DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Strategic Analysis Support (WBS 4.1.1.30)

April 5th, 2023
Data, Model and Analysis

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Project Overview

Objective: Develop and apply an array of analysis to support BETO strategic direction, coordinate analytical efforts, inform external/internal collaborations across EERE.

- **Evaluate emerging areas of interest**
  - SAF pathway analysis for SAF Grand Challenges,
  - Decarbonization options for USDRIVE tech team, and for transportation and industry sectors.
- **Utilize analyses beyond traditional** biorefinery focused **TEA/LCAs** to identify both technical and non-technical barriers, mitigation strategies, and R&D needs.
- **Investigate environmental justice** for biorefinery deployment.
- **Develop defensible methodologies, analyses, and tools** to understand the impact of expanding the bioeconomy and leveraging existing infrastructure.

1. **Approach:** Management, Team and Risk Mitigation

Principal Investor: Ling Tao

- **Strategic Support**
- **Strategic TEA (Ling Tao)**
- **Sustainable Process Design (Eric Tan)**
- **Refinery Optimization (Michael Talmadge)**
- **Jobs Analysis (Yimin Zhang)**
- [redacted]

Primary Risk

Project recommendations cannot keep up with rapid changing externalities; data

Mitigation Strategies

- ❑ Team stays current on technical and advancements of biofuel industry and technology development.
- ❑ Frequent collaboration and check-ins with other offices and industrial experts to ensure **integration and alignment with BETO's mission and priority.**
- ❑ Advance analysis R&D and focus on critical issues.

1. **Approach:** Task Structure

Develop Models and Conduct Analysis to Support Strategic Decisions

Strategic Support (Ling Tao)	Provide analyses of emerging strategies
Strategic TEA (Ling Tao)	Identify drivers, barriers, and R&D needs
Sustainable Process Design (Eric Tan)	Support informed process designs
Refinery Optimization (Michael Talmadge)	Assess refinery integration opportunities
Jobs Analysis (Yimin Zhang)	Estimate jobs for a growing bioeconomy
[redacted]	Research EJ issues for bioenergy

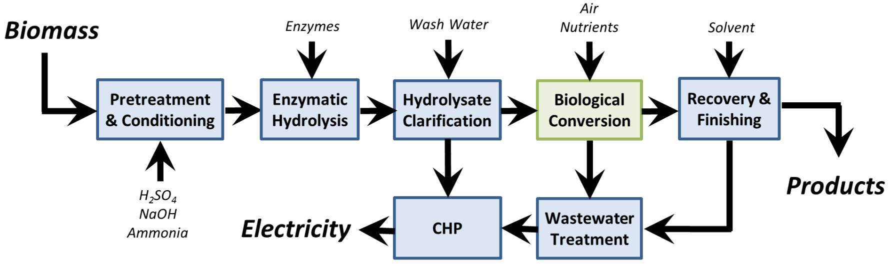
Communication and Collaborations:

- Assumptions and tools used in analysis are consistent with state-of-market and state-of-art.
- Tasks are **integrated** to provide holistic output for strategy development.
- Analysis results and approaches are **verified by stakeholders and industrial advisors.**
- Results shared via peer-reviewed publications, presentations, web-based tools, and technical reports.

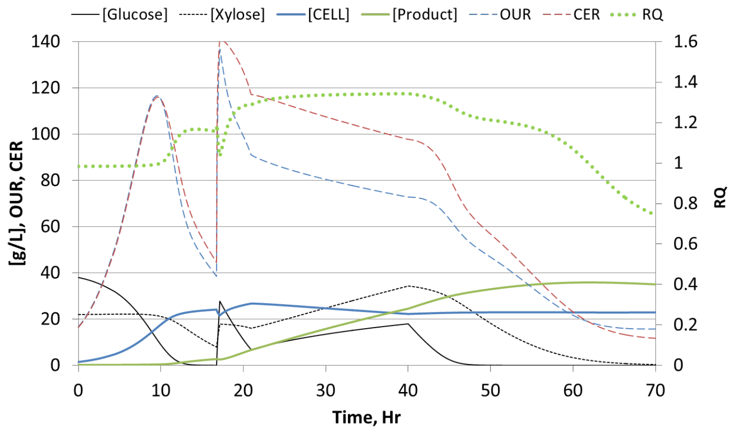
1. Approach: TEA Methodology

Strategic TEA (Ling Tao)

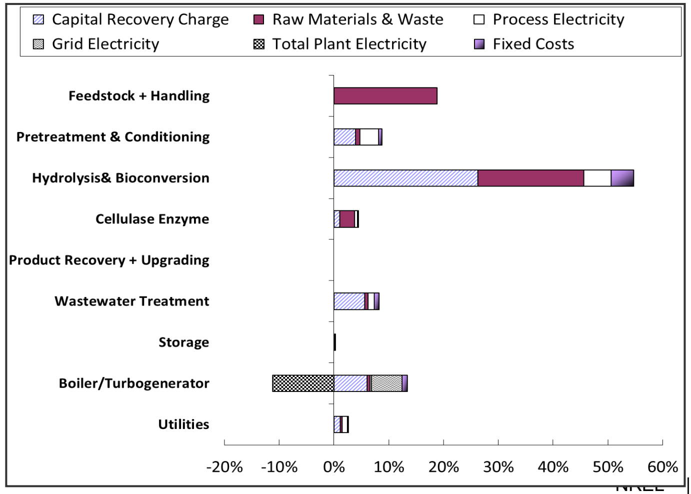
1) Conceptual process is **formulated or refined based on current research** and expected chemical transformations.



2) Unit operations are **modeled using experimental data and evaluated for costs**.



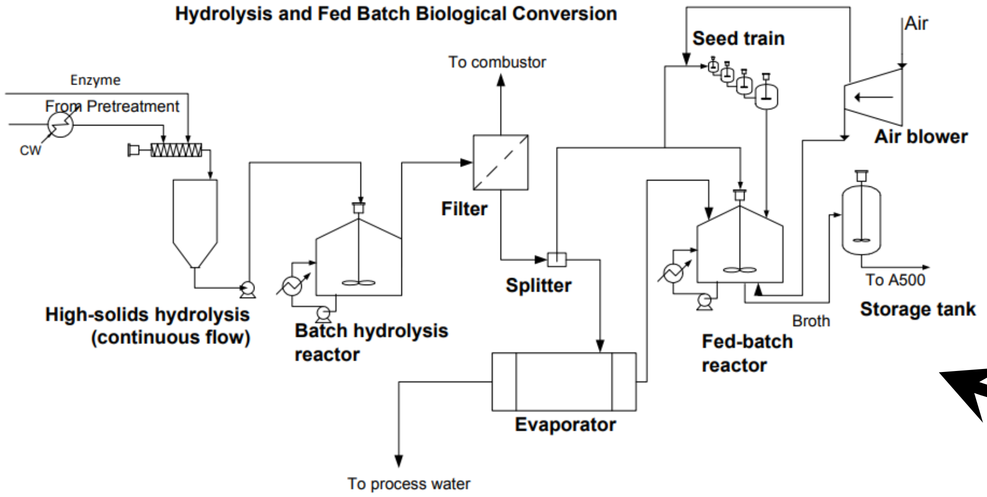
3a) Identify **major cost drivers**.



3b) Identify **the major sustainability drivers**.

GREET LIFE-CYCLE MODEL

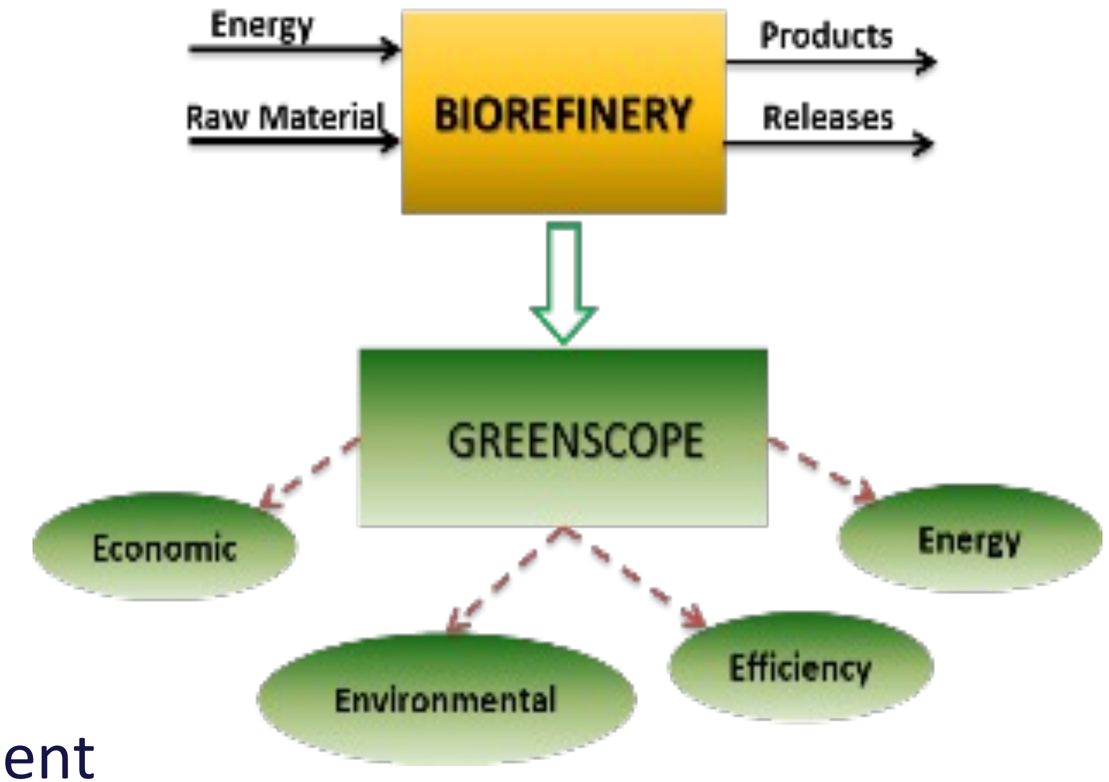
4) Results and learning for **improved process designs**.



1. **Approach:** Sustainable Process Design

Sustainable Process Design (Eric Tan)

GREENSCOPE for sustainability performance assessment of biomass-to-fuel conversion processes.



MODEL CAPABILITIES:

- Integrated framework.
- Wide range of sustainability metrics.
- Four performance areas: Environment, Energy, Economics, and Efficiency.
- A holistic sustainability analysis where the designers and decision-makers can implement changes to the process design and understand impacts at the unit-operations level.

1. Approach: Jobs Analysis for SAF

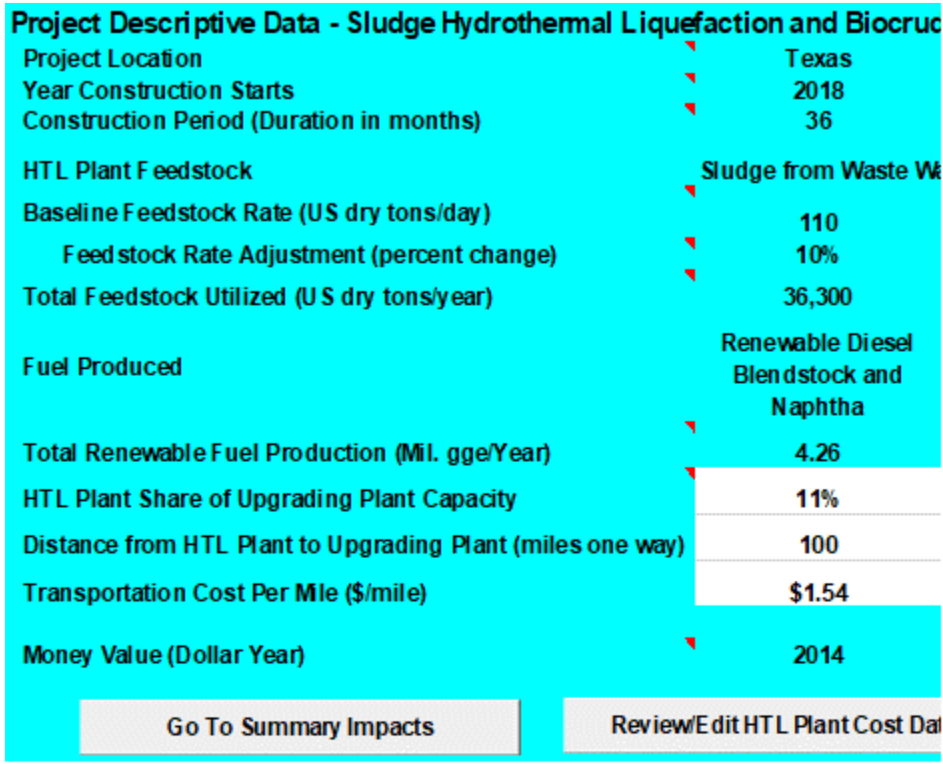
Jobs Analysis (Yimin Zhang)

RELEVANCE: Publicly available tool for estimating the economic impacts of potential bioenergy technologies on local jobs.

PROBLEM: Lack of tools for evaluating the broad socioeconomic impact of bioenergy technologies.

APPROACH: Input-output model for estimating economic impacts for wet waste (sludge, in particular)-to-biofuel blendstocks.

OUTCOMES: Developed a Jobs and Economic Development Impact model to estimate the jobs impact of producing biofuels.



Project Descriptive Data - Sludge Hydrothermal Liquefaction and Biocruc	
Project Location	Texas
Year Construction Starts	2018
Construction Period (Duration in months)	36
HTL Plant Feedstock	Sludge from Waste Wa
Baseline Feedstock Rate (US dry tons/day)	110
Feedstock Rate Adjustment (percent change)	10%
Total Feedstock Utilized (US dry tons/year)	36,300
Fuel Produced	Renewable Diesel Blendstock and Naphtha
Total Renewable Fuel Production (Mil. gge/Year)	4.26
HTL Plant Share of Upgrading Plant Capacity	11%
Distance from HTL Plant to Upgrading Plant (miles one way)	100
Transportation Cost Per Mile ($/mile)	$1.54
Money Value (Dollar Year)	2014
Go To Summary Impacts	Review/Edit HTL Plant Cost Dat

https://www.nrel.gov/analysis/jedi/

1. Approach: Advance State of Art Analysis by Synergize Economics, Sustainability and Technology Evaluations

Strategic TEA (Ling Tao)

Sustainable Process Design (Eric Tan)

Jobs Analysis (Yimin Zhang)

ECONOMIC METRICS

Minimum fuel selling price (MFSP) baseline cost ($/gge)
MFSP target cost ($/gge)
Percent of SAF production dependent on coproducts (%)
Capital cost per unit of product (million $/million gge)
Feedstock costs ($/ton)
Payback period (years)
ROI (%)
Feedstock availability (million dry tons/yr)
SAF production potential (billion gge/yr)
Hydrocarbon product distribution (%)

Analysis data and key insights on carbon conversion technologies.

How to meet BETO sustainability goals?

PROCESS TECHNOLOGY METRICS

Process data
Blending limitation with current Jet A fuel (%)
SAF use in commercial or military aircrafts
Production facility
TRL (number)

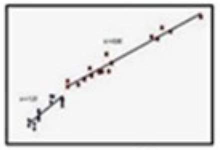
SUSTAINABILITY METRICS

SAF yield (gge/dry ton)
Energy intensity (GJ/kg)
Fossil energy consumption
Carbon intensity (g CO_2eq/MJ)
GHG emissions reduction (%)
Water consumption (gal/gge)
Respiratory effects potential (%)
Ecotoxicity to aquatic life potential (%)

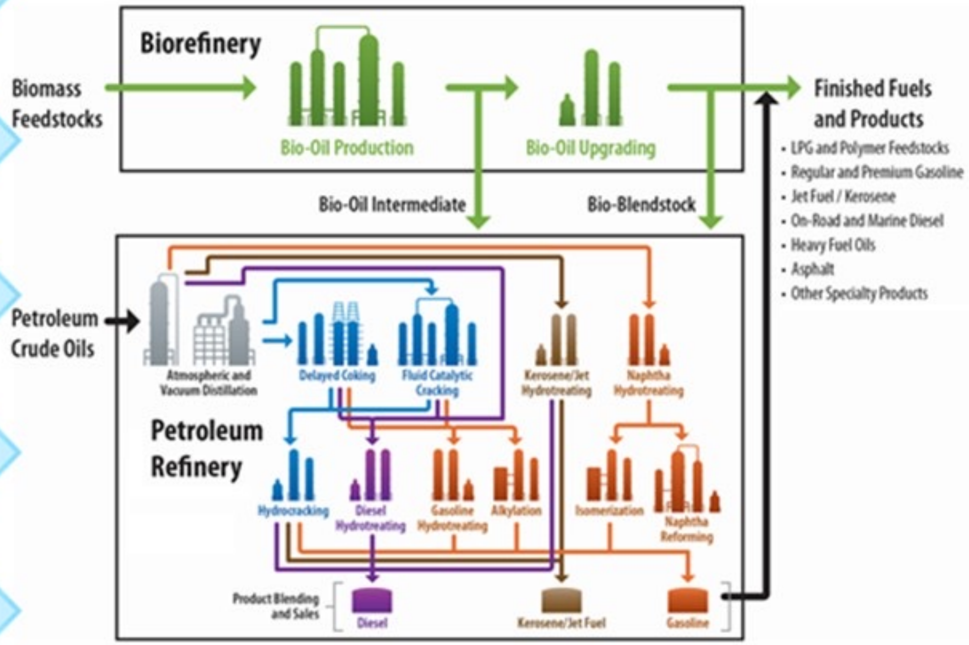
How many billion gallon of SAF could be made from bio-based feedstocks?

1. Approach: Refinery Integration Analysis

- Refinery configuration and unit capacity basis from EIA.
- Bio-blendstock/-intermediate cost, props, yields from TEA.
- ASTM fuel specifications consistent with industry.
- Crude and product pricing data from OPIS and PRISM.
- Market projections from EIA, OPIS, ADOPT.
- Refinery capital investment basis from published sources.
- Direct industry input through several on-going projects.



Biorefinery Models in Aspen Plus, Excel, Python



Refinery Models in Aspen PIMS By AspenTech

- Integrated with LCA calculations.
- Bioeconomy Optimizations.
- R&D needs via data gaps.

Outputs:

- Optimized refinery solutions
- Valuations of bio-inputs.
- Effective policy designs to de-risk biofuels production in refineries.

Related Projects:

- Co-Optima (McCormick)
- Marine fuels (Newes)
- Clean Fuels (McCormick)
- TC analysis (Dutta)
- TC upgrading (Griffin)
- Bioeconomy (Tao)

Build a "meta-model" representation of US refinery network for bioeconomy analysis.

1. Approach: Environmental Justice Analysis

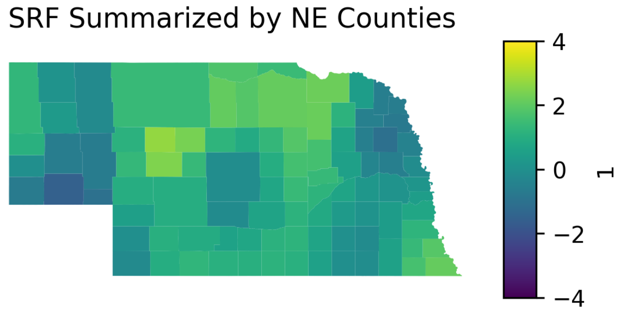
Justice 40 sets a goal of 40% of the benefits of federal investments going to disadvantaged communities

Objective: EEJ analysis is an important part of future energy systems analysis and requires decisions and data at community-scale to support the Biden Administration's Justice 40 priority.

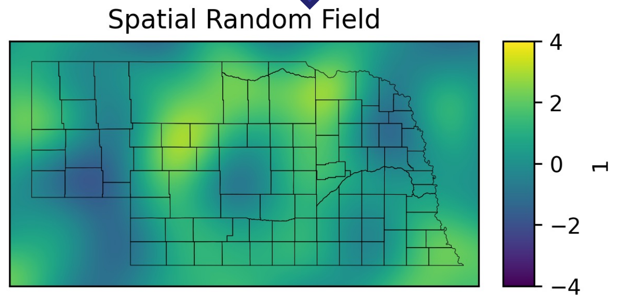
Approach: Most BETO models have native geospatial resolutions not sufficient to meet Justice 40's requirements, which is census tract level. Downscaling is the process of estimating high resolution values from low resolution data and enables community-level analysis *without alteration to existing models.* However, downscaling introduces additional and unavoidable uncertainty.

Outcomes: Identify statistical methods from the field of spatial statistics that can produce high-resolution data with quantified uncertainty from BETO models that have lower native resolution (most common is county, state or regions).

- Prioritize one method for testing
- Apply method to an example BETO model
- Evaluate results including uncertainty.



Low -resolution synthetic data



High-resolution estimates

2 – Progress and Outcomes: Strategic Support Task

Strategic Support (Ling Tao)

Strategic Goal:

- Support BETO's strategic mission and analysis needs.
- Utilize a range of approaches, work collaboratively with partner labs and agencies, to investigate critical questions.
- Handoff results and outcomes of analyses to support core BETO projects.

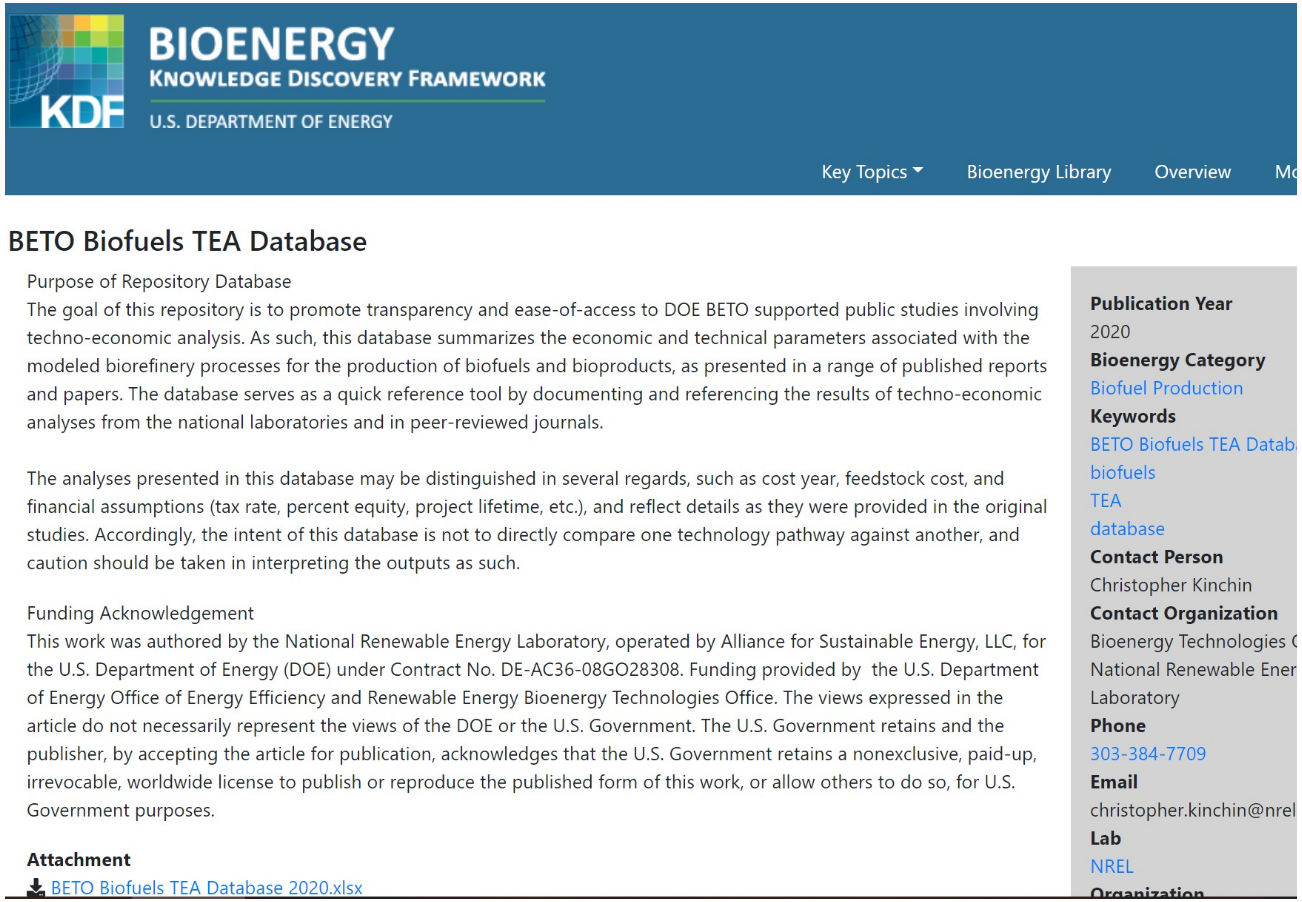
2. Progress and Outcomes: Public DOE BETO Biofuels TEA Database

MOTIVATION: Support transparency of and ease of access to DOE BETO supported public techno-economic analysis data.

GOAL: Develop and publicly release a biofuels cost data base that summarizes key inputs utilized in conversion TEAs.

OUTCOMES:

- 50+ DOE BETO funded TEA studies, including design reports, SOT reports and publications.
- Reviewed by lead analysts to ensure consistency.
- Provide annual update with new TEAs.



BIOENERGY
KNOWLEDGE DISCOVERY FRAMEWORK
KDF
U.S. DEPARTMENT OF ENERGY

Key Topics Bioenergy Library Overview Mo

BETO Biofuels TEA Database

Purpose of Repository Database

The goal of this repository is to promote transparency and ease-of-access to DOE BETO supported public studies involving techno-economic analysis. As such, this database summarizes the economic and technical parameters associated with the modeled biorefinery processes for the production of biofuels and bioproducts, as presented in a range of published reports and papers. The database serves as a quick reference tool by documenting and referencing the results of techno-economic analyses from the national laboratories and in peer-reviewed journals.

The analyses presented in this database may be distinguished in several regards, such as cost year, feedstock cost, and financial assumptions (tax rate, percent equity, project lifetime, etc.), and reflect details as they were provided in the original studies. Accordingly, the intent of this database is not to directly compare one technology pathway against another, and caution should be taken in interpreting the outputs as such.

Funding Acknowledgement

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Attachment

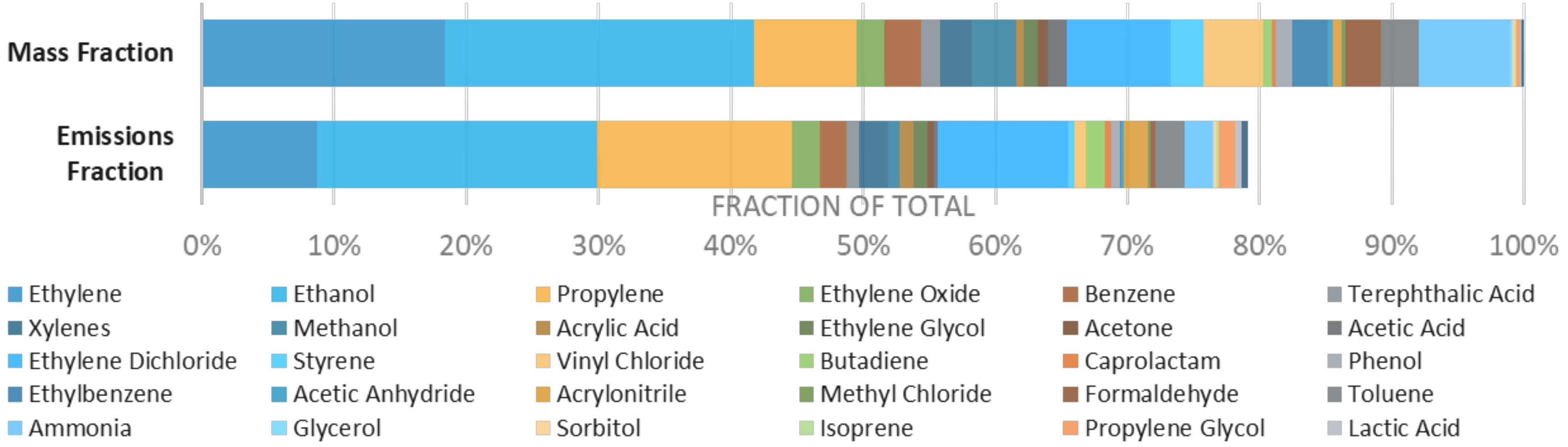
BETO Biofuels TEA Database 2020.xlsx

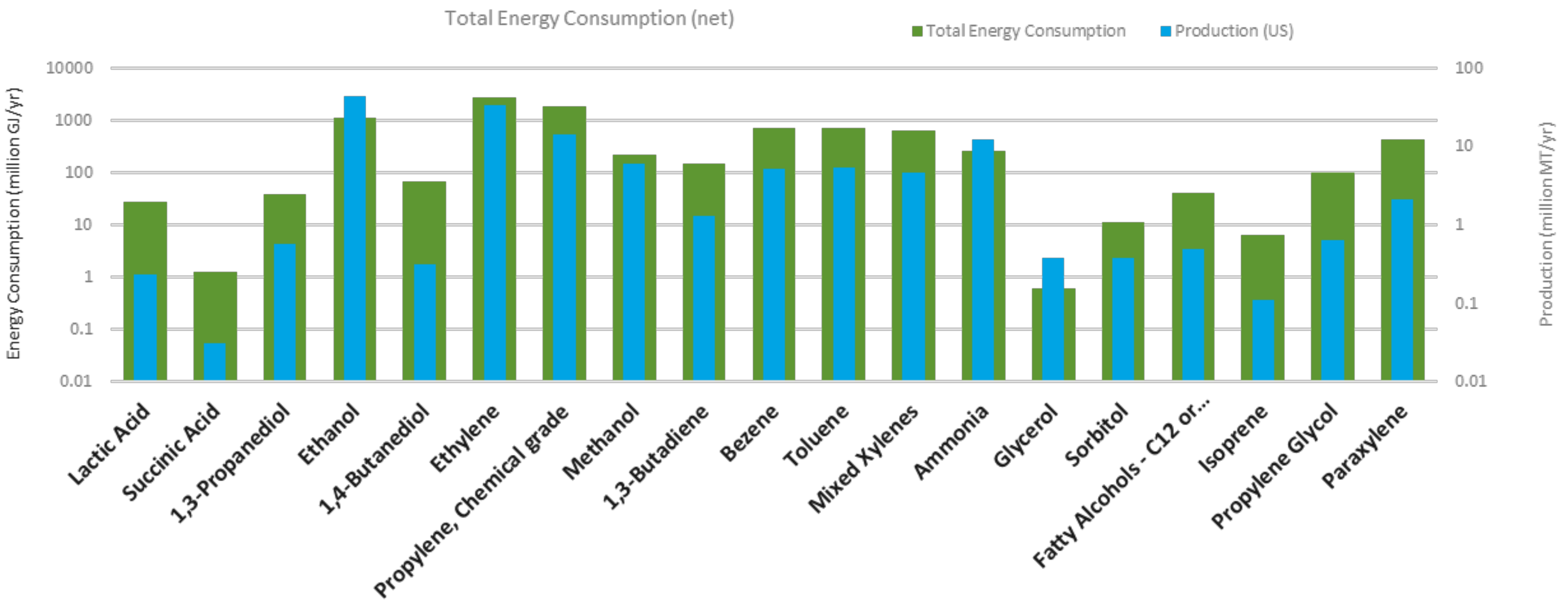
Publication Year
2020
Bioenergy Category
Biofuel Production
Keywords
BETO Biofuels TEA Datab
biofuels
TEA
database
Contact Person
Christopher Kinchin
Contact Organization
Bioenergy Technologies
National Renewable Ener
Laboratory
Phone
303-384-7709
Email
christopher.kinchin@nrel
Lab
NREL

Available for download on the Biomass KDF:
https://bioenergykdf.net/content/beto-biofuels-tea-database

2. Progress and Outcomes: Renewable Chemical Analysis

Update to 2016 Chemical Market Analysis Technical Report





MOTIVATION

Chemical production accounts for 5.5% of US GHG emissions and biomass-derived chemicals could significantly reduce GHG emissions.

GOAL

How to reduce chemical industry emission by 100 million ton?

OUTCOMEs

- Meet BETO’s targets.
- Evaluate market drivers (market size, chemical price, market share, end uses), conversion pathways, carbon/energy intensities.

2. Progress and Outcomes:

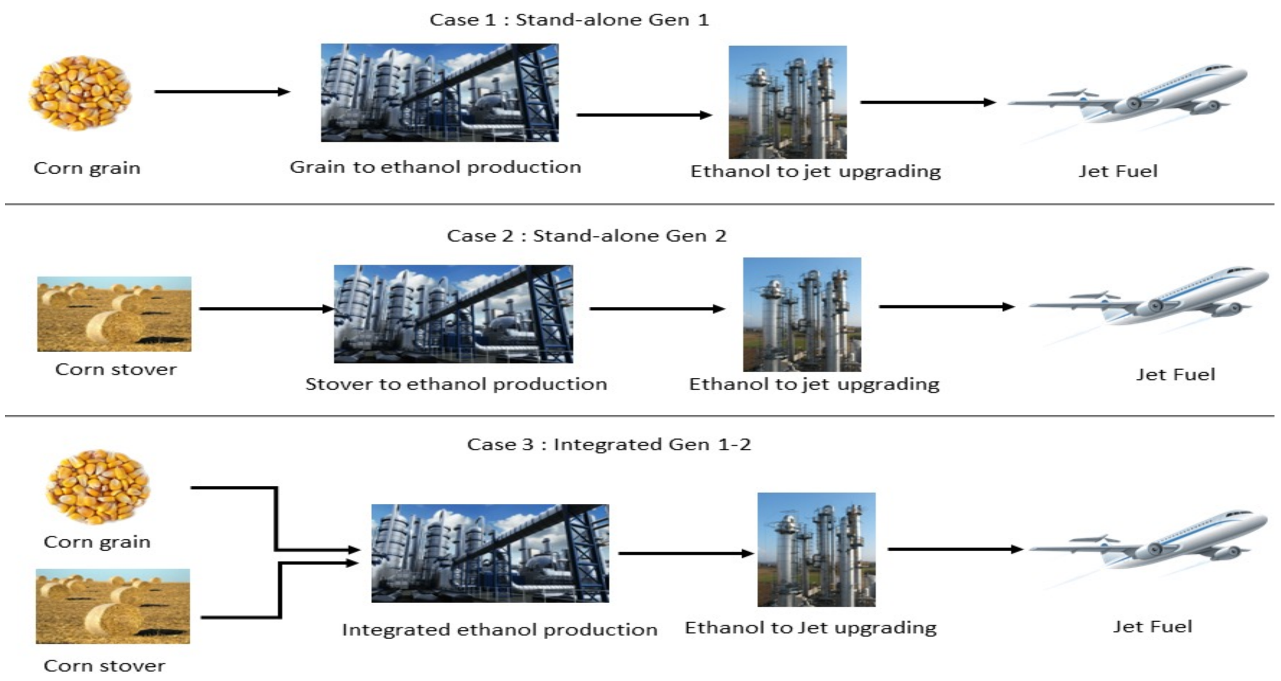
Integrated LCA and TEA on Corn Grain and Corn Stover Ethanol

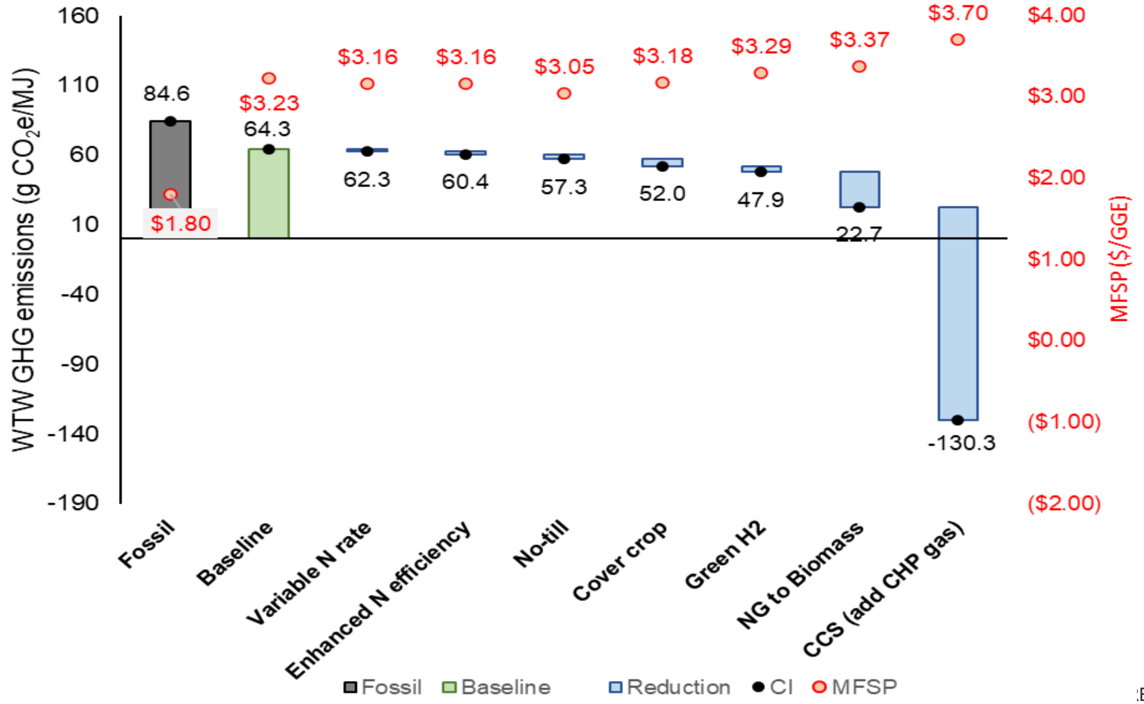
MOTIVATION: Address BETO strategy to achieve net-zero SAF.

GOAL: Achieve net-zero ethanol-to-jet (ETJ) production with cost trade-offs.

OUTCOMES:

- Conducted TEA and LCA study on various ETJ decarbonization strategies.
- Identified scenarios to achieve net-zero SAF and their cost implications.
- Investigated farming practices with biochar options.





2 – Progress and Outcomes: Integrated Analysis on SAF

Strategic TEA (Ling Tao)

Sustainable Process Design (Eric Tan)

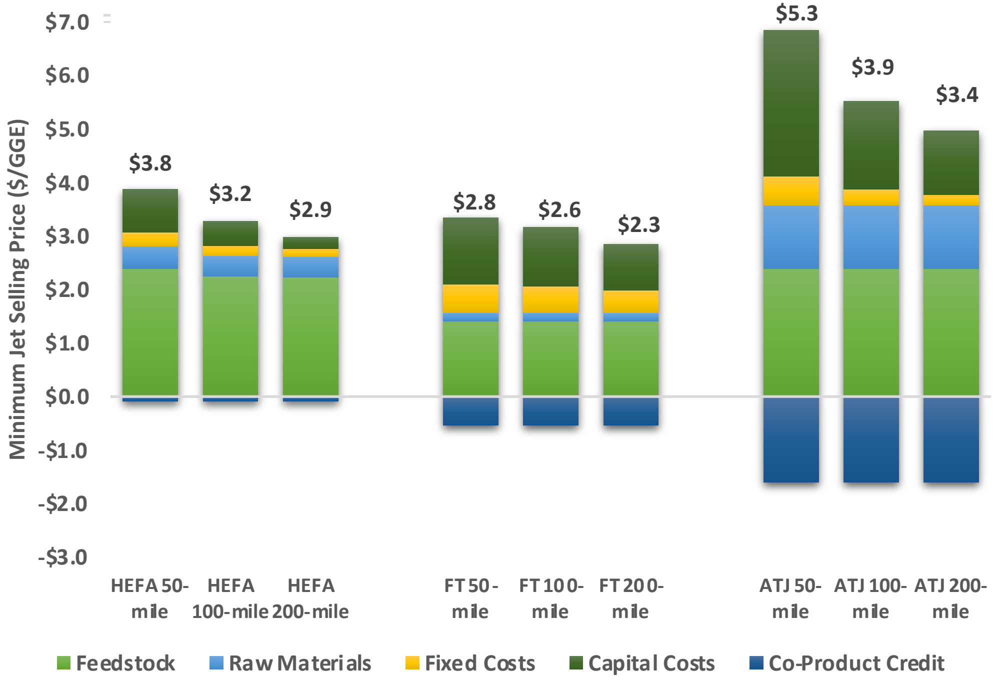
Jobs Analysis (Yimin Zhang)

Strategic Goal:

- Perform TEA to highlight R&D needs for emerging strategies.
- Incorporate and integrate sustainability into conversion process design.
- Understand the potential of job creation and economic benefits resulting from the build-out of new biorefineries.
- Supply key data for the SAF Grand Challenge Report, GREET, BSM, BETO and other EERE offices.

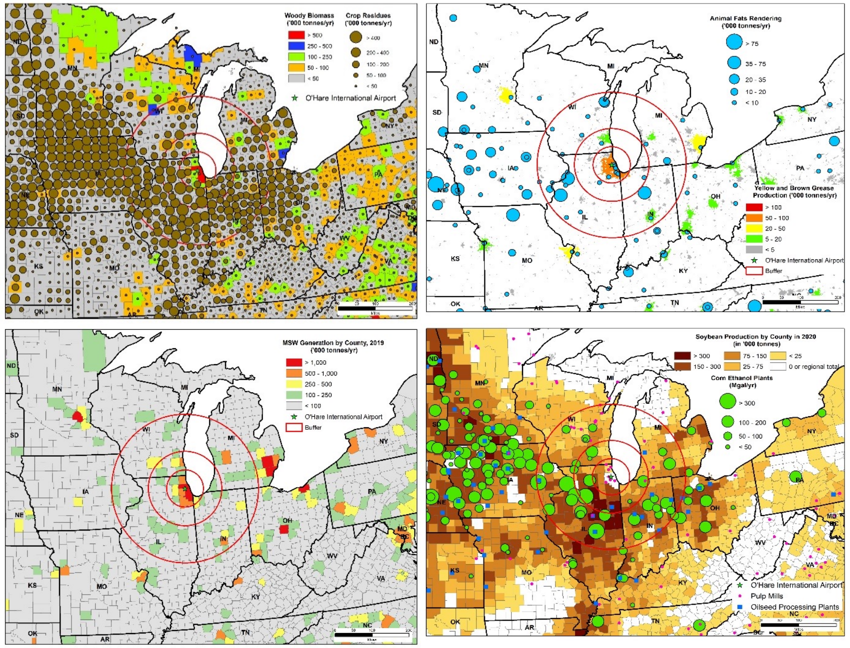
2. Progress and Outcomes: SAF Regionalization Study

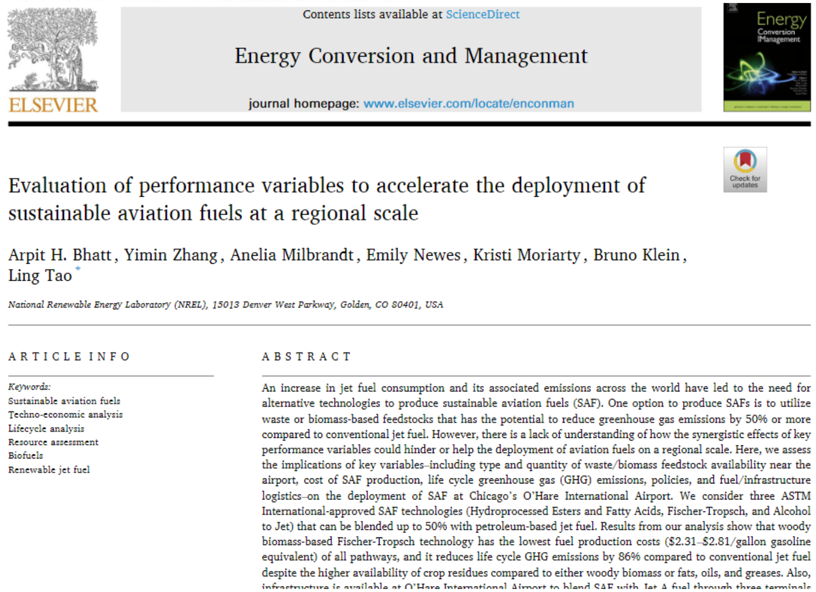
Evaluate synergistic impacts of key performance variables on the deployment of SAF at Chicago O'Hare Airport (ORD).



Performance Variables:

- Feedstock availability
- Production cost
- Lifecycle GHG emissions
- Policy incentives
- Infrastructure compatibility





Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale

Arpit H. Bhatt, Yimin Zhang, Anelia Milbrandt, Emily Newes, Kristi Moriarty, Bruno Klein, Ling Tao *

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ARTICLE INFO

Keywords:
Sustainable aviation fuels
Techno-economic analysis
Lifecycle analysis
Resource assessment
Biofuels
Renewable jet fuel

ABSTRACT

An increase in jet fuel consumption and its associated emissions across the world have led to the need for alternative technologies to produce sustainable aviation fuels (SAF). One option to produce SAFs is to utilize waste or biomass-based feedstocks that has the potential to reduce greenhouse gas emissions by 50% or more compared to conventional jet fuel. However, there is a lack of understanding of how the synergistic effects of key performance variables could hinder or help the deployment of aviation fuels on a regional scale. Here, we assess the implications of key variables–including type and quantity of waste/biomass feedstock availability near the airport, cost of SAF production, life cycle greenhouse gas (GHG) emissions, policies, and fuel/infrastructure logistics–on the deployment of SAF at Chicago's O'Hare International Airport. We consider three ASTM International-approved SAF technologies (Hydroprocessed Esters and Fatty Acids, Fischer-Tropsch, and Alcohol to Jet) that can be blended up to 50% with petroleum-based jet fuel. Results from our analysis show that woody biomass-based Fischer-Tropsch technology has the lowest fuel production costs ($2.31–$2.81/gallon gasoline equivalent) of all pathways, and it reduces life cycle GHG emissions by 86% compared to conventional jet fuel despite the higher availability of crop residues compared to either woody biomass or fats, oils, and greases. Also,

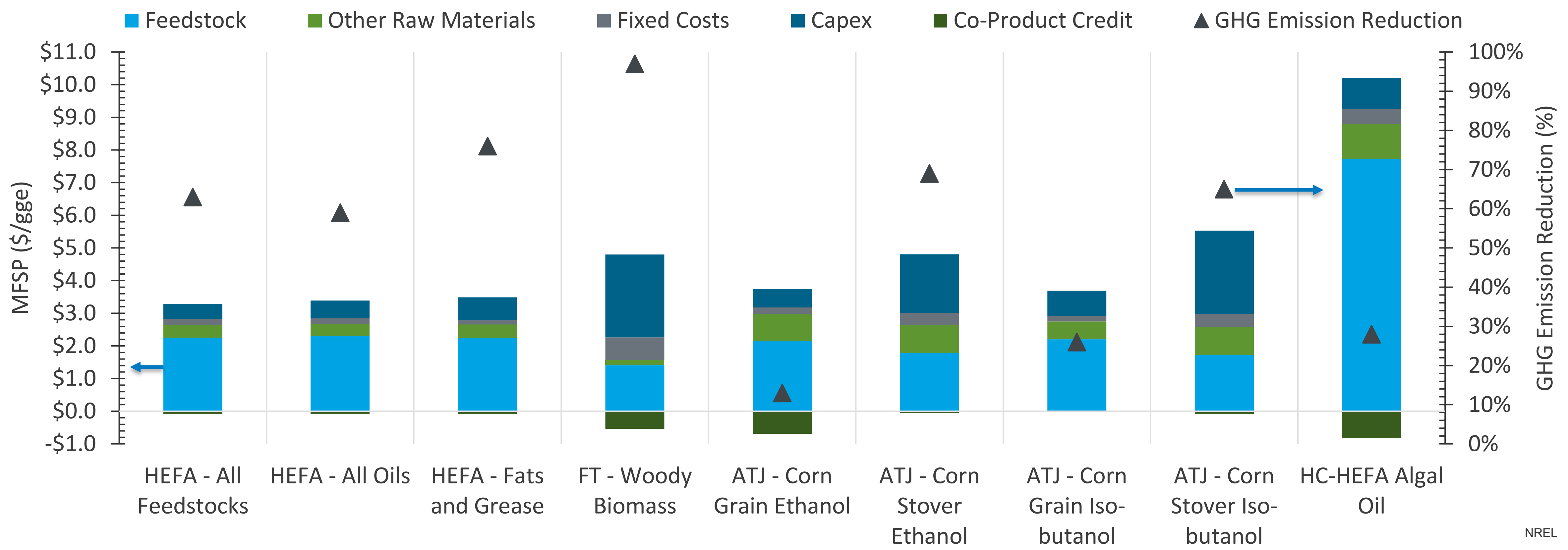
OUTCOMES

- Displace up to 55% of ORD's jet fuel with SAF potentially.
- Lifecycle GHG emissions could be reduced up to 86%.
- Feedstock cost & renewable fuel incentive are key cost drivers.

2. Progress and Outcomes: Cross-Comparison of ASTM Approved SAF Pathways

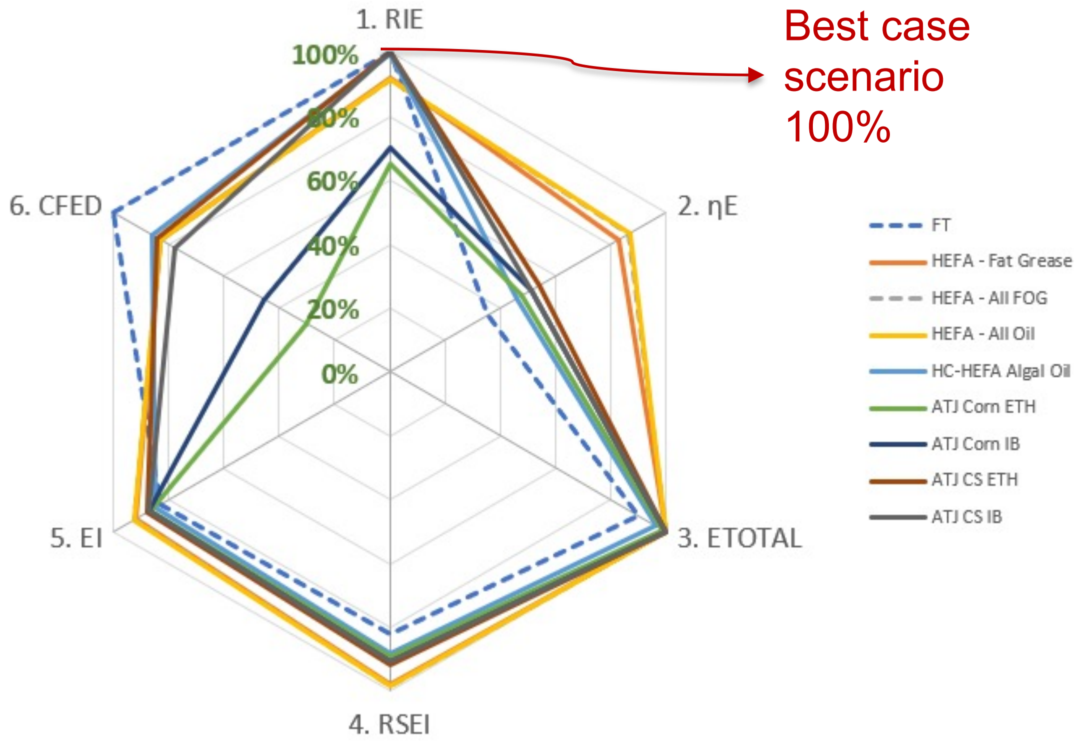
Update the 2016 SAF Analysis Technical Report and Support SAG Grand Challenge

Goals: Develop strategies for SAF development, deployment, and commercialization to meet targeted 3 billion gallons of SAF production by 2030. Identify strategies and R&D opportunities to meet technology, economic, and sustainability goals.

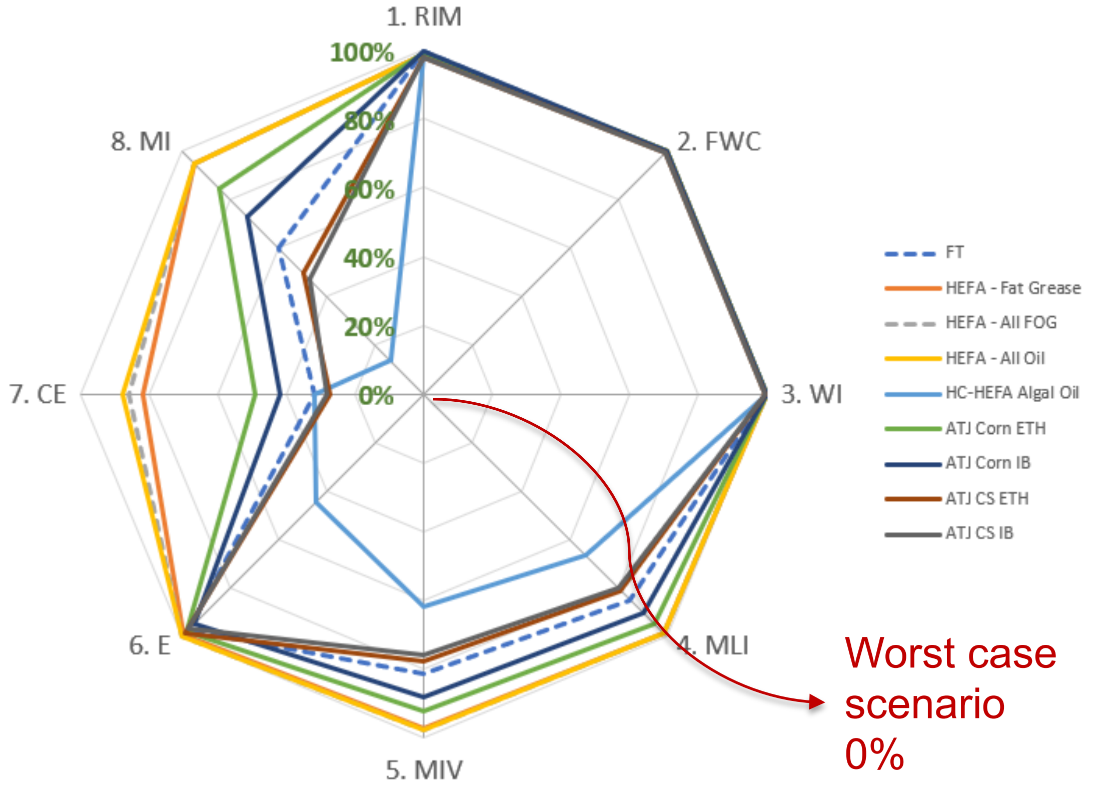


2. Progress and Outcomes: GREENSCOPE on Integrated Sustainability

Energy Indicators



Efficiency Indicators



Energy: Renewability-energy index, is >90% for all pathways except corn ATJ.

Efficiency: Compared to other pathways, HEFA Algae exhibits the lowest score in all material efficiency indicators.

2 – Progress and Outcomes: Refinery Optimization

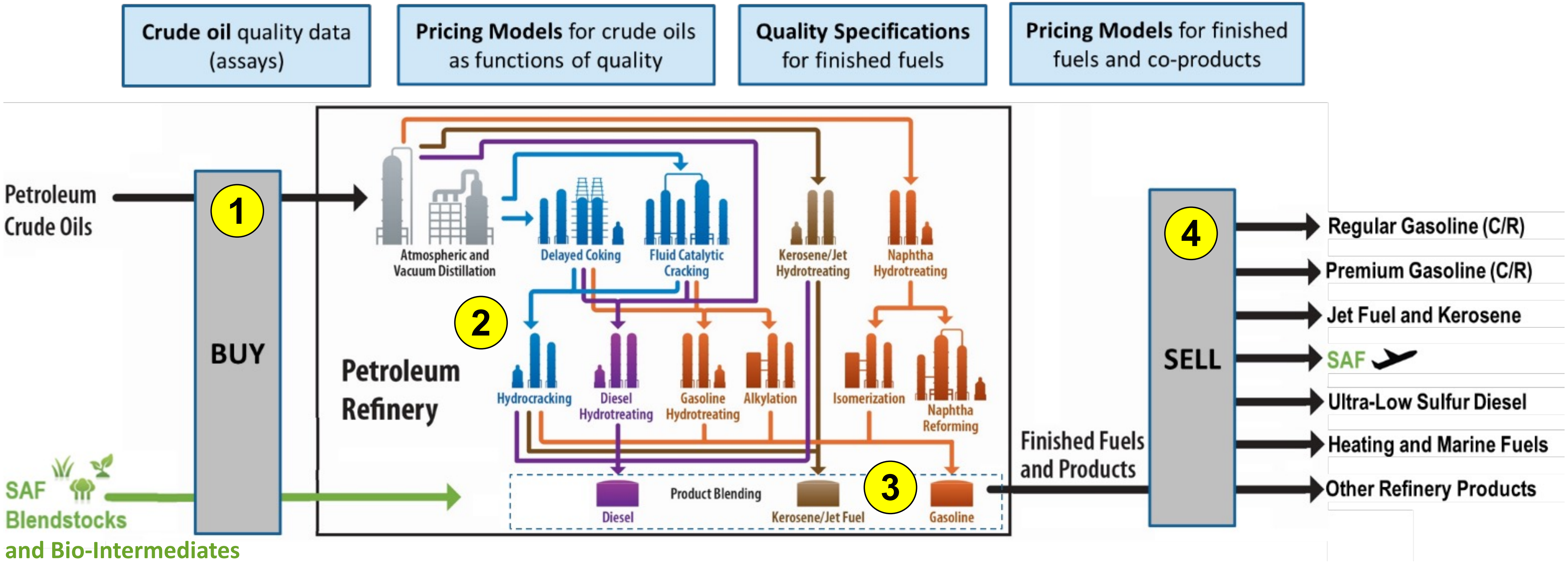
Refinery Optimization
(Michael Talmadge)

Strategic Goal:

Seek opportunities for biofuels in the context of petroleum refineries.

1. Approach: Aspen PIMS Modeling

Refinery Optimization (Michael Talmadge)



(1) Materials the refinery can purchase with purchase prices, qualities, quantities.

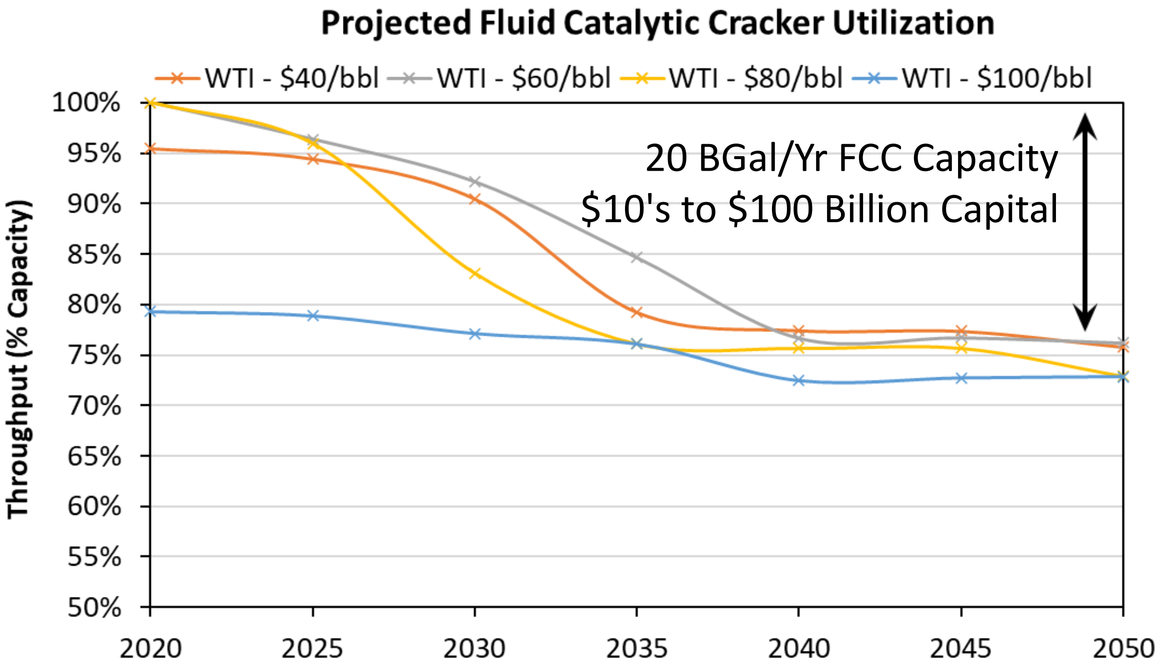
(2) Conversion options for purchased crudes and intermediates.

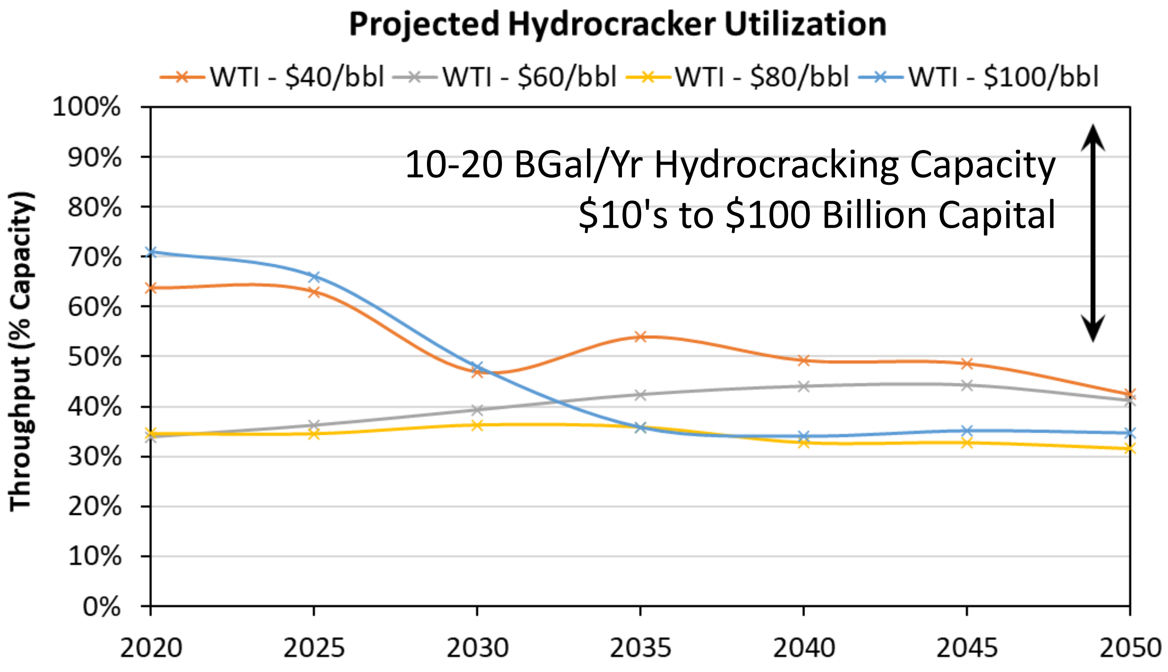
(3) Blending properties and ASTM specifications for making fuels.

(4) Products for sale with prices and target quantities.

2. Progress and Outcomes: Refinery Utilization & Optimization Modeling

Equipment utilization projections for high-complexity refinery model.
Fuel projections based on EIA AEO-2022 corrected with NREL-ADOPT EV projections at ~40%.





- Utilizing projected fuel demands with refinery models to estimate capacity availability for fluid catalytic cracking and hydroprocessing units over time.
- Developing integration strategies that align with projected availability.

2 – Progress and Outcomes: Environmental Justice

Strategic Goal:

Provide environmental justice analysis on biorefineries.

[redacted]

2. Progress and Outcomes: Geospatial Downscaling for Energy and Environmental Justice (EEJ)

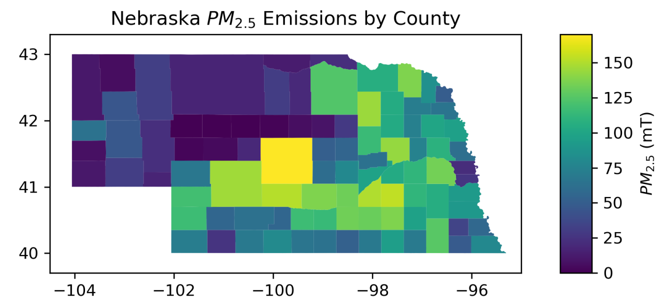
[redacted]

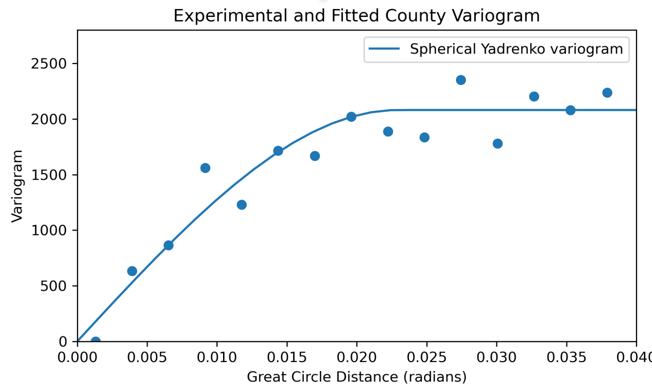
Progress: Statistical methods from the literature were evaluated for relevance to the spatio-temporal scale of BETO models.

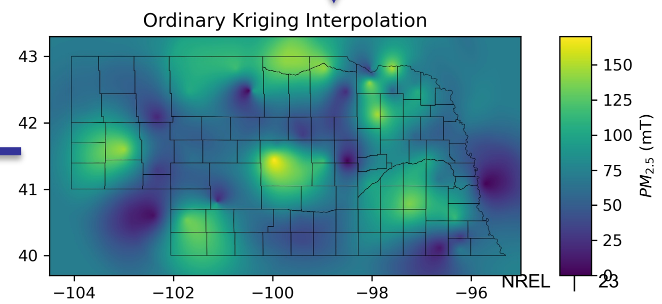
- Conditional simulation chosen as highest potential method.
- Expected error calculated using high-resolution synthetic data (16%).
- Conditional simulation applied to NREL's BETO-supported *Feedstock Production Emissions to Air Model* (FPEAM) county-level data to produce estimates at a resolution valid for EEJ analysis → census tract level.

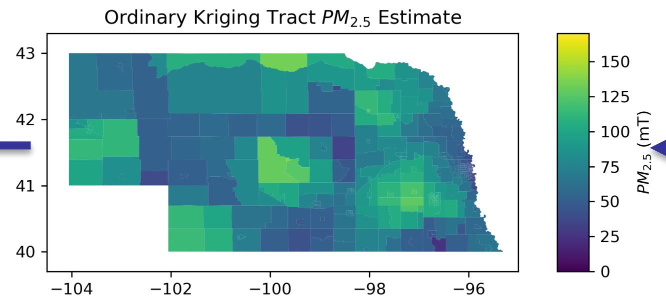
Outcome:

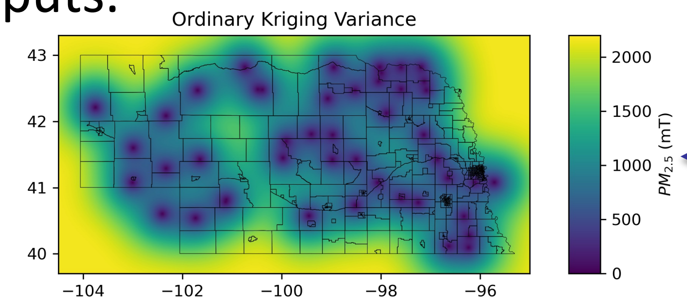
- Successfully downscaled from model native resolutions at county level to Justice 40 census tract level.
- Should be generally applicable to any BETO (or other) model with geospatial outputs.











3. Impact: Outcomes Support and Bridge a Range of DOE BETO Projects and Beyond

Supply Chain Sustainability Analysis

Analysis & Sustainability Interface (Multi-criteria)

Strategic Analysis Support (Multi-criteria)

GREET Development (LCA)

Algae LCA (LCA)

Biomass Sourcing

Supply Scenario Analysis (Resource Assessment)

Microalgae Analysis (Resource Assessment)

Algae System TEA (TEA)

Biomass Transport + Pre-Processing Logistics

Feedstock Supply Chain Analysis (Resource Assessment, TEA)

Biorefinery Conversion

BC Analysis (TEA)

TC Analysis (TEA)

Wet Waste HTL (TEA)

Algae HTL (TEA)

Algae System TEA (TEA)

Jet/Vehicle End-Use

Note: Additional work conducted under DMA and SDI

Feedstock Type

Terrestrial

Wet Waste

Algae

3. Impact: Provided strategic support to the SAF Grand Challenge

Strategic Support (Ling Tao)

Strategic TEA (Ling Tao)

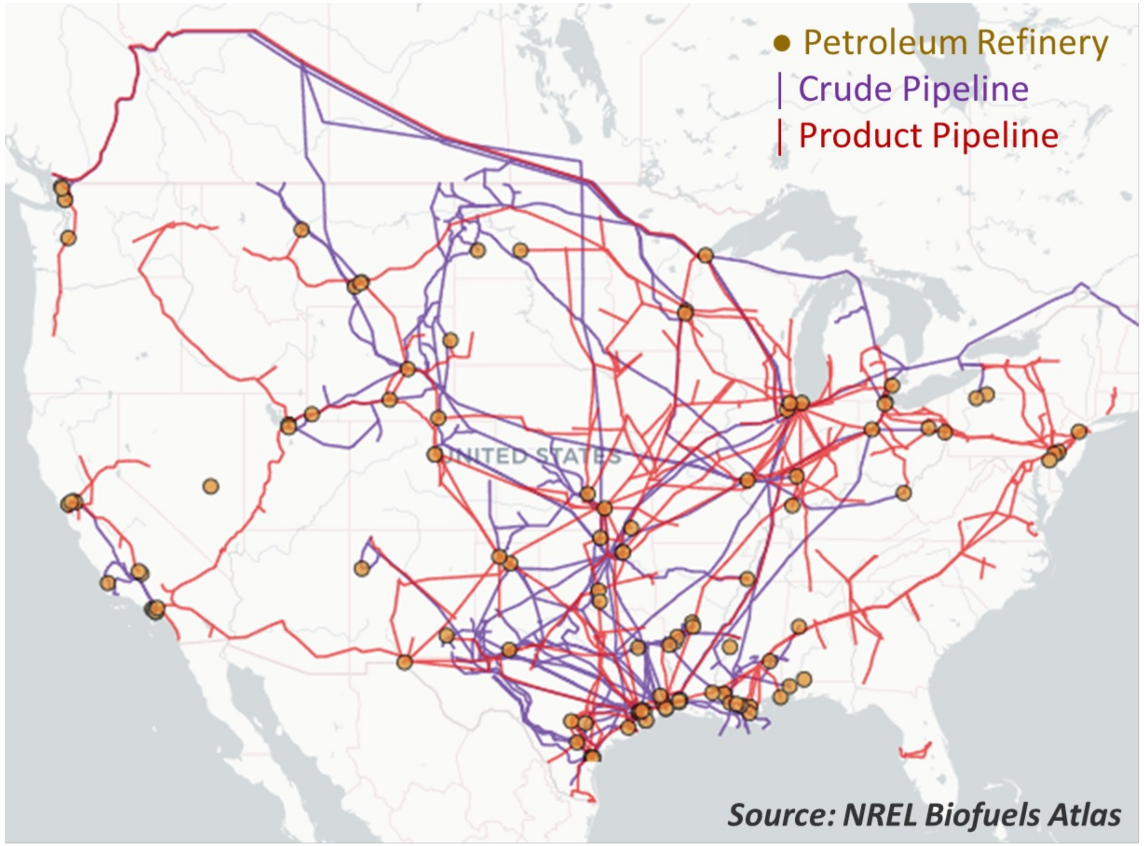
CAAFI
COMMERCIAL AVIATION ALTERNATIVE FUELS INITIATIVE

- **Provide strategic supports to the office.**
- **SAF Grand Challenge Team Receives 2022 Secretary's Achievement Award.**
- **Decarbonization transportation and industry sectors.**
- **11+ peer-reviewed papers and book chapters.**
- **7+ conference and invited talks.**

3. **Impact:** Provide Strategic Guidance to Industry

Refinery Optimization (Michael Talmadge)

- 200 B-Gal per year of diesel hydrotreating (DHT), hydrocracking (HCU) and fluid catalytic cracking (FCC) processing capacity in the US.
- Others plus utilities, WWTP, etc.



Source: NREL Biofuels Atlas

Refinery Capacity Summary (B-Gal per year unless noted)	
US Total / PADD	Totals
Atmospheric Distillation	290.5
Vacuum Distillation	131.6
Naphtha Hydrotreating	70.6
Kerosene Hydrotreating	24.0
Diesel Hydrotreating	70.0
Gas Oil and Resid Hydrotreating	51.2
Gasoline Hydrotreating	44.8
Hydrocracking	37.2
Fluid Catalytic Cracking	85.1
Thermal Cracking (Coking and Visbreaking)	44.9
Naphtha Reforming	54.8
Alkylation	19.8
Isomerization	11.6
Aromatics	4.8
Asphalt and Road Oil	10.6
Fuels Solvent Deasphalting	6.1
Hydrogen (MMCFD)	2,893
Lubricants	4.0
Petroleum Coke	13.5
Sulfur (Short Tons per day)	40,453

Source: EIA 2022 Refinery Capacity Report: https://www.eia.gov/petroleum/refinerycapacity/

3. Impact: Refineries as Future Decarbonization Hubs

Refinery Optimization (Michael Talmadge)

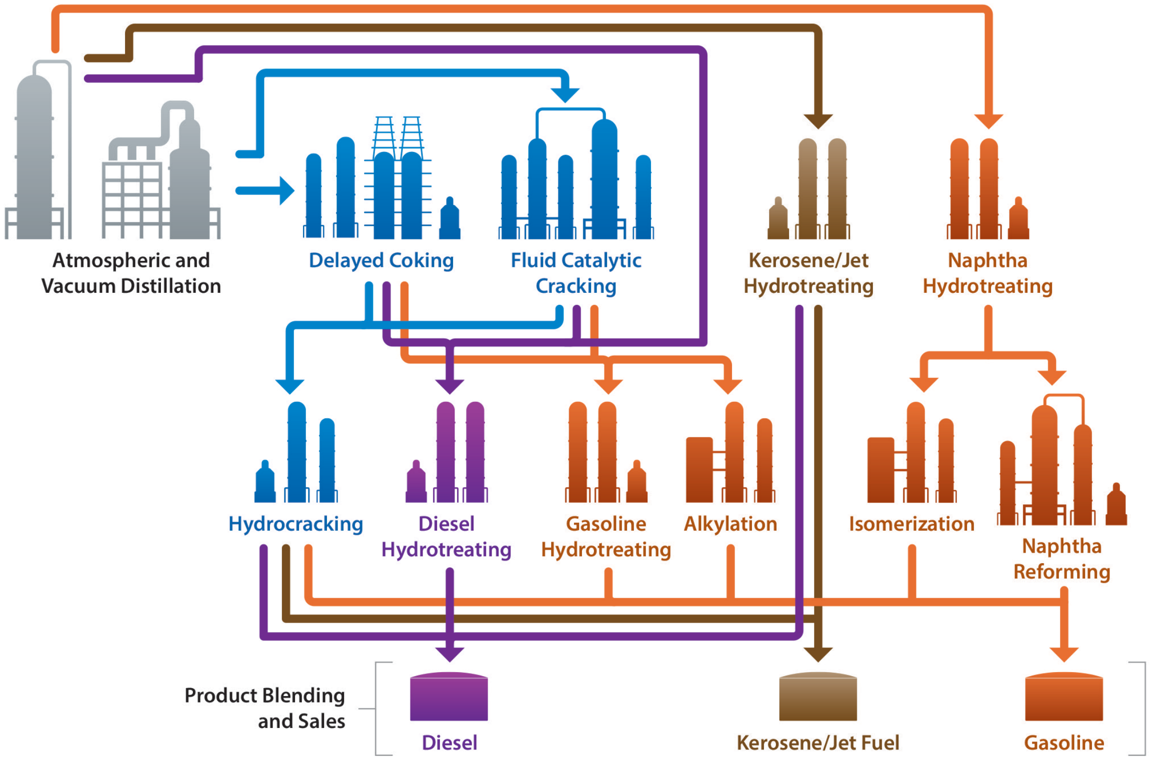
- Refineries are logical locations for consideration as future decarbonization hubs for integrating emerging technologies.
- Existing environmental controls, water treatment, heat and power systems.

Low Carbon Feedstocks

Optimize for Product Slate

Renewable Power

Green Hydrogen



Olefin Chemistry

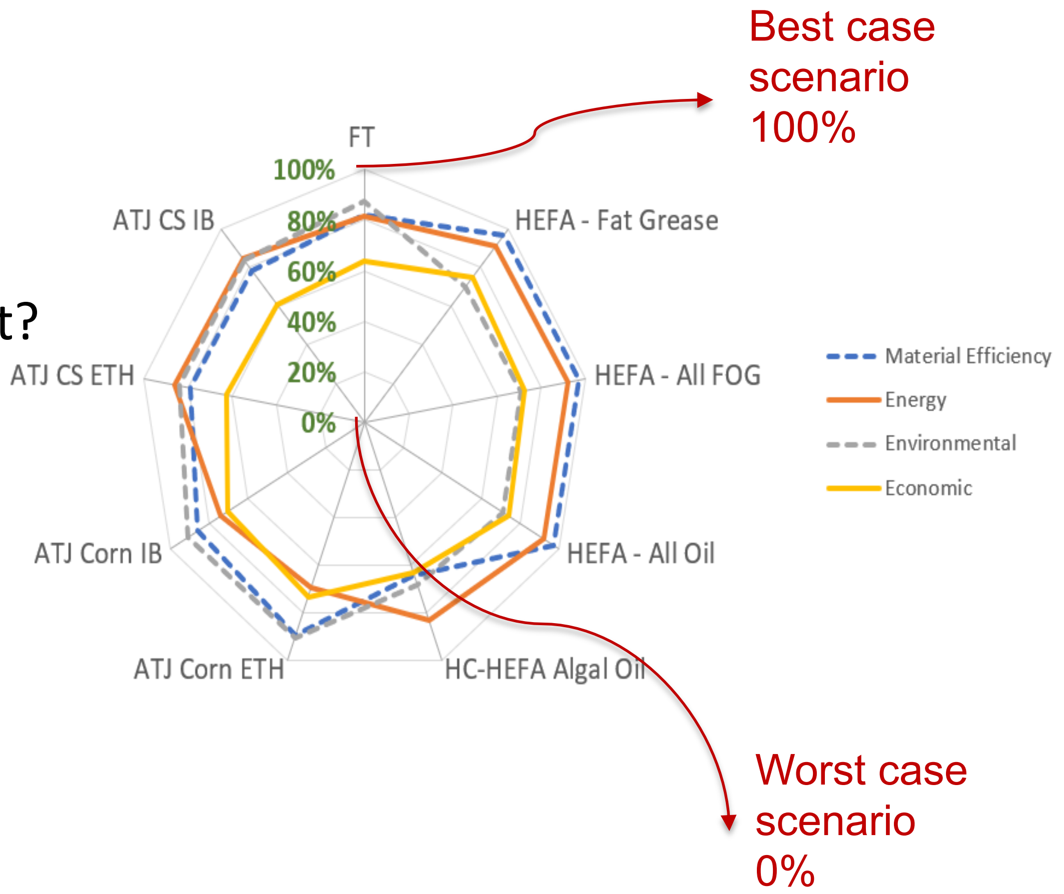
Renewable Chemicals

CO_2 Capture and Utilization

Solid Carbon Sequestration

3. **Impact:** Multi-Dimensional Analysis Provides Insights on Opportunities for Achieving Improved Sustainability for SAF

- **Funding agency**
  - Informed BETO where to allocate the resources.
- **Researcher & process designers**
  - Identified process areas need sustainability improvement?
  - Assessed the challenges and opportunities for achieving the best possible sustainability targets.
- **Other stakeholders**, including agencies outside of BETO like EPA, EERE SA, VTO, FCTO and many others:
  - Evaluated ASTM D7566 approved SAF pathways exhibit a high degree of sustainability in material efficiency and energy.
  - Enabled result dissemination and stakeholder engagements.



Average sustainability scores for four sustainability aspects: material efficiency, energy, environmental, and economic.

3. Impact: Geospatial Downscaling for Energy and Environmental Justice (EEJ)

- **What is the value or impact to BETO?**
  - Our mission is to produce 35 billion gallon of SAF in 2050, and under the Justice 40 initiative, 40% of benefits for federal investment would need to go to disadvantage communities.
  - Our generally applicable method can enable the use of BETO models to evaluate compliance with Justice 40 goals.
- **What is the impact or relevance on DEI goals?**
  - The capability developed could be applied to, for instance, Justice40 evaluation of proportion of health benefits for disadvantaged communities for projects like CCS systems on SAF plants (e.g., ExxonMobil announced plans).
  - CCS systems can reduce co-pollutant emissions on top of carbon emission reduction.

Summary

Approach	• Integrate multiple dimension strategic supports for BETO, external/internal stakeholders. Consult experts globally to get the best data; work closely with stakeholders to define need and key questions. • Transparent, rigorous models with a consistent set of assumptions. • Integrated task structure to provide holistic analysis for strategy development and decision making, especially for SAF.
Progress and Outcomes	• Successfully supported the SAF Grand Challenge Report. • Completed integrated analysis on ASTM approved pathways addressing cost, sustainability, technology readiness level and policies. • Evaluated biogenic feedstocks to existing US refinery for refinery optimization and capital recovery. • Disseminate technical results to web-based tools and in high impact publications.
Impact	• Support and bridge a range of DOE BETO projects. • Supported the SAF Grand Challenge and continue to support ongoing SAF activities for various federal offices. • Provide long term impacts on utilizing refineries.

Quad Chart Overview

Timeline

- *Project start date: 2021*
- *Project end date: 2024*

	FY22 Costed	Total Award
DOE Funding	*$675K*	*$1,875*

TRL at Project Start: 1-9

TRL at Project End: 1-9

Project Partners*

- National laboratories: ANL, INL, LLNL, ORNL, PNNL
- NREL—core platform analysis
- NREL—Market and Policy Impact Analysis
- NREL—SI, VT
- Industry: Exxon-Mobil, ICM, USDRIVE
- Government agencies: CAAFI, DOE-SA, DOE-AMO, DOE-FCTO, DOE-VTO, DOD, DOT, EPA
- Academia: MIT, University of Chicago, Colorado School of Mines

Project Goal

- Provide sound, unbiased, and consistent analyses to inform BETO strategic direction.
- Comparative analyses of biomass conversion processes to evaluate emerging areas of interest.
- Model and tool development to support BETO and to understand the impact of expanding bioeconomy.

End of Project Milestone

- Summary report on ASTM approved SAF pathways using integrated analysis of cost, sustainability, and technology evaluations.
- Summary report on renewable chemical analysis research: Report analysis findings on integration of TEA/LCA with supply chain analysis for 5+ renewable chemicals, including understandings and learnings on supply/demand or dynamic market perturbations, environmental related metrics such as carbon intensity and land impacts, economic related metrics such as payback periods and policy related metrics such as carbon pricing and RINs.

Funding Mechanism

Lab call

Acknowledgements

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PNNL: Lesley Snowden-Swan, Aye Meyer, Corinne Drennan

ANL: Michael Wang, Uisung Lee, Troy Hawkins, Peter Hua Chen, Eunji Yoo, Hao Cai

LLNL: Hannah Goldstein, Wenqin Li, Daniel Sanchez (Berkeley)

INL: Damon Hartley

Other industrial and academic collaborators

Bioenergy Technologies Office (BETO):

Andrea Bailey, Zia Haq, Jay Fitzgerald, Reyhaneh Shenassa, Art Wiselogel, Mark Shmorhun, Ian Rowe, Beau Hoffman, Nichole Fitzgerald, Kevin Craig, Jim Spaeth

Additional Slides

Acronym List

ADOPT	NREL Automotive Deployment Options Projection Tool
AEO	Annual Energy Outlook
ANL	Argonne National Laboratory
ASTM	American Society for Testing and Materials
ATJ	Alcohol to Jet
BETO	Bioenergy Technology Office
BSM	Biomass/Biofuel Scenario Model
CCS	Carbon Capture Sequestration/Storage
CI	Carbon Intensity
CS ETH	Corn Stover Ethanol to Hydrocarbon
CS IB	Corn Stover Isobutanol
DHT	Diesel Hydrotreater
DOE	Department of Energy
EEJ	Energy Environmental Justice
EERE	Office of Energy Efficiency & Renewable Energy
EERE SA	Office of Energy Efficiency & Renewable Energy Strategic Analysis Office
EIA	United States Energy Information Administration
EJ	Environmental Justice
EPA	United States Environmental Protection Agency
EV	Electric Vehicles
FCC	Fluid Catalytic Cracker
FCTO	Fuel Cell Technology Office
FOG	Fat Oil and Grease
FPEAM	Feedstock Production Emissions to Air Model
FT	Fischer Tropsch
GHG	Greenhouse Gas
GREENSCOPE	Gauging Reaction Effectiveness for the ENvironmental Sustainability of Chemistries with a Multi-Objective Process Evaluator
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HCU	Hydrocracker Unit
HEFA	hydroprocessed Esters and Fatty Acids
LCA	Life Cycle Assessment
LLNL	Lawrence Livermore National Laboratory
MFSP	Minimum Fuel Selling Price
NREL	National Renewable Energy Laboratory
OPIS	Oil Price Information Service
ORD	Chicago O'Hare Airport
PNNL	Pacific Northwest National Laboratory
R&D	Research and Development
ROI	Return on Investment
SAF	Sustainable Aviation Fuel
SOT	State of Technology
TEA	Techno-Economic Analysis
TRL	Technology Readiness Leve
VTO	Vehicle Technology Office
WTI	West Texas Intermediate
WWTP	Wastewater Treatment Plant

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1. Bhatt AH, Zhang Y, Milbrandt A, Newes E, Moriarty K, Klein B, Tao L. Evaluation of performance variables to accelerate the deployment of sustainable aviation fuels at a regional scale. Energy Conversion and Management. 1;275:116441. 2023
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1. Tao L, “USDRIVE Net Zero Carbon Fuel Team (NZTT)”. Coordinating Research Council (CRC) Sustainable Mobility Committee workshop. Invited talk, December 2022
2. Tao L, “How can we decarbonize commercial aviation by 2050”. BU IGS workshop, Invited Talk, October 2022
3. Tao L, “Sustainable Aviation Fuel Integrated Analysis”. 2022 COMPREHENSIVE ENERGY STRATEGY, SECTION 16a-3d OF THE CONNECTICUT GENERAL STATUTES, Invited Talk, June 2022
4. Yoo E., Lee U., Tao L, Harris K., “Toward Net-Zero Carbon Fuels through Carbon Capture, Utilization and Sequestration”, 19th International Conference on Carbon Dioxide Utilization, Princeton University, June 2022
5. Tao L, Harris K., Lee U., and Yoo E., “Toward Net-Zero Carbon Fuels through Carbon Capture, Utilization and Sequestration”, TCBiomass, April 2022
6. Ou L, Li S, Tao L, Phillips S, Hawkins T, Singh A, Snowden-Swan L, Cai H. Techno-economic Analysis and Life-Cycle Analysis of Renewable Diesel Fuels Produced with Waste Feedstocks. ACS Sustainable Chemistry & Engineering. 2021 Dec 27.
7. “An Integrated Sustainability Evaluation of Biochemical Deconstruction and Conversion of Biomass to Fuels and Products via Integrated Biorefinery Pathway through Short-Chain Carboxylic Acid Intermediates,” The International Symposium on Sustainable Systems and Technology (ISSST), Virtual, June 22-24, 2021.

Responses to Previous Reviewers' Comments

Reviewer comment: Strategic support is crucial to synthesize the findings from disparate workstreams within the portfolio and turn them into useful recommendations for BETO. This project had a clear map of the management plan, illustrating the how the overarching strategic support links together four different teams in order to develop harmonized analysis towards DoE's broader goals. This project establishes a clear management plan on what outputs are expected from each team they are working with and how they fit into the overall approach. The progress of this project already includes outputs relevant towards BETO's overall strategy on the economics and sustainability of emerging bioenergy pathways.

Response: We thank the reviewers for their helpful feedbacks and comments. Our goal for all of our analyses is to develop defensible studies and tools in support of the strategic direction of BETO. Going forward, we will work to adopt suggestions from the panel to integrate analysis aspects in this project by performing assessment on cost, environmental and socioeconomic metrics in a holistic approach. We will continue to publish TEA data via a KDF database so that valuable analysis research data are publicly accessible. Taking suggestions from the panel, we will add additional features/data to the TEA database: 1) add economic assumptions table; 2) make clarification on which TEA is for targets or for state-of-technology, and 3) add a summary table on key TEA metrics for more general audiences. Focusing on SAF and marine fuels, the refinery models as an optimization tool with targeting on maximizing gross refinery margins, will provide insights on opportunities and dynamics impacts when integrating bioenergy with refinery. We will continue to implement the GREENSCOPE sustainability framework to assess the impacts of BETO's core and novel conversion pathways, focusing on key metrics on environmental sustainability to help assess tradeoffs. Additionally, we will integrate sustainability and economic analysis with a multi-objective decision analysis approach when comparing design options or pathway alternatives. Our job analysis on estimating local (e.g., county) green jobs will be coupled with demographic information/projections to understand how social and economic benefits may distribute among different population and communities. Finally, we appreciate the encouragement on advancing single sensitivity analysis to multivariate sensitivity analysis or stochastic analysis, as a new tool to help identify tradeoffs and synergies among drivers for BETO's strategic directions. Our team works diligently to be highly integrated within the A&S platform portfolio and the overall BETO portfolio.

1. Approach

Critical Success Factors	Challenges	Approach to overcome
Model results are accurate and recommendations from the models are relevant.	• Availability and quality of input data. • Model is not representative.	• Consult subject matter experts globally to get the best and most accurate data. • Perform sensitivity analysis to understand impact of assumptions and uncertainty in data. • Engage third party reviewers to build transparent models.
Apply the appropriate method/tool to address questions.	A wide range of analysis approaches can be employed.	• Coordinate across analysis projects to identify appropriate tools to address questions. • Engage with industry and science experts to review and verify approach.
Clearly define critical questions to address.	Scope shift.	• Work closely with stakeholders to define needs and key questions.

2. Progress and Outcomes: Integrated Analysis on ASTM Approved Pathways

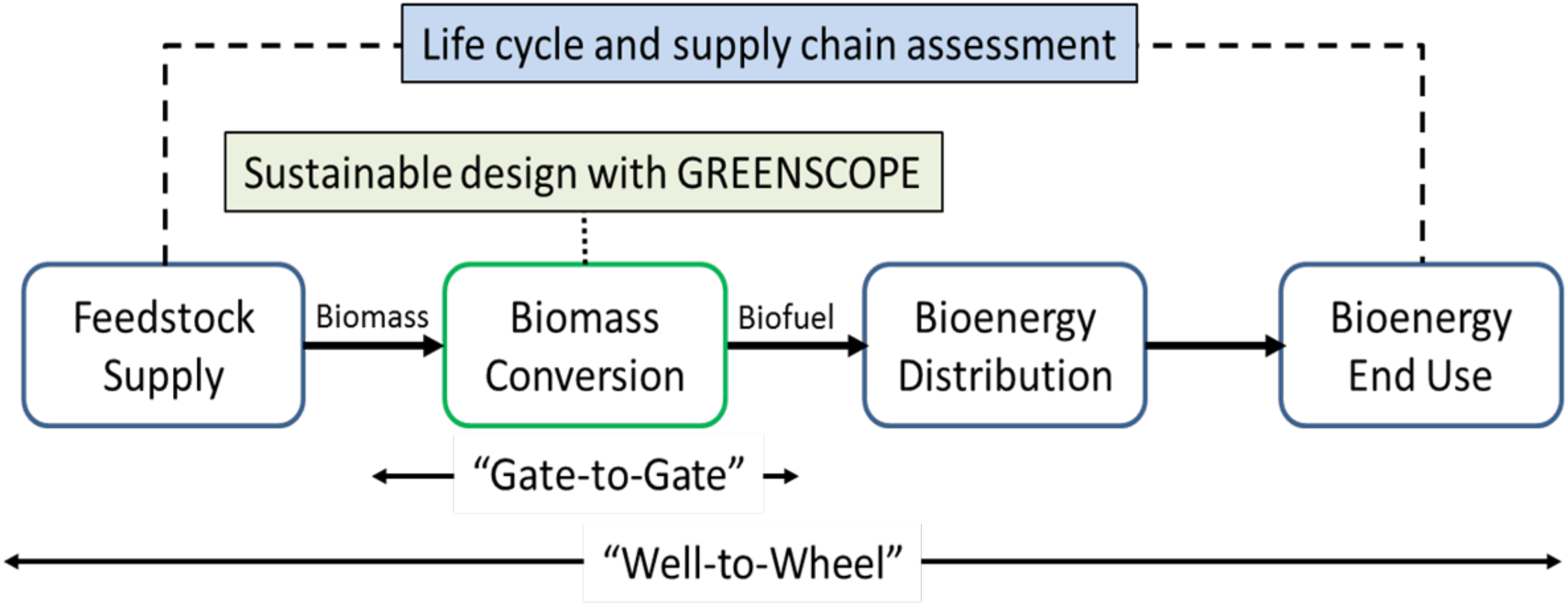
Cross-Comparison of Selected ASTM-Approved Pathways

Pathway No.	Technology Pathway	Design Scenario	Approved Name	Blending Limitation
1	Fischer-Tropsch synthetic paraffinic kerosene	Woody biomass to jet fuels	FT-SPK, ASTM D7566 Annex A1	50%
2	Hydroprocessed esters and fatty acids	All fats, oils, and grease to jet fuels	HEFA-SPK, ASTM D7566 Annex A2	50%
3		All oils (e.g., soybean oil, camelina oil, jatropha) to jet fuels		
4		Fats and grease (e.g., used cooking oil, yellow grease) to jet fuels		
5	Alcohol-to-jet synthetic paraffinic kerosene	Cellulosic biomass (through ethanol route) to jet fuels	ATJ-SPK, ASTM D7566 Annex A5	30%
6		Corn grain (through ethanol route) to jet fuels		
7		Cellulosic biomass (through isobutanol route) to jet fuels		
8		Corn grain (through isobutanol route) to jet fuels		
9	Hydrocarbon-hydroprocessed esters and fatty acids	Algal oil to jet fuels	HC-HEFA-SPK, ASTM D7566 Annex A7	10%

Potential Feedstocks Toward SAF Implementation

Category	Agricultural/forest residues/energy crops	Starchy crop	Vegetable oil/FOG	Algal oil	MSW
Constituents	Cellulose, hemicellulose, lignin	Starch	Triglycerides	Triglycerides	Cellulose, hemicellulos, lignin
Preprocessing/ Pretreatment	Particle size reduction, drying, solvent extraction, acid dilution	Particle size reduction	Oil extraction		Sorting
Productivity (dry MT/acre/year)	3-4.5/1.6-8.5/ 3.5-7	3-4.5 (corn grain)	18-636 gal/acre	6,000-15,000 gal/acre	-
Fuel Yield (gal per dry MT feed)	76-83/47	80 of corn grain	170-216/210	100 gal/dry MT feed	21.3
Value-Added Intermediates	Sugar mixture, levoglucosan, lignin	Distillers dried grains	Propane	Protein	
Availability (million MT)	139-679	109	4.1/0.9		292
High Oxygen Content, Low Product Yield, Transportation		Always prioritized as food crop; high water consumption	Lower availability	Large land area required;	
Prices	$110-$125/MT	$215/MT of corn	700-1,600/480		
Associated Processes Toward SAF	GFT, pyrolysis, ATJ, direct sugar to hydrocarbon	Direct sugar to hydrocarbon	HEFA, esterification	HC-HEFA	GFT, pyrolysis

Sustainable Process Design



- LCA or SCSA – the entire system beyond the manufacturing facility is assessed.
- GREENSCOPE sustainability assessment – focused only on gate-to-gate (i.e., biorefinery only) where the designer has the firsthand opportunity to exert any design changes, excluding biorefinery upstream and downstream processes.

Sustainable Process Design

- GREENSCOPE Indicators

Environmental Indicators	Symbol	Unit	Description
Stratospheric ozone-depletion potential	ODP	kg CFC-11 eq/kg	The atmospheric impact of this subcategory is based on the potential of each substance to deplete ozone relative to chlorofluorocarbon-11, ODP- the ozone depletion potential. This gives the total mass of CFC-11 equivalent of the process.
Stratospheric ozone-depletion intensity	ODI	kg CFC-11 eq/$	
Global warming potential	GWP	kg CO2 eq/kg	This is the total mass of carbon dioxide equivalents emitted per unit output. This complementary metric includes CO2 equivalents emitted from the treatment of waste streams and the burning of fuel needed to generate the energy for the process. The CO2 emissions resulting from the generation of electricity and steam are included in this metric, even though the electricity or steam is purchased rather than generated onsite.
Global warming intensity		kg CO2 eq/$	
Photochemical oxidation (smog) potential	PCOP	kg O3 eq/kg	The atmospheric impact of this subcategory is based on the potential of each substance to react with NOx to form tropospheric ozone based on the maximum incremental reactivity (MIR) scale.
Aquatic acidification potential	$WP_{acid,water}$	kg SO2 eq/kg	The aquatic impact of this subcategory is based on the potential of substances to release H+ ion modifying the H2O pH drastically. The total mass of released H+ ions by unit mass of acid is the unit of this environmental burden. In other words, quantifying the exceedance of critical loads of PH in water.
Eutrophication potential	EP	kg N eq/kg	The impact of this subcategory is defined as the potential for over-fertilization of water and soil, resulting in increasing the growth of biomass in the water. The phosphate capacity to generate eutrophication is used as reference unit.
Eutrophication potential intensity	EPI	kg N eq/$	
Ecotoxicity to aquatic life potential	WP_{tox}	CTUe/kg	The aquatic impact of this subcategory is based on the reciprocal of the Environmental Quality Standard (EQS) of the substance divided by the reciprocal of the EQS of formaldehyde.
Ecotoxicity to aquatic life intensity	WPI_{tox}	CTUe/$	
Respiratory effects potential	RESP	kg PM2.5 eq/kg	Criteria pollutants, with various sizes and forms of particulate matter (e.g., PM 2.5 and PM10) and pollutants, which lead to respiratory impacts related to particulates (e.g., sulfur oxides and nitrogen oxides).
Respiratory effects intensity	RESI	kg PM2.5 eq/$	
Fossil fuel depletion	FUD	MJ/kg	As all resource depletion, which are related to damages to human wealth that result in diminished future availability or an increased effort to satisfy a need. Fossil fuel depletion is the increase in unit energy requirements per unit of consumption for each fuel that provides an estimate of the incremental energy input cost per unit of consumption.
Fossil fuel depletion intensity	FUDI	MJ/$	
Mass of hazardous materials input	$M_{haz.mat.}$	kg/hr	Total mass of hazardous substances fed to the process.
Specific hazardous materials input	$M_{haz.mat.spec.}$	kg/kg	Total mass of hazardous substances fed to the process per unit of valuable product.
Number of hazardous material inputs	$N_{haz.mat.}$	Dimensionless	Number of hazardous substances fed to the process.

Sustainable Process Design

- GREENSCOPE Indicators

Efficiency Indicators	Symbol	Unit	Description
Renewability-material index	RI_M	kg/kg	The ratio of the consumption of renewable resources to total consumption.
Fractional water consumption	FWC	m^3/kg	The volume of fresh water, excluding rainwater, consumed per unit of product.
Water intensity	WI	m^3/$	The volume of fresh water used per sales revenue.
Mass loss Index	MLI	kg/kg	The ratio between the total nonproduct mass out of the process to the mass of the desired product.
Value mass intensity	MI_V	kg/$	The ratio between the total mass fed to the process over the sales revenue of the valuable product.
Environmental factor	E	kg/kg	The ratio of the mass of waste per unit of mass of the desired product.
Carbon efficiency	CE	%	The fraction of carbon in the reactants (for this study: biomass feedstock) remaining in the final product.
Mass intensity	MI	kg/kg	The ratio between the total mass fed to the process over the mass of the desired product.

Energy Indicators	Symbol	Unit	Description
Renewability energy index	RI_E	Fraction	The ratio of the net energy supplied from renewable resources to the net energy supplied to the process.
Resource energy efficiency	ηE	MJ/MJ	The ratio of the energy content of the product to the total material-input energy.
Total energy consumption	E_{TOTAL}	MJ/hr	Total energy consumed by the process or process unit as primary fuel equivalent.
Specific energy intensity	R_{SEI}	MJ/kg	Total energy consumed by the process or process operating unit as primary fuel equivalent per unit mass of product.
Energy intensity	EI	MJ/$	Measurement of the net fuel-energy consumed to provide the heat and the power requirements for the process per unit of sales revenue or value added.
Cummulative fossil energy demand	CFED	MJ/MJ	Measurement of a product represents the direct and indirect fossil energy use throughout the life cycle, including the energy consumed during the extraction, manufacturing, and disposal of the raw and auxiliary materials.

Sustainable Process Design

- GREENSCOPE Indicators

Economic Indicators	Symbol	Unit	Description
Revenues from eco-products	REV	$1x10^6$ \$/yr	The net revenues from the sale of products categorized as eco-products.
Total liquid waste cost	$C_{l,tot}$	$1x10^6$ \$/yr	These are the costs related to the handle of liquid waste produced during the day-to-day operation of a manufacturing plant: external waste removal fees, internal storage, personnel, waste treatment, and transportation costs.
Production cost	E_{PC}	$1x10^6$ \$/yr	The sum of raw material costs, treatment cost of output flows, and labor cost.
Capital cost	C_{TM}	$1x10^6$ \$/yr	The capital cost is the combination of one-time expenditures or fixed capital investments and the working capital investments.
Total water cost	$C_{water,tot}$	\$/yr	These are the costs related to the water demand costs during the day-to-day operation of a manufacturing plant: process use water, boiler feed water, etc.
Total solid waste cost	$C_{s,tot}$	$1x10^6$ \$/yr	These are the costs related to the handle and disposal of solid waste produced during the day-to-day operation of a manufacturing plant: external waste removal fees, internal storage, personnel, waste treatment, and transportation costs.
Turnover ratio	TR	\$/\$	The ratio of gross annual sales to fixe capital investment. This a faster evaluation method suitable for order of magnitude estimates. For the chemical industry as a rule of thumb, TR ~ 0.5.
Rate of return on investment	ROI	%	ROR does not consider the time value of money. It represents the non-discounted rate at which money is earned from the fixed capital investment. The annual net profit is an average over the life of the plant after start-up.
Capital charge factors	CCF	1/yr	The CCF accounts the time value of money in a profitability analysis during a preliminary process design. There is a direct relationship between CCF and the DCFROR. A value of CCF=1 yr^{-1} can be considered for a high risk project.

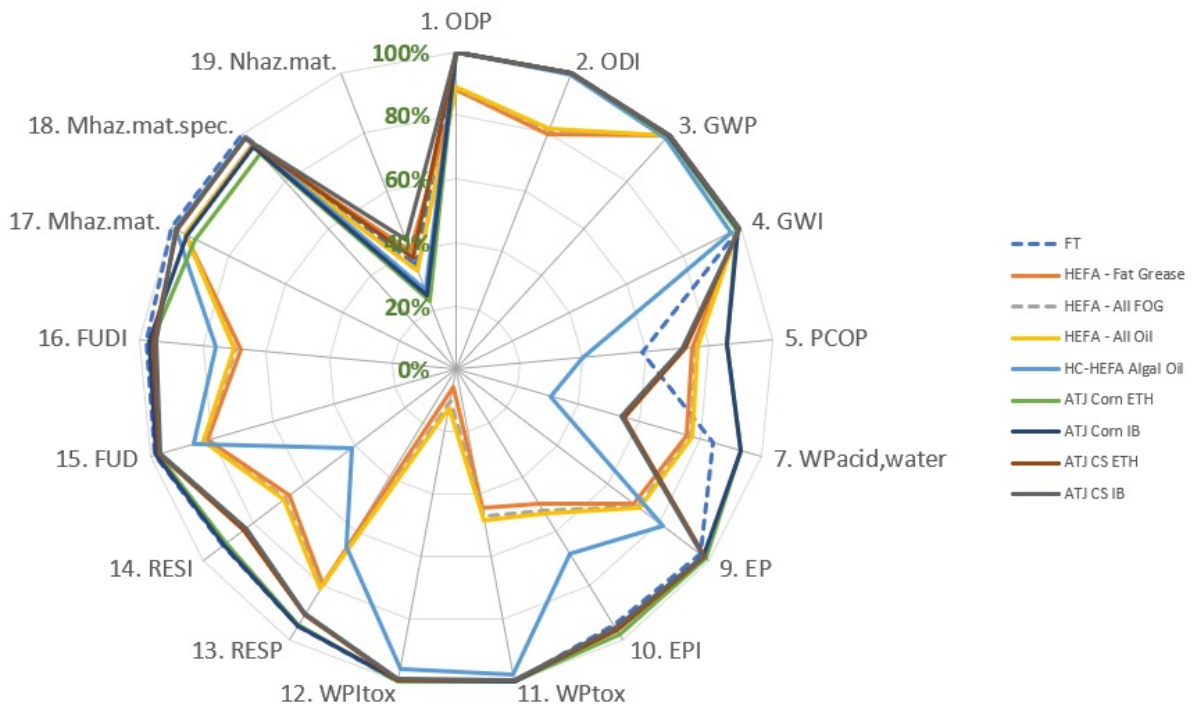
2. **Progress and Outcomes:** Cross-Comparison of ASTM Approved SAF Pathways

Evaluated cost, sustainability, technology readiness level, policies' impacts on large scale commercialization potentials of ASTM approved SAF pathways.

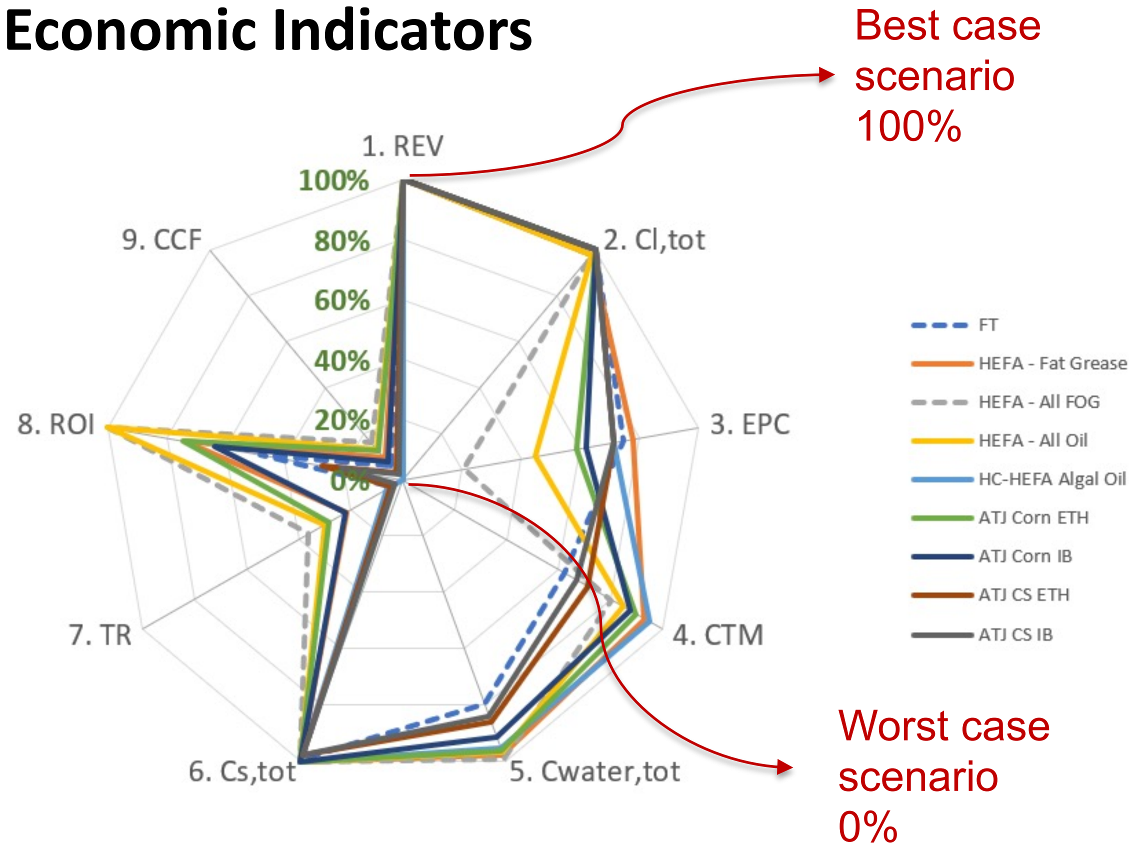
	Technology Readiness Metrics						Economic Metrics										Sustainability Metrics						Totals		
	Process Data	Blending Limitation	SAF Use in Commercial Aircrafts	Production facility	Technology Readiness Level	Technology & Process Gaps	MFSP Base	MFSP Target	SAF Dependence on Coproducts	Capital Costs	Feedstock Costs	Payback Period	Feedstock Availability	SAF Potential	ROI @ $4.4/GGE	Product Distribution	SAF Yield	Energy Intensity	Carbon Intensity	GHG Reduction	Fossil Energy Consumption	Water Consumption	🔵 F	🟢 N	🔴 U
HEFA – All FOG	🔵	🔵	🔵	🔵	🔵	🟢	🟢	🔵	🟢	🔵	🔴	🔵	🟢	🔵	🔵	🟢	🔵	🔵	🟢	🟢	🔵	🔵	14	7	1
HEFA – All Oil	🔵	🔵	🔵	🟢	🔵	🟢	🟢	🟢	🟢	🔵	🔴	🟢	🔴	🟢	🟢	🟢	🔵	🔵	🟢	🟢	🔵	🔵	9	11	2
HEFA – Fats and Grease	🔵	🔵	🔵	🔵	🔵	🟢	🟢	🟢	🟢	🟢	🔴	🟢	🔴	🟢	🔴	🟢	🔵	🔵	🔵	🔵	🔵	🔵	11	8	3
FT – Woody Biomass	🔵	🔵	🟢	🟢	🟢	🟢	🔴	🟢	🔴	🔴	🟢	🔴	🔵	🔵	🔴	🟢	🟢	🔵	🔵	🔵	🔵	🟢	8	9	5
ATJ – Corn Stover Iso-butanol	🔵	🟢	🔴	🔴	🟢	🟢	🔴	🔴	🔵	🔴	🟢	🔴	🔵	🔵	🔴	🔵	🔴	🟢	🟢	🟢	🟢	🟢	5	9	8
ATJ – Corn Grain Iso-butanol	🔵	🟢	🟢	🟢	🟢	🟢	🟢	🟢	🔵	🟢	🔴	🔴	🔵	🔵	🔴	🔵	🟢	🔴	🔴	🔴	🔴	🟢	5	10	7
ATJ – Corn Stover Ethanol	🔵	🟢	🔴	🔴	🟢	🟢	🔴	🔴	🔵	🔴	🟢	🔴	🔵	🔵	🟢	🔵	🔴	🟢	🔵	🟢	🟢	🔴	6	8	8
ATJ – Corn Grain Ethanol	🔵	🟢	🟢	🟢	🟢	🟢	🟢	🔵	🔵	🔵	🔴	🔵	🔵	🔵	🔴	🔵	🟢	🟢	🔴	🔴	🟢	🔵	9	9	4
HC-HEFA Algal Oil	🟢	🔴	🔵	🔴	🟢	🔴	🔴	🔴	🔴	🔴	🔴	🔴	🟢	🟢	🔴	🔴	🟢	🔴	🔴	🔴	🔴	🟢	1	6	15

2. Progress and Outcomes: GREENSCOPE on Integrated Sustainability

Environmental Indicators



Economic Indicators



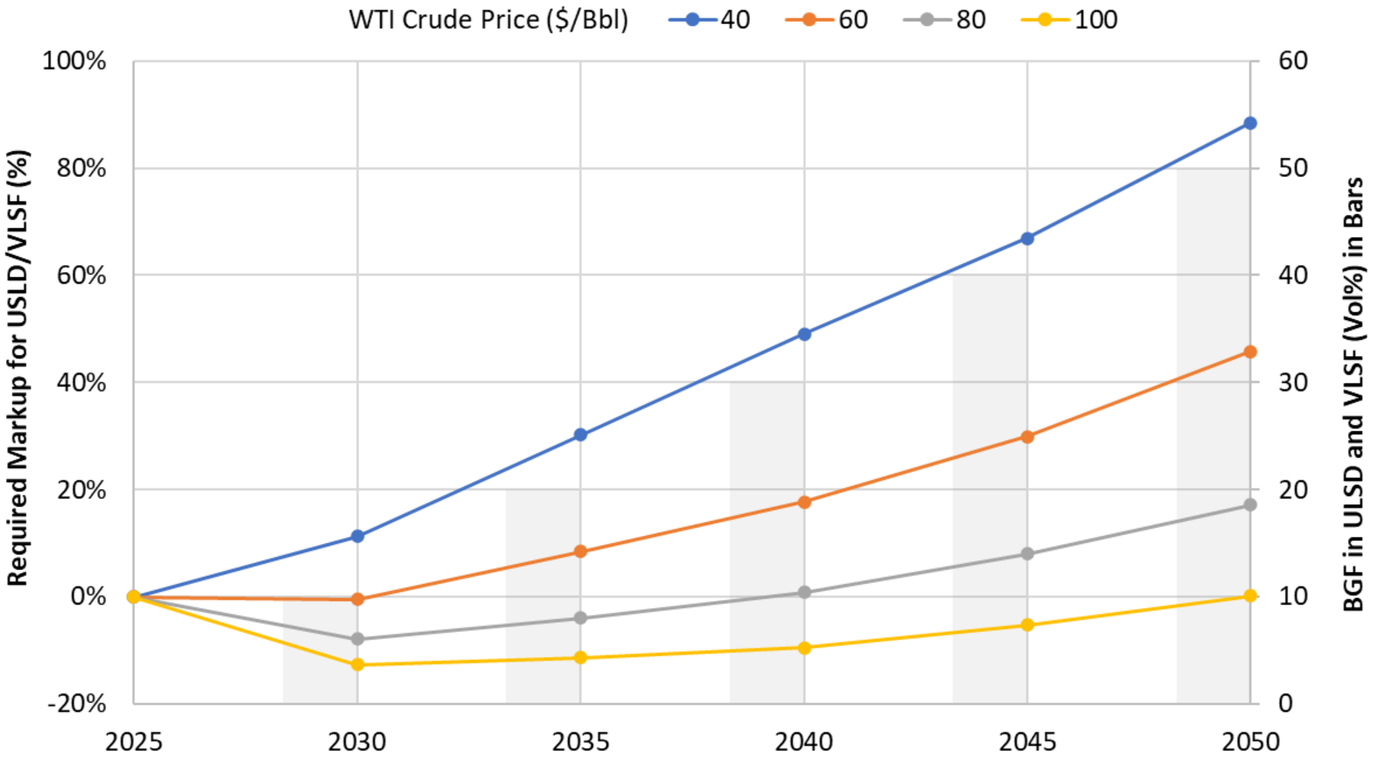
Environmental: Low scores on hazardous materials inputs.

Economics: Low turnover ratio and low capital charge factors.

2. Progress and Outcomes: Refinery Analysis Demonstration

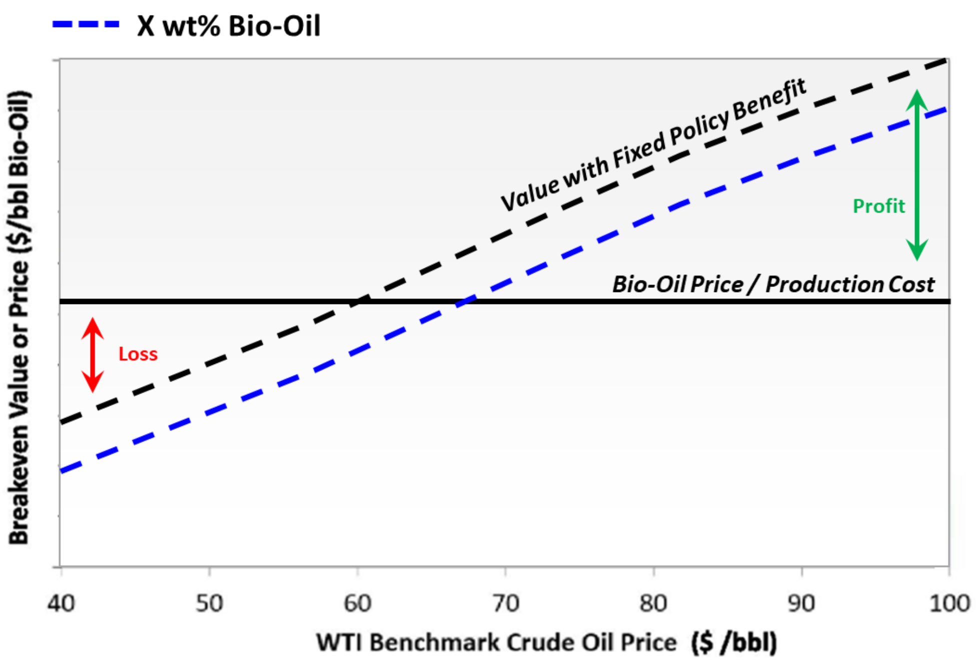
- Demonstrated refinery transitions to bio-inputs to meet target biogenic fractions in ultra-low sulfur diesel (ULSD) and very low sulfur fuel oil (VLSFO) products.
- By defining pricing, yields, blending properties, biogenic content targets, and fuel specifications, the refinery model optimizes to a solution.
- Pricing for bio-inputs static for FY22 milestone (nth-plant). Learning basis will be applied in FY23.
- Shifting to SAF production focus.

Bio-Blendstocks	Bio-Intermediates
HEFA Renewable Diesel	Fast Pyrolysis Oil
Fischer-Tropsch Diesel	Catalytic Fast Pyrolysis Oil (Mid-Oxygen)
Soy Biodiesel	Catalytic Fast Pyrolysis Oil (Low-Oxygen)

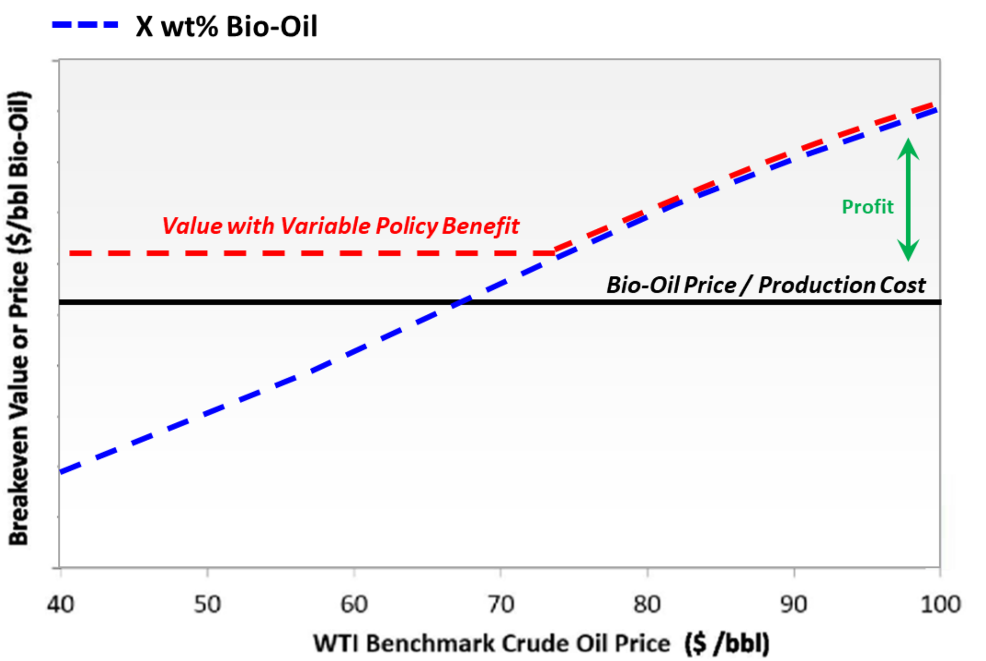


2. **Progress and Outcomes:** Evaluating Risk Mitigation from Incentives

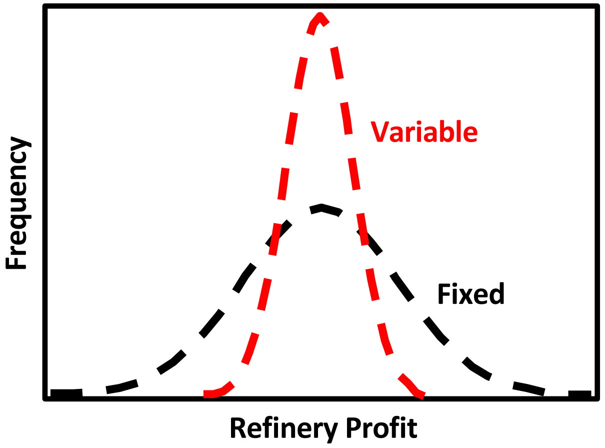
Fixed Incentive Structure



Variable Incentive Structure



- Optimizing models with biogenic feedstocks.
- Utilizing profitability impact to evaluate risk reduction approaches in policy design.



3. Impact: Integrating R&D, Analysis, and Industry Focus

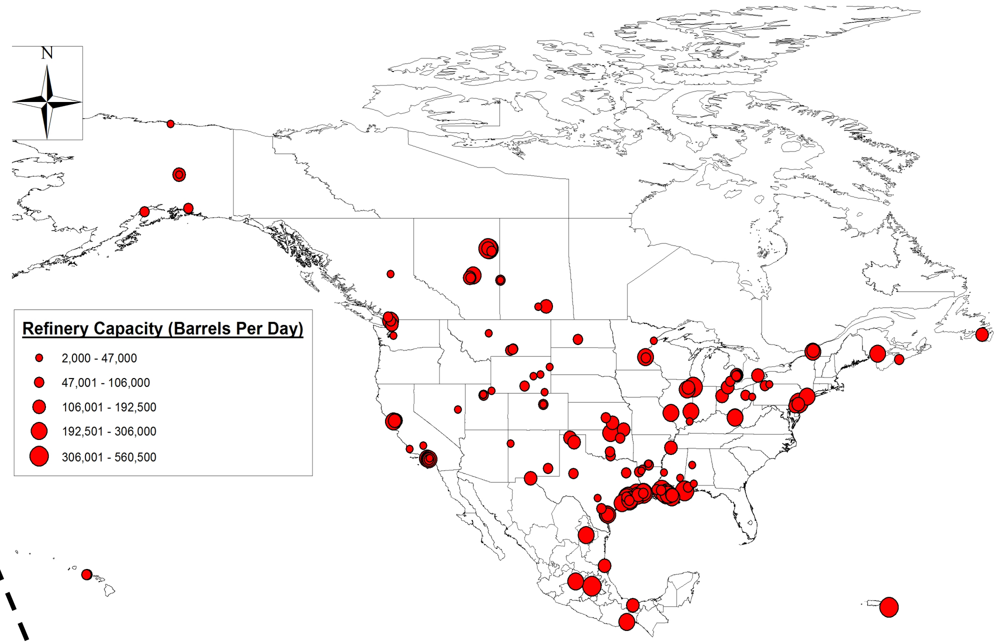
Refinery Optimization Modeling

Experimental Data on Co-Processing and Standalone Upgrading
Hydroprocessing – Kristiina Iisa 2.3.1.314
Fluid Catalytic Cracking – Calvin Mukarakate, Reinhard Seisar 3.4.3.306-308

Aspen Plus Modeling for Co-Processing in Diesel Hydrotreater (DHT), Hydrocracker (HCU) and Fluid Catalytic Cracker (FCC)
TC Analysis – Abhijit Dutta 2.1.0.302

Aspen PIMS Refinery Optimization Modeling with Bio-Intermediates and Bio-Blendstocks
Catalytic Upgrading – Mike Griffin 2.3.1.314

Bioeconomy Optimization Modeling



Bioeconomy Resource Optimization with US Refinery Network
Strategic Analysis – Ling Tao 4.1.1.30
BSM - Emily Newes 4.1.2.32