OAK RIDGE National Laboratory

DOE Bioenergy Technologies Office (BETO) 2021 Project Peer Review

4.1.2.41 - Biofuels National Strategic Benefits Analysis

03/12/2021

Analysis and Sustainability

Rocio Uria-Martinez and Paul N. Leiby

ORNL

ORNL is managed by UT-Battelle, LLC for the US Department of Energy

U.S. DEPARTMENT OF ENERGY

Project Overview

- Project started being funded by BETO in 2012 building on ORNL internally-funded tool to evaluate the fuel market impacts of biofuel
  - It has evolved in scope (biofuel conversion paths, inclusion of bioproducts) following BETO's portfolio
- Goal:
  - Develop tools and methods to **assess, quantify, and explain the economic and energy security/resilience benefits of biofuels and bioproducts**
- Relevance:
  - Identifies, for planners and investors, opportunities and contributions of bioenergy/products in context of volatile, changing markets and incentives
  - Highlights special roles (octane), diversification benefits, resilience
- FY19-FY21 focus:
  - Economic analysis of various opportunities for bioeconomy growth:
    1. Biofuel use to improve light-duty vehicle (LDV) fuel economy through an **octane performance standard**
    2. Value of **bioproducts to support growth and improve resilience** of the U.S. advanced biofuel industry
    3. Evaluating potential benefits from HPC implementations of existing model (BioTrans)
    4. Marine biofuels (emerging topic)

1 – Management

Risks managed

- **Quarterly milestones and deliverables set in Annual Operating Plan**
  - Project merit-reviewed in FY18
- **Progress updates to BETO**
  - Monthly and quarterly written updates; monthly A&S calls
  - Quarterly check-in videoconference with BETO

To ensure project is well aligned with BETO's Multi-Year Program Plan

- **Interaction/Coordination with other BETO researchers**
  - **Personnel: Primary researchers (Uria and Leiby) in coordination with others (Z.Li, E.Newes)**
  - with ORNL Conversion platform researchers on bioproduct pathways/markets
  - with BETO Marine Biofuels Team/NREL in defining scope of marine fuel market analysis

To avoid duplication and manage effective collaboration

- **External communications**
  - Informal and Conference presentations
  - Peer-reviewed publications

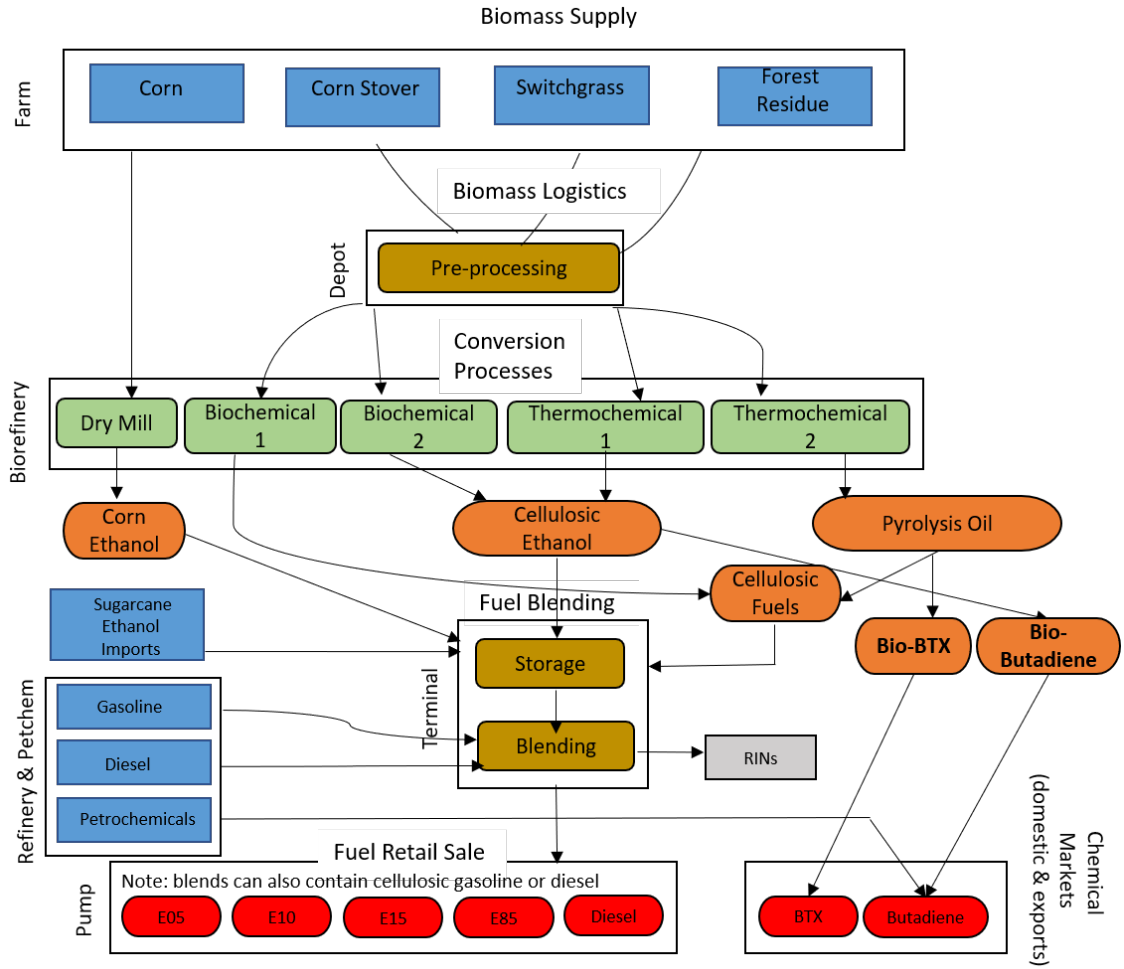
To assure scientific quality and relevance

- **Replicable research workflow**
  - Code/Script-based, Rmarkdown documentation
  - Project-oriented Git repository from source data to final reports

For efficiency, code & data integrity & scientific replicability

2 – Approach

1. Extension and application of **economic equilibrium model** of biofuel/bioproducts supply chain for scenario analysis
   - BioTrans is a dynamic, partial equilibrium model
     - 30-year horizon, by year. National scope, by Census Divisions
     - Solves for market outcomes, prices, investments
     - Maximization of producer + consumer surplus. Implies cost minimization along the supply chain.
   - Extended with selected products, data, constraints
   - In FY20, initiated migration to HPC platform
     - Responds to FY19 Peer Review Comment
     - Enables new capabilities
     - Richer scenario sets; New questions addressable as increasing model granularity becomes workable
2. **Empirical analyses** of biofuel & petroleum fuel market data
   - Estimate interactions between biofuels and petrofuels, volatility, Opportunities for risk reduction



KEY INPUTS
- Reference market conditions
- Biomass supply curves
- Biofuel pathways technoeconomic parameters
- Vehicle (LDV) stock characteristics
- Regulatory constraints

KEY OUTPUTS
- Investment in durable infrastructure (biorefineries & fuel retail)
- Harvested biomass mix & prices
- Biofuel production mix & prices
- LDV fuel mix & prices

2 – Approach: Challenges

Challenges facing the technical approach	Response	Status
Data availability	• Treat technoeconomic and market data availability as an important criterion in selecting bioproducts for analysis • Frequent interaction with other BETO researchers in bioproduct space • For bioproducts not yet commercialized, actual market data will not exist. In those cases, estimated potential market size will be based on the volume of related products (typically, petroleum-based versions of the bioproduct) and assumptions about the degree of substitutability	Ongoing
Bioproduct complexity	• Focus on leading/representative bio-product pathways relevant to gain insight on the cost and value of different levels of product flexibility • Identify BETO researchers and industry stakeholders to help vet model data and assumptions	Ongoing
Omission of possible near-term strategic behavior by firms	• Recognize that short-run behavior may differ from competitive market; short-run risks and losses may be borne	Ongoing
HPC implementation	• Tested in small scale model; HPC x86 cluster; feasibility assessed in Go/No Go decision	Resolved

2 – Approach: Task 2. Value of integrated biorefineries (mix of fuel and bioproducts) for bioeconomy growth & resilience

Model competition between petrochemical and bioproducts w/ technologic & regulatory constraints

A) **Supply curves** of petrochemical products

- Data inputs: annual reference quantity, price, supply elasticity parameter.
- Captures price response to increasing competition from bio-based chemicals

B) Include a **simplified refinery and petrochemical plant model**

- Requires data on input-output relationships and costs
- Allows more direct modeling of correlation between crude oil & petrochemical prices

Current representation in BioTrans follows *approach A.*

Represent different opportunities for biofuel/product system flexibility

A) **Technical potential for substitution** and its costs
- Process engineering considerations
  e.g., thermochemical conversion process can better switch across biomass types

B) **Flexibility for a single participant** and its value
- Increases with price volatility
- Decreases with correlation among the prices of alternative outputs
- Drop-in vs performance-advantaged bioproducts

C) **National-scale flexibility** and its value
- Differences in scale, process from biorefinery to biorefinery
- Supply chain limitations
- Regulatory constraints

This project mostly addresses *dimension C*

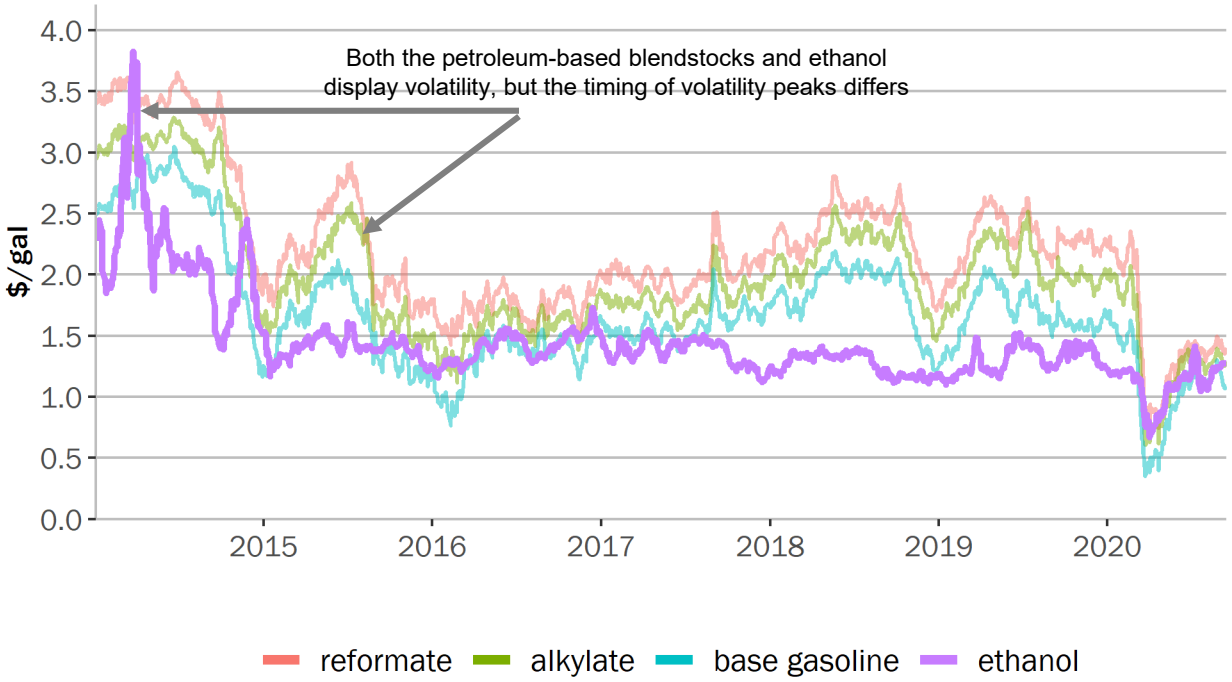
3 – Impact

- This project offers a **complementary wider-picture analysis** to projects that focus on development of specific biofuel or bioproducts
  - Understanding system-level substitution and complementarity relationships helps identify the most promising opportunities for using U.S. biomass
- **Identify, quantify and communicate opportunities for biomass use with potential economic benefit**: ID ways in which bioenergy systems can be both resilient to shocks and contribute to price stability
  - Bio-based fuels can be economically and environmentally beneficial as octane source: An Octane standard creates an opportunity for biofuels to improve LDV fuel efficiency, reducing ghg emissions, at lower cost
  - Biofuels and bioproducts considered jointly reveal ways in which the bioenergy system can be more resilient (e.g. more stable revenue & prices) and therefore the overall fuel system can be more resilient
- **Generating insights** on the system-wide effects of introducing new biofuels and bioproducts that help maximize social benefits and mitigate risks for bioeconomy participants
  - Insights on equilibrium responses, price outcomes, and demand changes supported by established economic analysis

OPS pursues fuel efficiency gains; can also yield portfolio diversification benefits

- High-octane fuels (HOF) improve fuel efficiency by enabling optimization of turbocharged gasoline engine designs
- OPS would specify minimum Octane number for gasoline-based fuels (higher than current regular gasoline)
  - to become available by a certain year; from that same year, OEMs would offer vehicles with engines optimized for HOF
- OPS is technology neutral: petroleum-based or biomass-based blendstocks can be used
  - Biomass-based blendstocks also can contribute to reductions in carbon emissions over the fuel lifecycle
  - Ethanol is already produced at large scale and has been consistently cheaper (in $/gallon) than petroleum-based alternatives in recent years

U.S. wholesale price of gasoline, alkylate, reformate, and ethanol



Correlation of daily price returns

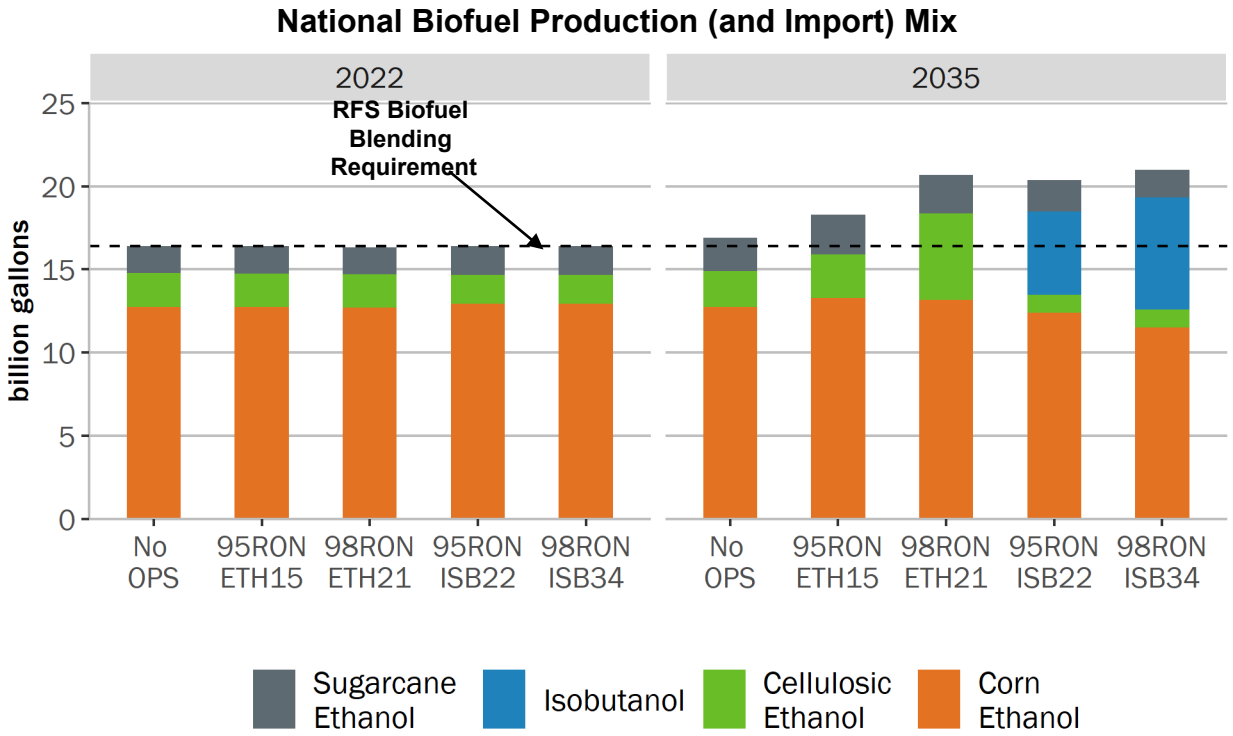
Base gasoline – ethanol	Base gasoline – alkylate	Base gasoline – reformate
0.19	0.91	0.86

Empirical analysis of the price series shows:

- Petroleum blendstock prices are *cointegrated* (i.e., move together in the long-run)
- Ethanol price is **not cointegrated** with petroleum blendstocks
- Ethanol price changes ~uncorrelated. Lagged base gasoline price explains prices of alkylate, reformate

To 2035, find the biofuel industry could experience moderate growth

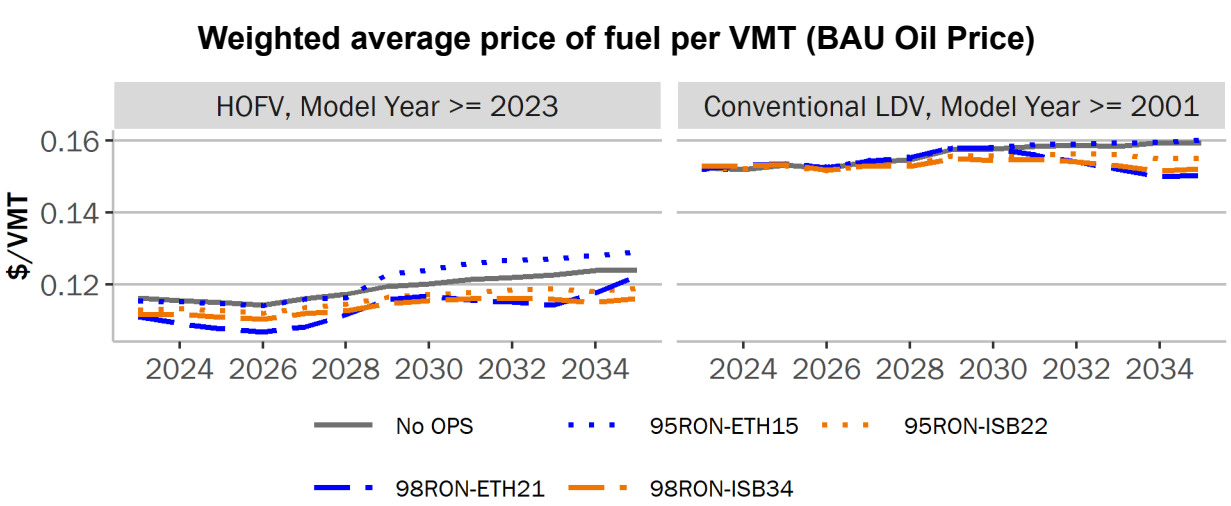
We ran scenarios for promising bio-based octane-enhancers and found them to be competitive with petroleum-based alternatives and saw increase in biofuel use under the OPS

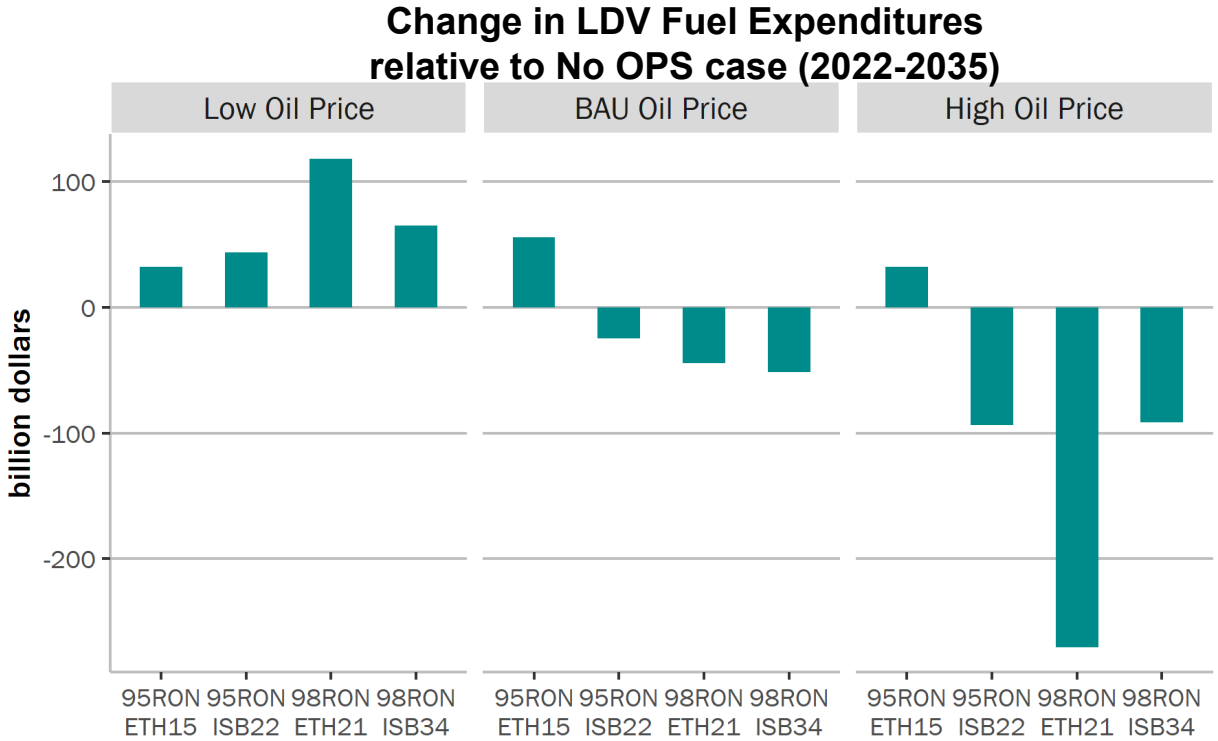


Notes:
- Labels on the x-axis depict combinations of RON number (e.g., 95RON) and cellulosic-based octane-enhancing blendstocks (e.g., ISB22 is 22% isobutanol)
- Isobutanol is produced from a mixture of stover and switchgrass (Cai et al., 2018)

- **Increase in domestic biofuel production** (2022-2035) resulting from OPS cases is modest because HOFVs are a limited share of LDVs during that period
  - Production increase ranges from 8% (95RON-ETH15) to 32% (95RON-ISB22) in 2035 relative to 2022
  - In No OPS case, domestic production starts declining by 2035
- Corn ethanol production is below 15 bgy in every scenario
  - Some cellulosic ethanol (using cheapest cellulosic feedstocks) becomes competitive beyond 13 bgy of corn ethanol production
- *Extra investment costs* in biorefinery capacity and alternative fuel dispensing equipment for OPS
  - Range from $10 billion (95RON-ETH15) to $20 billion (98RON-ISB34) by 2035

All LDV owners may benefit from the introduction of an OPS; **oil prices matter**. Small increase in total LDV fuel use during transition period.





- Fuel cost & use is ***lower*** for vehicles optimized for higher octane, and using biofuel octane source.
- Decrease in E10 prices is due to lower gasoline demand and price.
- During initial years of OPS, total LDV fuel use may increase while more conventional LDVs on the road

Notes:
- Does not reflect other fuel-efficiency or environmental benefits
- Mileage per gge gains for HOFVs (relative to a conventional LDV of same vintage using regular E10): 2.1% (95RON-ETH15), 3.7% (95RON-ISB22), 2.9% (98RON-ETH21), 5.2% (98RON-ISB34)

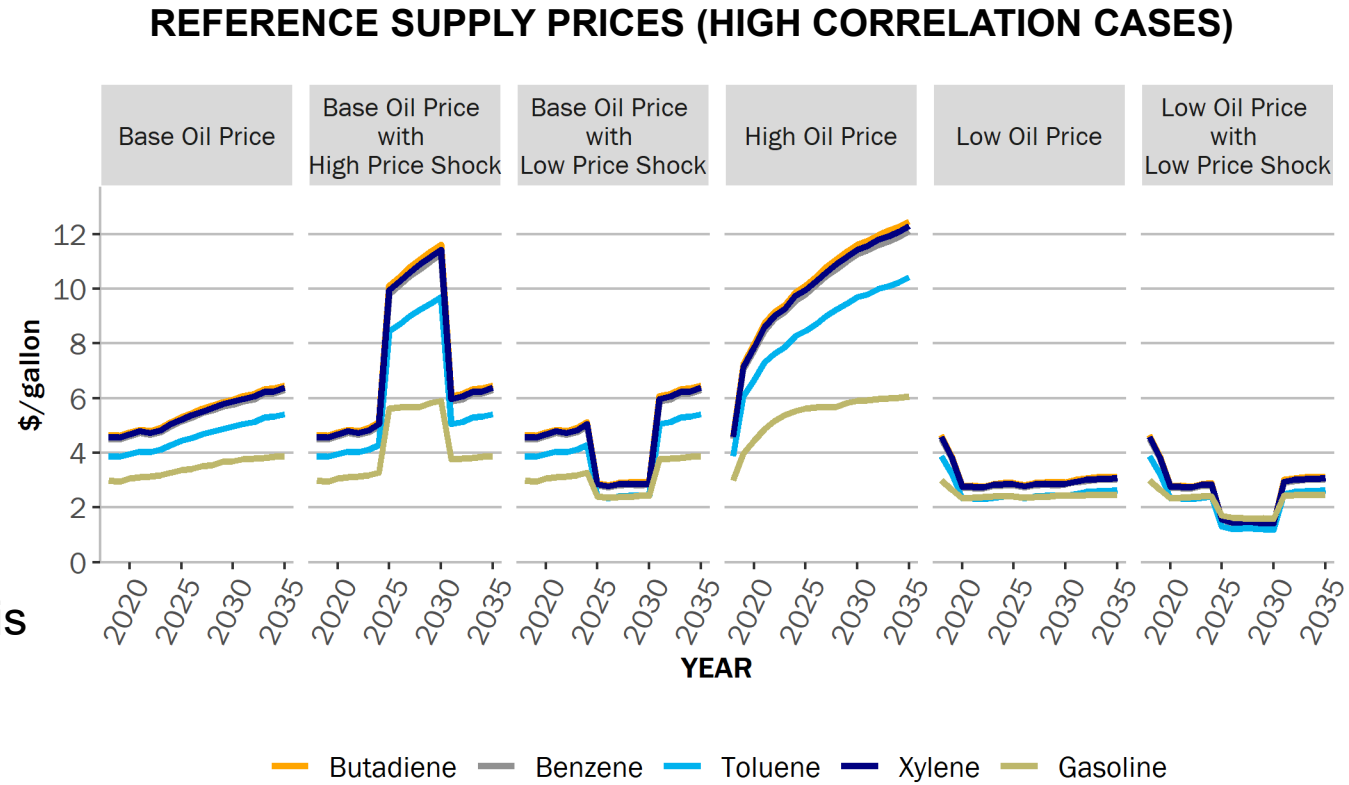
- Increasing the octane of gasoline-based fuels delivers fuel efficiency gains for vehicles with optimized engines (HOFVs)
  - using biomass-based blendstocks as octane enhancers helps achieve more stable fuel prices and may lead to lower fuel prices (in $/VMT) for all LDVs depending on oil price trajectory
- Under OPS, biofuel contributes cost-effectively, and see increased biofuel production driven by pace of HOFV sales and oil price path.

Scenario assumptions

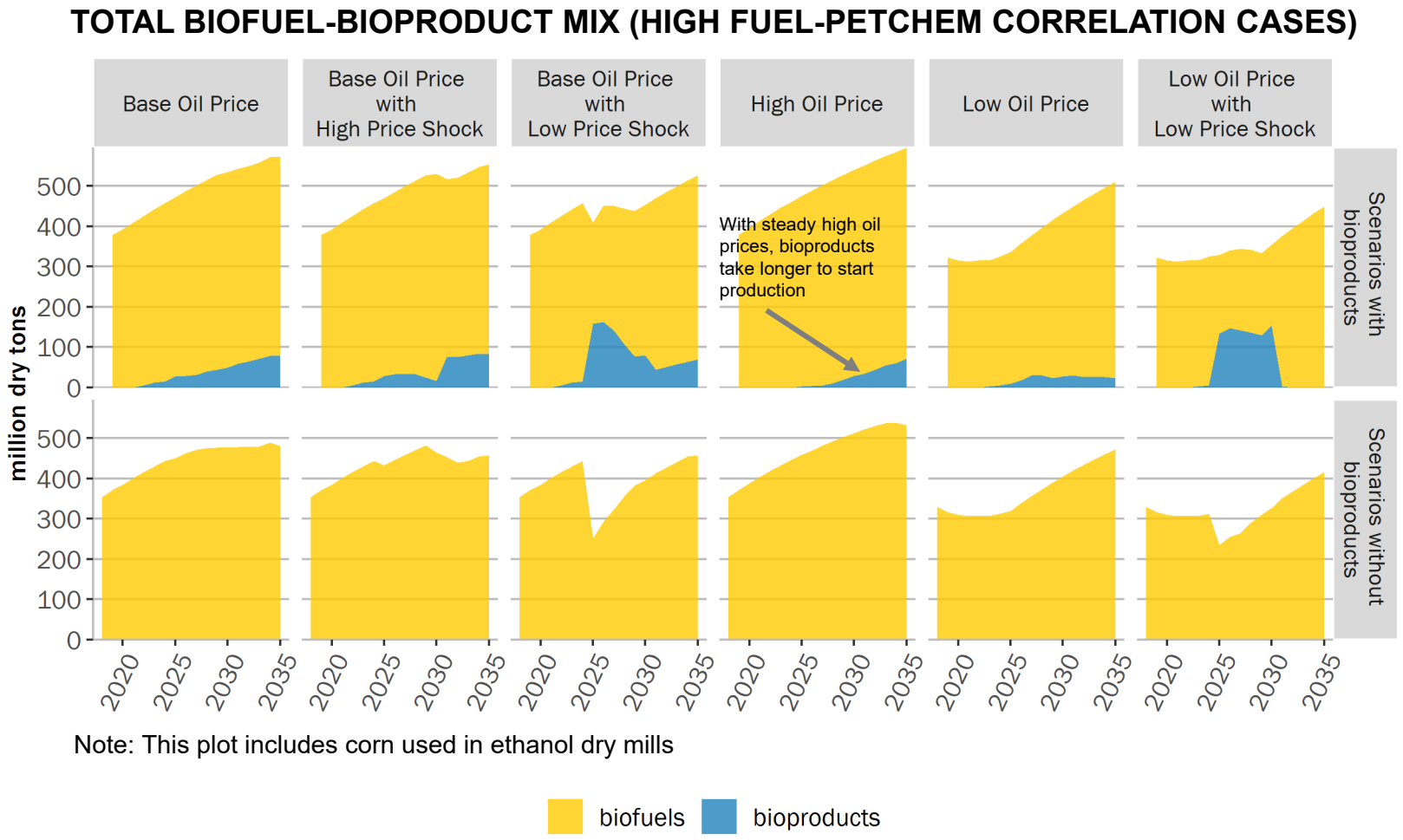
- Consider Two **flexible integrated biorefinery types**:
  - Cellulosic ethanol production facility with add-on unit to convert ethanol into butadiene
  - Fast pyrolysis biorefinery with flexibility to choose how to allocate pyrolysis oil across
    - Cellulosic gasoline and diesel (fixed proportions)
    - Bio-based benzene, toluene, and xylene (fixed proportions)

- **Six price scenarios** driven by petroleum price futures:
  - AEO2019 Base Oil Price;
    - Base with High or with Low Price Shock
  - AEO2019 Low Oil Price;
    - *Low Oil Price or Low with Low Price Shock*
  - AEO2019 High Oil Price

- Correlation between petro-fuel & petrochemical prices initially taken as 0 or 1
  - All else equal, flexibility to adjust product mix is more valuable when price correlation among outputs is lower (or negative)

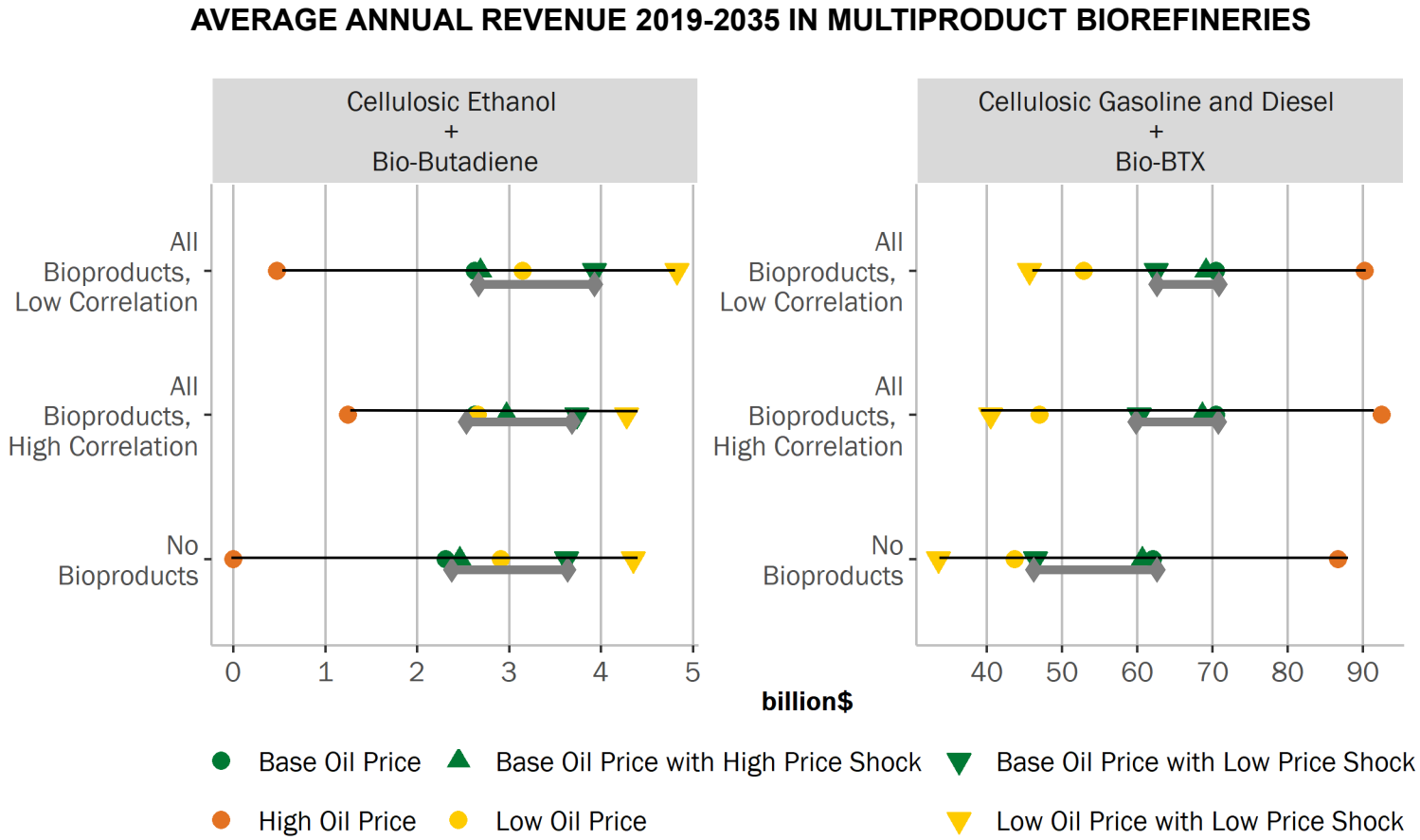


Output mix depends on oil price paths, but ability to vary mix adds resilience. Inclusion of bioproducts in product slate increases harvested biomass (0.5%-12% by 2035)



- Bioproducts still only a small fraction of projected biomass market
  - Except during low price shocks, less than 20% of harvested biomass goes toward bioproducts
- Total biofuel production is greater during high oil price periods
- Bioproduct volumes can increase during periods of low oil prices, **adding resilience**
- Even when fuel-product prices are correlated, the relative profitability changes across scenarios
  - When oil prices go up the profitability of fuels increases relative to the profitability of bioproducts

Addition of bioproducts to product slate leads to **more stable total revenue**



Note: Installed processing capacity ranges from 11 to 27 million dry tons in 2035 capacities for the cellulosic ethanol + bio-butadiene integrated biorefinery and from 227 to 392 million dry tons of biomass for the fast pyrolysis biorefinery,

Revenue outcomes/rankings vary across multiproduct biorefineries

- For biorefineries producing cellulosic ethanol and bio-butadiene, revenue is highest in low oil price scenarios
  - Cellulosic ethanol is a complement to gasoline in production of E10
- For biorefineries producing cellulosic gasoline and diesel and bio-BTX, revenue is highest in high oil price
  - Cellulosic gasoline is a perfect substitute for petroleum-based gasoline in production of E10

- Product slate flexibility (biofuel-bioproduct combinations) contributes to the economic resilience of integrated biorefineries.
  - Including bioproducts in the output slate tends to increase average revenue over time *and* make it more stable.
- Some bioproducts help biorefinery owners most during high oil prices; others during low oil prices (depending on the type of biofuel)

Tested HPC implementation, enables more extensive/deeper analysis

BioTrans implementation to date:

- Desktop-based, Uses proprietary software (GAMS) with license restrictions/cost, computationally intensive

HPC Motivation

- Expanded sensitivity analysis
  - Speed gains depend on number of cores available for the analysis
- Increased model granularity
  - Spatial: from Census Division to state level
  - Temporal: from annual to monthly periods

HPC implementation tests:

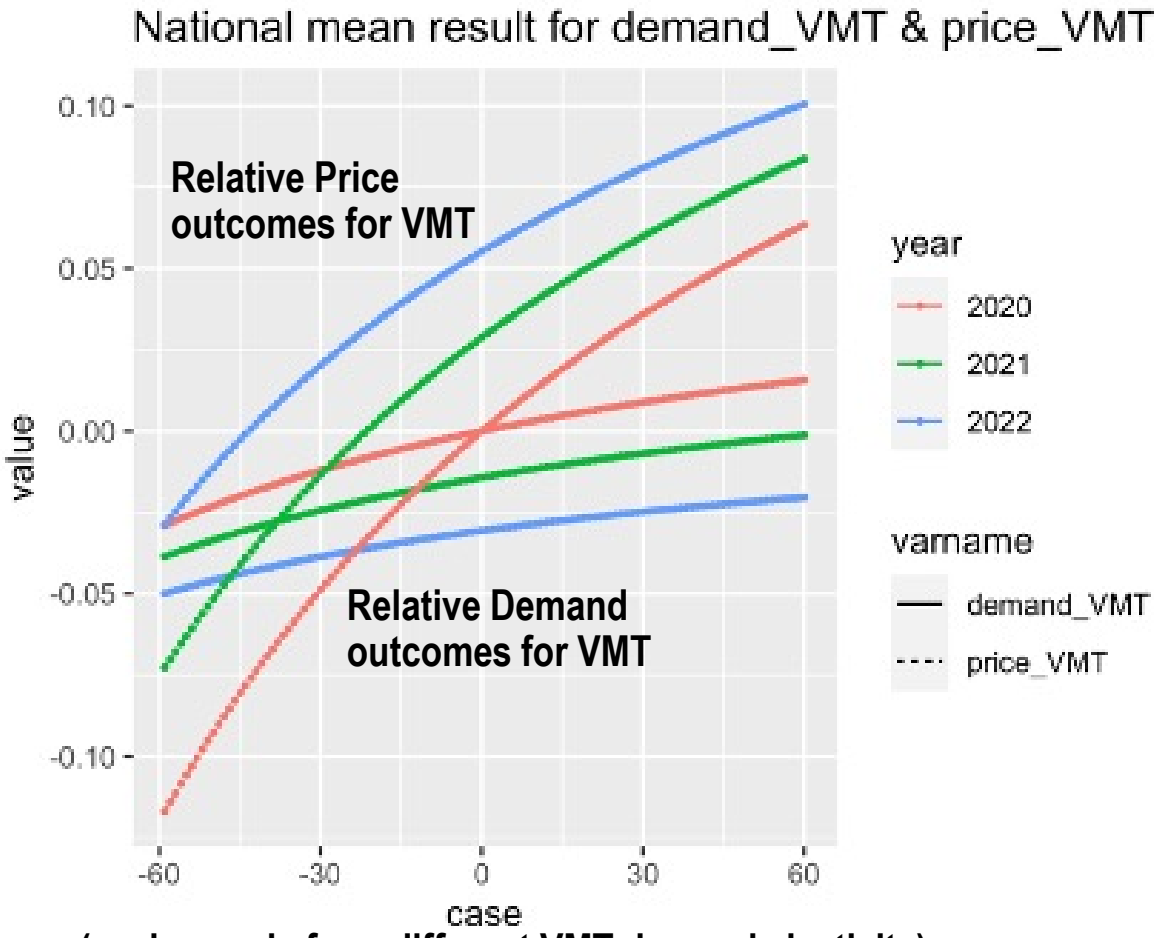
- Implemented on ORNL CADES, Parallel/cluster computing tools & methodologies
- Julia/JuMP utilized as open-source programming language & solvers
  - Mixed complementarity program formulation finds market equilibrium solution
  - Also allows representation of non-competitive market structures and game theory equilibrium models that are not easily studied in an optimization context

4 – Progress & Outcomes: Task 3. FY20 Q3 Progress: Able to Produce Large Numbers of Cases Efficiently on HPC, Easing Sensitivity Analysis and Improved Model Detail

SPEED TEST RESULTS: 1 vs. 3, 10, 30 CORES

Processors, Cases	Time Measure	Parallel Computation	Serial Computation	Ratio (speedup)/ case
3 procs, 60 cases	Total Case Run Time	55.9	142.9	2.6:1
3 procs, 60 cases	Total Case Run Time *incl startup*	72.9	158.2	2.2:1
10 procs, 120 cases	Total Case Run Time	34.8	295.5	8.5:1
30 procs 240 cases	Total Case Run Time	32.5	554.4	17.0:1

- HPC implementation used for initial tests is immediately scalable to larger numbers of cores, larger problems.
- The capability to deploy BioTrans in HPC environment facilitates more extensive scenario analysis and analysis at finer spatial or temporal scales, on BETO/ORNL Ridge Machine.



(each case is for a different VMT demand elasticity)

- Each point is a separate solution case. HPC enables smooth sensitivity analysis with respect to price-responsiveness of VMT demand

Summary

- Project uses market equilibrium modeling and empirical data analysis to assess, quantify and explain potential economic benefits from various biomass end uses
- Analysis of higher-octane fuel standard indicates **competitiveness of some bio-based octane enhancing blendstocks**, vs. petroleum-based
- Advanced biofuel industry could contribute to higher octane fuel, improving combustion engine efficiency, and experience moderate biofuel growth
  - Reduced fuel use by high-octane optimized vehicles
  - In BAU (AEO Reference Case) reduced costs exceed estimated investment costs
  - Oil prices matter for net cost
- Exploration of flexible/multiproduct biorefinery illustrates **Value of bioproducts for bioeconomy growth & resilience;** illustrates how bioproduct output mix depends on oil price paths
- Addition of **bioproducts** to the **flexible product slate leads to generally higher and more stable total revenue across scenarios**
- **HPC implementation** of multicore economic equilibrium optimization **allows** case exploration and **sensitivity analysis at scale**, enables **higher spatial and temporal resolution**
- **Next:** We are **extending these economics-based analyses to** explore role of **biofuels in Marine sector** sulfur reduction (IMO-2020) and decarbonization

Quad Chart Overview

Timeline

- BETO funding started in 2012 building on an ORNL internally funded LDRD project
- Current project cycle:
  - Start date: 10/01/2018
  - End date: 09/30/2021
  - Percent complete: 75%

	FY19	FY20	FY21
DOE Funding (new BA)	$200K	$200K	$250K

Project Partners: NA

Funding Mechanism: AOP

Project Goal

To develop tools and methods to *assess, quantify, and explain the economic and energy security/resilience benefits of biofuels and bioproducts*

End of Project Milestone

By 9/30/2021, deliver to BETO technical report discussing the *effectiveness of multiproduct biorefineries* to improve the value proposition of cellulosic biofuels.

Barriers addressed

At-B. Analytical Tools and Capabilities for System-Level Analysis

At-D. Identifying New Market Opportunities for Bioenergy and Bioproducts

Supplementary slides

List of Acronyms and Abbreviations

BAU – Business as Usual

BTX – Benzene, Toluene, Xylene

bgy – billion gallons per year

CADES – Compute and Data Environment for Science

FY – Fiscal Year

GAMS – General Algebraic Modeling System

gge – gallons of gasoline equivalent

HOF – High-Octane Fuel

HOFV – High-Octane Fuel Vehicle

HPC – High-Performance Computing

HWOP – High World Oil Price

IMO – International Maritime Organization

LDV – Light-Duty Vehicle

LWOP – Low World Oil Price

OEM – Original Equipment Manufacturer

OPS – Octane Performance Standard

RON – Research Octane Number

VMT – Vehicle-Mile Traveled

Responses to Previous Reviewers' Comments

Reviewer Comments	RESPONSE TO COMMENTS
While this approach is very interesting, it seems somewhat academic or theoretical, and it is unclear how supply chain participants would use the modeling approach or results when defining a project or supply chain. The team should think carefully about and communicate how to enable this information to actually be used to help with deployment and supply chain development.	We acknowledge that, to maximize their impact, our results needs to be a) further translated into actionable insights and b) communicated to supply chain participants. A) Translating the results into actionable insights. In the supply shock scenario analysis, it would help to further unpack national aggregate shock costs to show the impacts for different market participants in different regions. We want to convey the effect of different supply chain configurations (investments) on mean revenue, revenue variability, and resilience to different types of shocks. Flexibility levers (e.g., advanced logistics, biorefinery feedstock flexibility, bioproducts) are one of the options to enhance resilience. For bioproducts, one of our planned industry-relevant contributions is to develop general classifications regarding process flexibility and substitutability with petro-based alternatives and identify strengths and vulnerabilities associated with introduction of bioproducts with different levels of those two attributes. The analysis framework can then be applied to any specific bioproduct pathway. B) Communicating our results in outlets that reach supply chain participants more easily. We will work to summarize and present our insights in outlets more likely to reach supply chain participants: articles in trade journals (e.g., Biomass Magazine) and/or presentations at more industry-focused conferences. Another potential avenue for increased engagement with industry stakeholder is through further development and publicizing of our current web interactive tool with a focus on key questions that would be of interest for supply chain participants and making accessible in KDF.
II believe Census Divisions are quite large, like the entire midwest is one Census Division, so I think it is a weakness to only model at such a spatially coarse scale. That being said it is not a weakness if the economic unit being modeled here is that large. The spatial scale of analysis should match the scale of the question, but it appears that biorefineries are making decisions at smaller scales than those modeled here.	We agree that some issues and outcomes can be better understood with a finer geographic resolution than we are currently modeling. Our principal attention is to aggregate national benefits/implications, so we need to be attentive to the appropriate scale for each issue. The design approach of the BioTrans model, in GAMS, separates data and equations/structure in a way that allows further spatial (and technological or temporal) disaggregation by altering the data tables alone, providing the data are available. So the challenges are gathering the needed data at a finer scale for resource markets, capital stock and feedstock/fuel logistic, and executing the model in a computational environment suitable for such a demanding model. As the later comment ("I would like to see future work to get to a finer spatial scale.") notes some data (fuel sales, biomass resource supply, transportation and logistics, etc.) are increasingly available at finer spatial levels. Other teams at ORNL are active in feedstock logistics. ORNL, through its existing High Performance Computing core capabilities, plus the planned new ORNL BETO HPC machine, is well-positioned to provide the necessary computational resources. So we also believe that this would be a good time an opportunity to extend the analysis to a finer spatial scale, or, as the comment under Future Work suggests "Or at least evaluate whether that would be a promising area or not."
They didn't mention drop-ins (which have become increasingly important to BETO) until Q&A, but evidently do address.	We do include a fast pyrolysis process producing drop-in gasoline and diesel as one of the pathways in BioTrans but it was "turned off" in the set of cases we presented for shock cost analysis. Our focus on ethanol cases in the Peer Review presentation is partly due to it being the only biofuel entering gasoline-based fuels in non-negligible quantities. For future work, we will increase the focus on drop-in biofuels (particularly for the analysis of bioproducts) in consonance with their greater interest for current BETO R&D goals. However, we will maintain also the ethanol-based pathways given their relevance to biofuel market outcomes in the nearer term, and as one approach to higher-octane fuels.

List of deliverables during FY21 Peer Review performance period

DELIVERABLE	DUE DATE
Summary of bioeconomy implications (e.g., volume and mix of biofuels and bioproducts, farmer and biorefiner revenues) from commercialization of bioproducts, with particular emphasis on resilience to oil and biomass supply shocks. Consider various degrees of process flexibility for 3 process types (1)integrated processes producing biofuels and bioproducts in fixed or somewhat variable proportions, 2)add-on process for biofuel-to-bioproduct conversions, 3)separable biomass-to-bioproduct processes). Results will be based on BioTrans model runs depicting competing petrochemical processes and bioproduct imports/exports. Findings will aim to inform BETO R&D bioproduct selection criteria by incorporating process flexibility and resilience considerations.	03/31/2019
Ranking of cost estimates to meet an octane performance standard (RON95 or RON98) using each of the blendstocks selected in Q1 under current levels of biofuel blending required by RFS and current CAFE fuel economy standards.	06/30/2019
Synthesis of key concerns and opportunities for the biofuel/products industry under an octane performance standard as identified by industry stakeholders, research community, and our initial economic analysis which will estimate impact of an octane performance standard on biofuel production mix and volumes in the 2020-2040 period under various combinations of octane levels and RFS futures.	09/30/2019
Detailed **data/deployment plan & initial tests for HPC implementation** of bioenergy/bioproducts supply-demand chain analysis (i.e., BioTrans). Implement and test a segment of BioTrans model and optimization code in HPC and confirm practicality of planned approach and estimate potential gains in capability. For instance, potential gains in speed enabled by HPC would allow increasing the granularity of the model in space (e.g., state or county level instead of Census Divisions as geographical units) or time (e.g., monthly periods instead of annual) as recommended by Peer Review comments. Will also enable more extensive sensitivity analyses for combinations of key model parameters.	12/31/2019
Represent **potential for product substitution for multiproduct biorefineries with varying levels of process flexibility** (e.g., integrated process for biofuel & bioproduct with fixed proportions vs. flexible biofuel-to-bioproducts processes). Model market outcomes (e.g., biofuel-bioproduct mix and prices) in response to changing market conditions depending on which of those multiproduct biorefinery paradigms becomes more prevalent.	03/31/2020
Discuss results from initial set of runs using BioTrans HPC version 0 model to **demonstrate benefits and potential of migration of BioTrans analysis to HPC platform.**	06/30/2020
SMART: Estimates of **net benefit (or cost) for society and for specific groups of market participants of an octane performance standard** for combinations of alternative of oil price futures, post-2022 RFS evolution and other relevant parameters (depending on outcome of go/no go, this deliverable will be based on a large number of scenarios using HPC computing or a more limited set of scenarios based on desktop implementation of BioTrans).	09/30/2020
Conceptual review of opportunities and challenges for biofuels in marine shipping and heavy-duty road transport. To identify promising biofuel adoption pathways for these transportation segments and assess data availability for depicting these end uses in the BioTrans model, the project team will: 1) communicate with other DOE-sponsored researchers developing/analyzing the role of biofuels for those transportation segments; 2) conduct a literature review, 3) draw insights from the fuel transition process currently underway in the marine sector (to fuels with lower sulfur content as mandated by the International Maritime Organization) to help identify the drivers of alternative fuel adoption decisions in the marine secto	12/31/2020

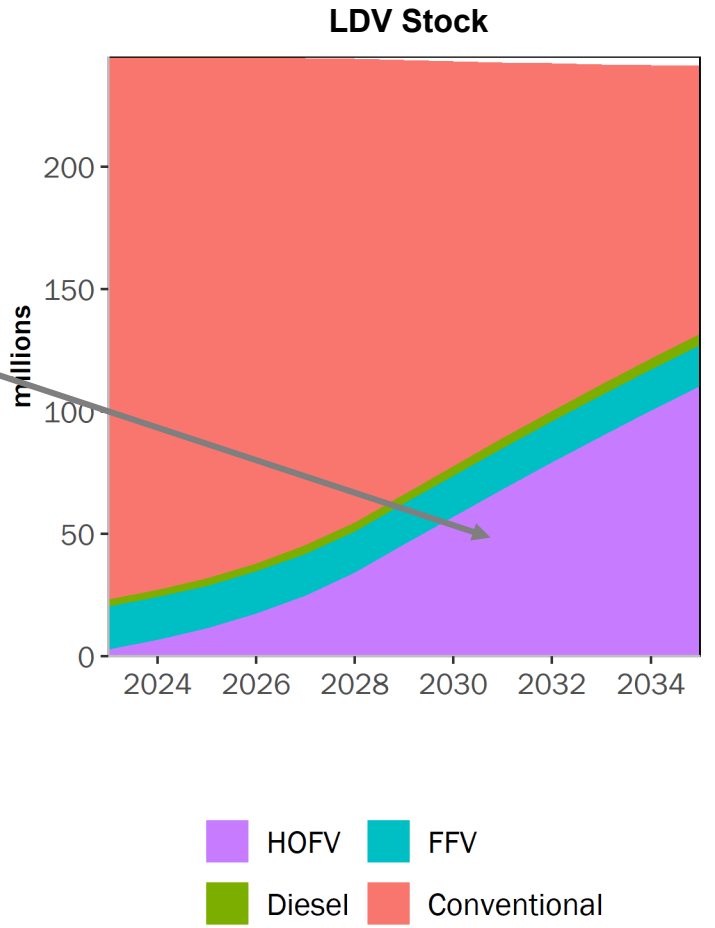
Scenarios ID attractive bio-blendstocks, explore contributions of bio-based vs. petroleum-based octane-enhancement

RON Number	Bio-based Blendstock	Oil Price Trajectory
No OPS	-	BAU
No OPS	-	LWOP
No OPS	-	HWOP
RON 95	ETH15	BAU
RON 95	ETH15	LWOP
RON 95	ETH15	HWOP
RON 95	ISB22	BAU
RON 95	ISB22	LWOP
RON 95	ISB22	HWOP
RON 98	ETH21	BAU
RON 98	ETH21	LWOP
RON 98	ETH21	HWOP
RON 98	ISB34	BAU
RON 98	ISB34	LWOP
RON 98	ISB34	HWOP

Note: In No OPS cases, HOFVs still get mileage gain if they use E15;no E10 HOF is available in that scenario

Assumptions:

- Scenarios are combinations of octane RON number, bio-based blendstock, and oil price trajectory
- OPS starts in 2023: High Octane Fuel (HOF) and Vehicles (HOFVs) start being sold
- In OPS cases, HOFV owners choose between fuel blends with same High Octane (RON) #
  - Biofuel-sourced extra octane
  - Petroleum-sourced extra octane (E10-HOF)
- Scenarios explore
  - the potential **uptake of HOF blends**,
  - **investment costs** of the various options,
  - LDV **fuel consumption** and
  - **vehicle-miles traveled** under various oil price trajectories.



OAK RIDGE National Laboratory