economic benefits.
Impact	▪ Enhance the value proposition for biofuels by identifying scalable, economically viable bioblendstocks that maximize engine performance and energy efficiency and minimize environmental impacts. ▪ Petroleum consumption, GHG emissions, water consumption, and PM2.5 emissions are all reduced when co-optimized fuels and engines emerge.
Progress & Outcomes	▪ Refinery impact analysis indicates that high octane, high sensitivity fuels (BSI and MM bio-blendstocks) and low sulfur, high cetane fuels (MCCI) could be valuable to refiners. ▪ Coupled LCA model development shows the decrease in refinery emissions and criteria pollutants. ▪ Efficiency increase with Co-Optima fuels and engine combination is the largest driver for LD adoption and reduction in aftertreatment costs is the key factor for HD adoption. ▪ Integrated benefits analysis demonstrate better air quality impacts and increase in domestic job growth.

Quad Chart Overview

Timeline
- Phase 1: October 1, 2015 to September 30, 2018
- Phase 2: October 1, 2019 to September 30, 2021

	FY20	Active Project
DOE Funding	$1,700K	$6,235K

Partner Labs
- ANL, NREL, PNNL (in coordination with INL, LANL, LBNL, LLNL, ORNL, SNL)

Barriers addressed
At-A. Comparable, transparent, and reproducible analysis.

Im-H. Lack of acceptance and awareness of biofuels as a viable alternative.

Project Goal
Co-Optima Goal: Advance the underlying science needed to develop biomass-derived fuel and engine technologies that will work in tandem to achieve efficiency, environmental and economic goals.

Analysis-Specific Goal: Guide Co-Optima research and development-guiding through analysis, illuminating scalability and sustainability of co-optimized technologies adopted at scale.

End of Project Milestone
Analysis has enabled identification of fuel-engine technologies in vehicles with boosted spark-ignition, multi-mode, and mixing controlled compression ignition engines that will lower cost and offers environmental and socio-economic benefits to road transportation.

Funding Mechanism
Co-Optima Consortium – FY2018 Lab Call

Additional Slides

Responses to Previous Reviewers' Comments

Comment	*Response*
	Generally, the 2019 reviewer comments were positive and as such, the ASSERT Team has followed the course set in the first year of Phase II. TEA and LCA activities have moved forward to address MM and MCCI bioblendstocks. The integrated benefits analysis has incorporated new aspects and expanded models to address diesel heavy duty vehicles per BETO guidance. Refinery analysis has advanced significantly to create new refinery models in PIMS and an accompanying LCA tool and produced results for BSI and MCCI bioblendstocks.
Most existing advanced biofuel processes generate multiple products that are often directed to different markets. There may be value in assessing coproducts as part of this analysis.	Co-products are a key aspect of the process models underlying the TEA and LCA studies. Results have been produced considering co-products, and the size of co-product markets is considered in determining scale up potential. The contribution of co-products to MFSP is explicitly tracked for bioblendstock screening to highlight cases where MFSP is dependent on co-product sales.
Given the potential to adapt/tweak some of the non-favored blendstocks that the Co-Optima team have identified if they offer other benefits (e.g., improved sustainability, etc.), it would be helpful to know if there is a strong GHG LCA or other sustainability reason to focus on the slightly lower priority blendstocks.	The team provides screening results for candidates that meet the screening criteria as well as those that do not. Further information is provided in the Top BSI Bioblendstocks and Top MCCI Bioblendstocks reports to identify promising bioblendstocks that did not fully meet the criteria.

Publications: Journal Articles

J.B. Dunn, E. Newes, H. Cai, Y. Zhang, A. Brooker, L. Ou, N. Mundt, A. Bhatt, S. Peterson, M. Biddy. ‘Energy, Economic, and Environmental Benefits Assessment of Co-Optimized Engines and Bio-Blendstocks.’ *Energy and Environmental Science*. 2020. 13. 2262-2274.

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N.A. Huq, X. Huo, G.R. Hafenstine, S.M. Tifft, J. Stunkel, E.D. Christensen, G.M. Fioroni, L. Fouts, R.L. McCormick, P.A. Cherry, C.S. McEnally, L.D. Pfefferle, M.R. Wiatrowski, P.T. Benavides, M.J. Biddy, R.M. Connatser, M.D. Kass, T.L. Alleman, P. St. John, S. Kim, D.R. Vardon ‘Performance-Advantaged Ether Diesel Bioblendstock by A Priori Design.’ PNAS. 2019. 116 (52) 26421-26430.

Publications: Reports

Gaspar D, West BH, Ruddy D, Wilke TJ, Polikarpov E, Alleman TL, George A, Monroe E, Davis R, Vardon D, Sutton AD, Moore CM, Benavides PT, Dunn J, Biddy MJ, Jones SB, Kass MD, Pihl JA, Debusk MM, Sjoberg M, Szybist J, Sluder CS, Fioroni G, Pitz WJ. 'Top Ten Blendstocks Derived From Biomass For Turbocharged Spark Ignition Engines: Bio-blendstocks With Potential for Highest Engine Efficiency.' U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy. Pacific Northwest National Laboratory. Richland, Washington. PNNL-28713.

Gaspar D, et. al. 'Top 11 Blendstocks Derived from Biomass for Mixing-Controlled Compression-Ignition (Diesel) Engines: Bioblendstocks with Potential for Decreased Emissions and Increased Operability.' U.S. Dept. of Energy, Office of Energy Efficiency and Renewable Energy. Pacific Northwest National Laboratory. Richland, Washington. PNNL-XXXXX. (forthcoming)

Publications: Forthcoming Articles

- Jiang Y, Phillips SD, Singh A, Jones SB, Gaspar DJ. ‘Economic Values of Low-Vapor-Pressure Gasoline-Range Bio-Blendstocks: Property Estimation and Blending Optimization.’ *In review.*
- Cai H, Li S, Tao L, Phillips S, Singh A, Ou L, Hawkins TR. ‘Environmental, Economic, and Scalability of Waste Feedstock-Derived Blendstocks for Mixing-Controlled Compression Ignition Engines.’ *Forthcoming, for submission to Environmental Science and Technology.*
- Singh A, Carlson N , Talmadge M, Jiang Y, Sittler L, Brooker A, Zaimes G, Hawkins TR, Newes E., Gaspar D, McCormick, R, Fioni G, Alleman T . ‘Economic Analysis of the Potential Value to Petroleum Refiners for Co-Optima Boosted-SI Bio-Blendstocks.’ *Forthcoming, for submission to Environmental Science & Technology.*
- Bartling AW, Benavides PT, Singh A, Phillips S, Hawkins TR, Wiatrowski MR, Kinchin CM, Tan ECD, Jones S, Biddy M, Dunn J. ‘Environmental, Economic, and Scalability Consideration of Selected Biomass-Derived Blendstocks for Mixing-Controlled Compression Ignition Engines.’ *Forthcoming, for submission to ACS SusChem Eng.*
- Benavides PT, Bartling AW, Phillips S, Singh A, Hawkins TR, Wiatrowski MR, Kinchin CM, Tan ECD, Jones S, Biddy M. Identification of key drivers in techno-economic & life-cycle analysis of MM Co-Optima fuels. *Forthcoming.*

Publications: Forthcoming Articles

- Young B, Hottle T, Hawkins TR, Zaimes G, Chiquelin C, Carlson N, Jiang Y, Talmadge M, Singh A, Dunn J. 'Environmental Analysis of the Potential Value to Petroleum Refiners for Co-Optima Boosted-SI Bio-Blendstocks.' *Forthcoming, for submission to Environmental Science & Technology.*
- Zaimes G, Hawkins TR, Young B, Singh A, Jiang Y, Talmadge M, Dunn J, Gaspar DJ. 'Environmental Analysis of the Potential Value to Petroleum Refiners for Co-Optima Boosted-SI Bio-Blendstocks.' *Forthcoming, for submission to Environmental Science & Technology.*
- Sittler L, Brooker A, Zaimes G, Cai H, Longman D, Curran S, Dunn J, Hawkins TR. 'Synergistic Co-Deployment of Hybridized & Co-Optimized Vehicles,' *Forthcoming, for submission to Environmental Science & Technology.*
- Sittler L, Burli, Hansen S, Newes S, Peterson S. 'Potential for first mover advantage in new fuel markets.' *Forthcoming.*
- Brooker A, Cai H, Oke D, Newes E, Sittler L, Avelino A, Hawkins TR 'Potential benefits of co-optimization of fuels for both heavy- and light-duty markets.' *Forthcoming.*
- Newes E, Singh A, Sittler L, Talmadge M, 'Integrating refinery decision logic into bioenergy deployment.' *Forthcoming.*
- Jiang Y, Talmadge M, Singh A, Hawkins TR, Zaimes G, Young B, Ramirez Corredores M, Economic, Energy, and Environmental Analysis of the Potential Value to Petroleum Refiners for Co-Optima MCCI Bio-Blendstocks. *Forthcoming.*