DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Bioeconomy Scenario Analysis

April 3, 2023

Data, Modeling, and Analysis

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Material includes unpublished preliminary data and analysis that is subject to change not for distribution, quotation, or citation

Project Overview: Bioeconomy Scenario Analysis

Support design of bioeconomy strategies by:

- Quantifying metrics for various potential goals (energy, economic, and environmental)
- Facilitating stakeholders in advancing sustainable, nationwide production of biofuels.

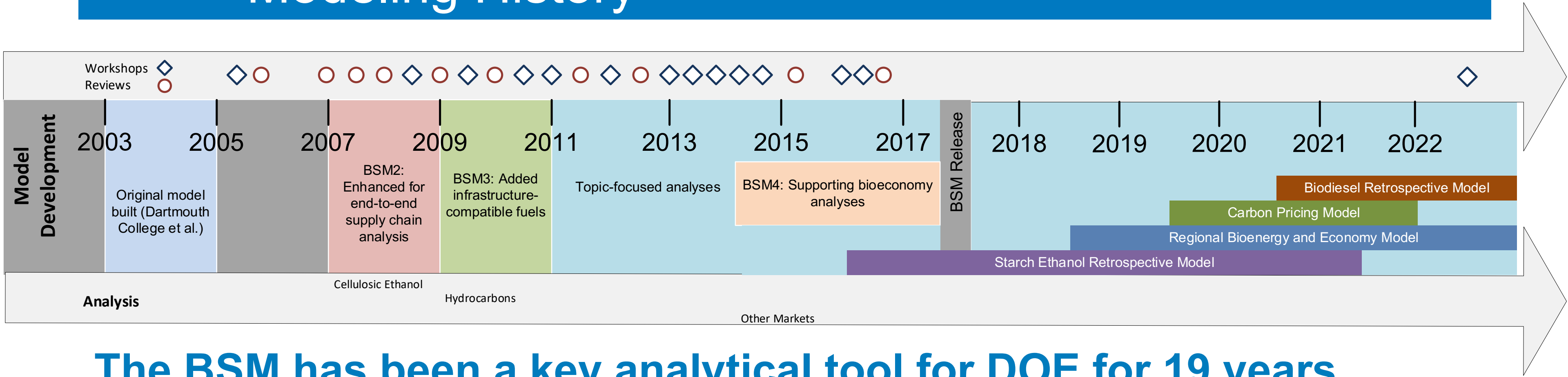
Encourage the creation of a bioenergy industry by enabling:

- Industry to understand industry growth potential under different technology and investment conditions, better targeting their development efforts
- Policymakers and federal offices to explore scenarios for economical, nationwide biofuels production
- Universities and other interested stakeholders interested in novel approaches to the bioenergy system.

Approach

We use a system dynamics approach (e.g., Bioenergy Scenario Model [BSM]) along with peer-reviewed data to model the bioeconomy, representing system-level feedbacks in the integrated supply chain.

Modeling History



The BSM has been a key analytical tool for DOE for 19 years.

The BSM is:

- Publicly available
- Peer-reviewed
- Evolving as needs change
- Validated
- State-of-the-art
- Award-winning.

Modeling Methodology Underpinnings

- Use modeling techniques that are appropriate and established
- Carefully consider level of detail
- Solve coupled ordinary differential equations
- Perform analyses using new tools and data when relevant.

Project Purpose

What are you trying to do?

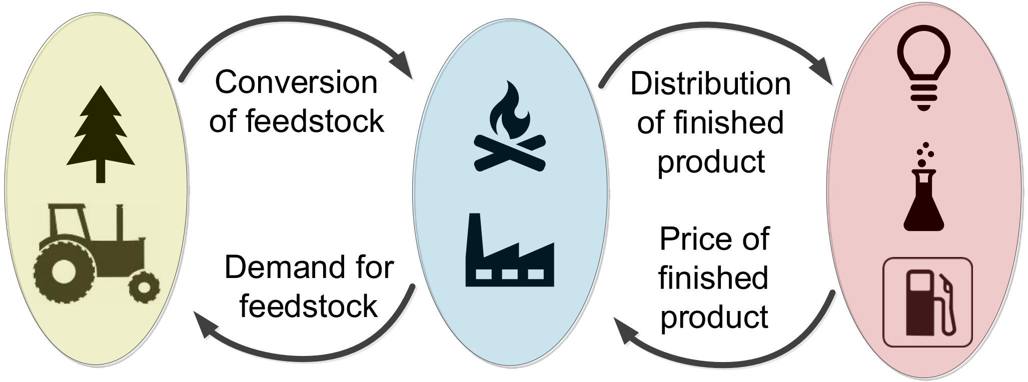
- Deliver context for decision makers
- Provide analytical support for strategy design
- Encourage creation of bioenergy industry.

How is it done today? Provide standard for bioeconomy scenario exploration through system dynamics modeling.

What are the limits? Data.

Why is it important?

- Establishment of bioeconomy decreases emissions.
- System dynamics highlights nonlinear interactions within the bioeconomy system across the supply chain.
- Decision makers can better evaluate strategy and goals.



Approach

Risk Identification and Mitigation Strategies

Inform BETO, other stakeholders, management, and policymakers of the implications of policy choices and market developments to **enable prioritization and evaluation** of various actions and enable researchers to design and analyze the impacts of additional biomass-to-bioenergy scenarios.

Risk Identification

- Overfitting, excessive complexity in models
- Missing institutional knowledge
- Lack of data for model inputs, validation, calibration

Risk Mitigation Strategies

- Ensure mathematics is appropriate to represent the system; avoid scope creep; answer questions appropriate to methodology
- Establish collaboration with meaningful information exchange
- Ensure modeling represents best available information

Approach

Multidisciplinary Team

Ling Tao
PhD chemical engineer with 20+ years of experience in advanced conversion technologies

Emily Newes
15+ years of experience in economics, energy data, modeling, and analysis

Jay Huggins
16+ years of experience in software and systems development

Danny Inman
PhD soil scientist with 15+ years of experience in bioenergy feedstocks, modeling, and advanced statistics

Steve Peterson
Principal BSM model architect; teaches system dynamics and energy system futures at Dartmouth

Swaroop Atnoorkar
Trained in energy systems engineering, with a focus on transportations systems and environmental analysis

Laura Vimmerstedt
25+ years of experience managing major transportation and energy analysis projects at NREL

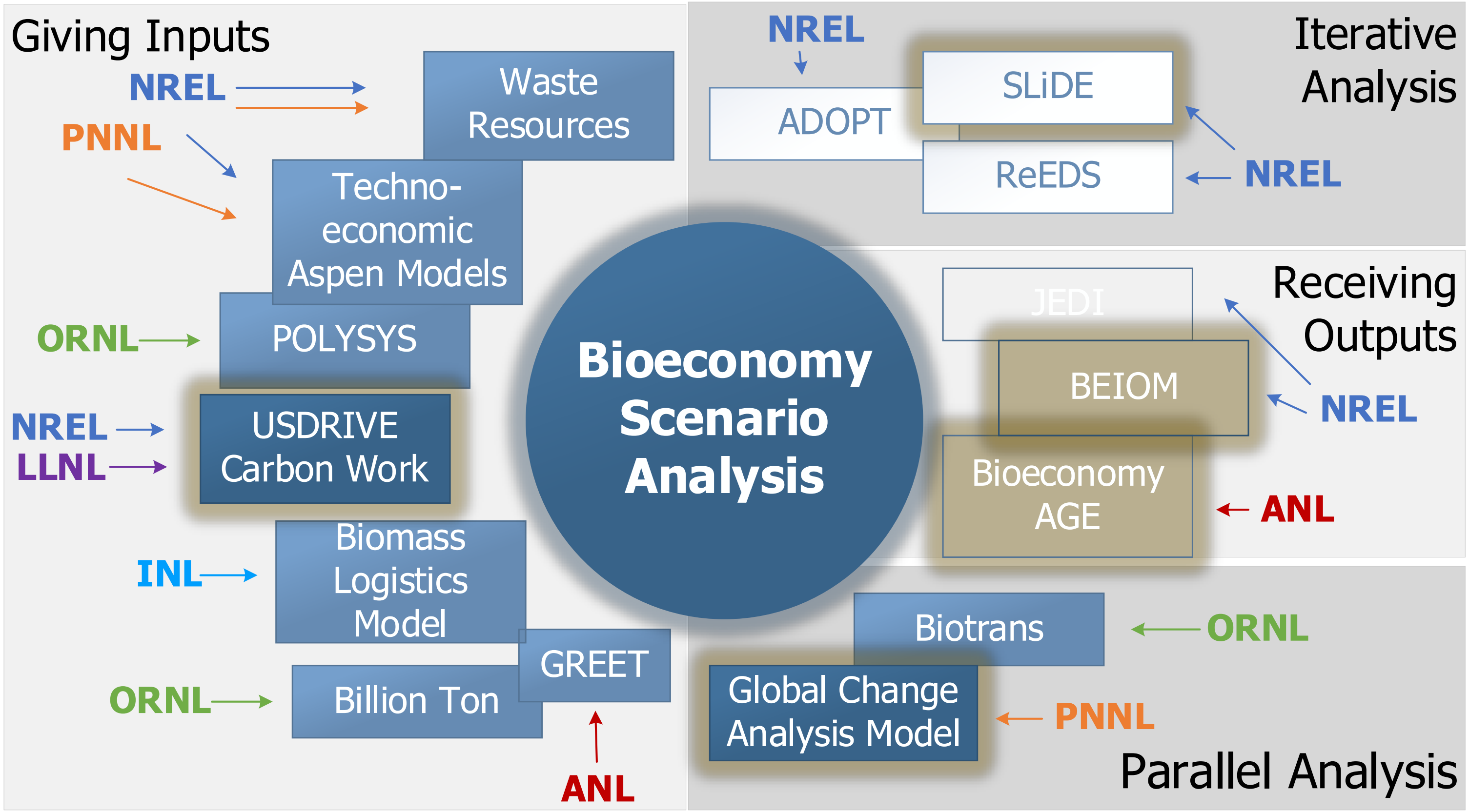
The multidisciplinary team is positioned to support bioeconomy model development and analysis.

Approach

Deep Connections with BETO Models

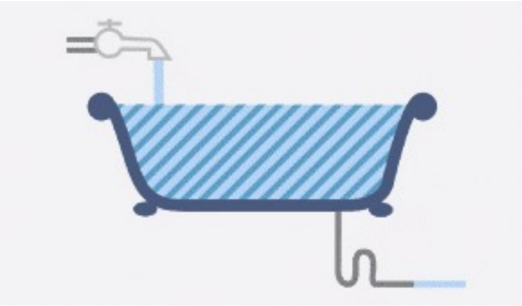
White boxes signify models not funded by BETO.

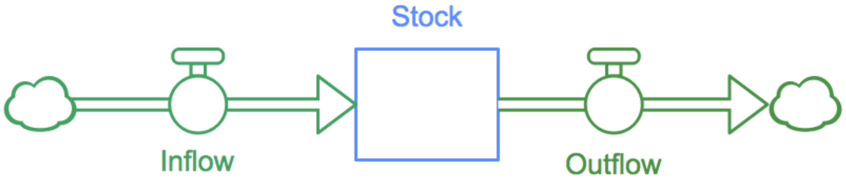
Yellow shading signifies expansion of current capability.



System Dynamics: Complex Nonlinear Systems

- System dynamics (SD) modeling is grounded in the theory of nonlinear dynamics and feedback control systems. SD uses coupled ordinary differential equations to represent complex (nonlinear) systems.
- SD was originally developed in 1950s at MIT. It originally focused on supply chain dynamics and has subsequently been used by wide range of organizations (e.g., GE, GM, DOE, and U.S. Department of Defense) in a broad set of application areas.
- Key concepts include accumulation, flow, feedback, and nonlinearity.
- Visual languages create a system of finite difference equations that are solved using standard numerical methods.
- Top-down approaches are used to develop models focused on system performance over time.



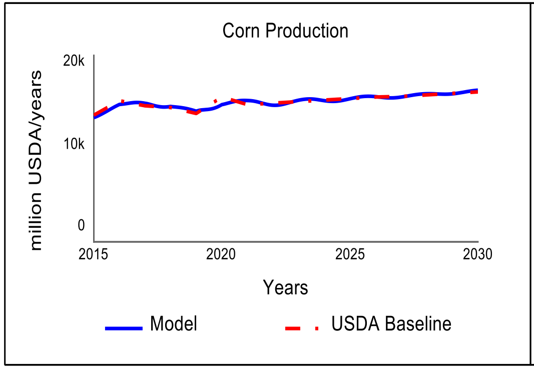


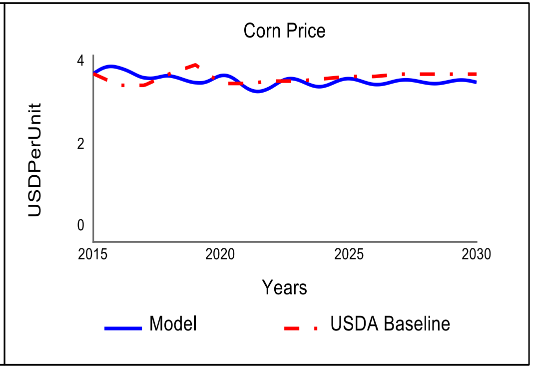
$$Stock(t) = stock(t_0) + \int_0^t [inflow(s) - outflow(s)]dt$$

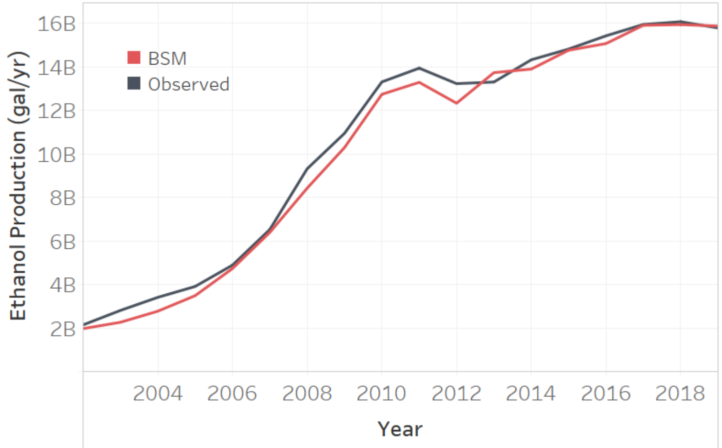
Model Calibration and Validation

Calibration Example: BSM-Simulated Corn Production versus USDA Long-Term Forecast (2020)

- Annual calibration: adjust assumptions to represent an industry
- Builds confidence in modeling assumptions
- For example, we calibrate crop production in the BSM against the U.S. Department of Agriculture's long-term forecast each year.







Validation Example: BSM-Simulated Starch Ethanol Production versus Historical Data

- Production levels, installed capacity, and timing of simulated results match observed production levels, installed capacity, and timing.
- BSM simulates human behavior.
- With existing logic and structure, the BSM can adequately reproduce the historical development of the starch ethanol industry in the United States.

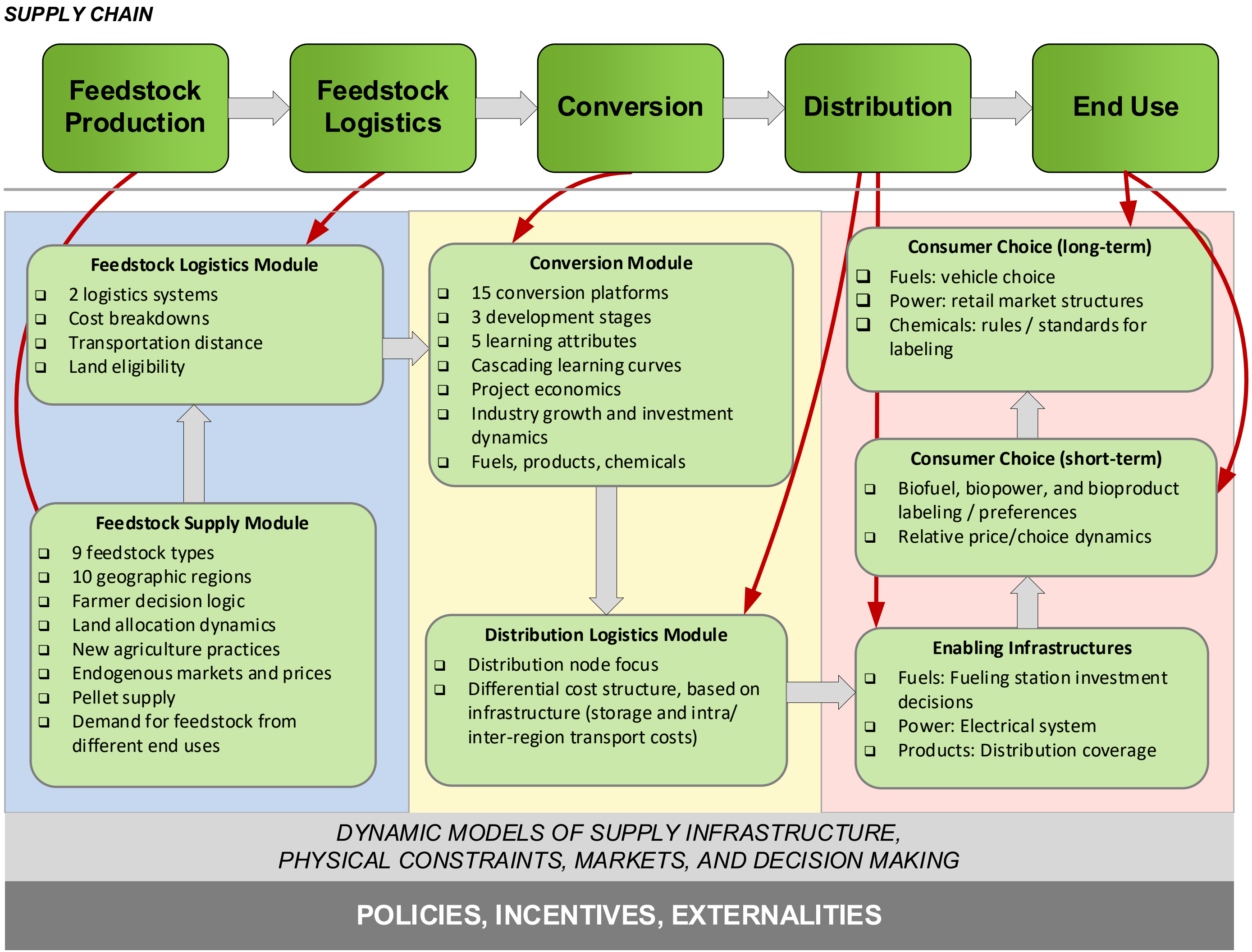
Goodness of Fit: Regressing BSM-simulated production values on observed industry values, we get an R^2 of 0.94, $p < 0.001$.

Approach

The BSM models the bioeconomy.

- Supply chain dynamics
- Feedbacks among systems of systems
- Challenge and opportunity identification

Source: MYPP 2016

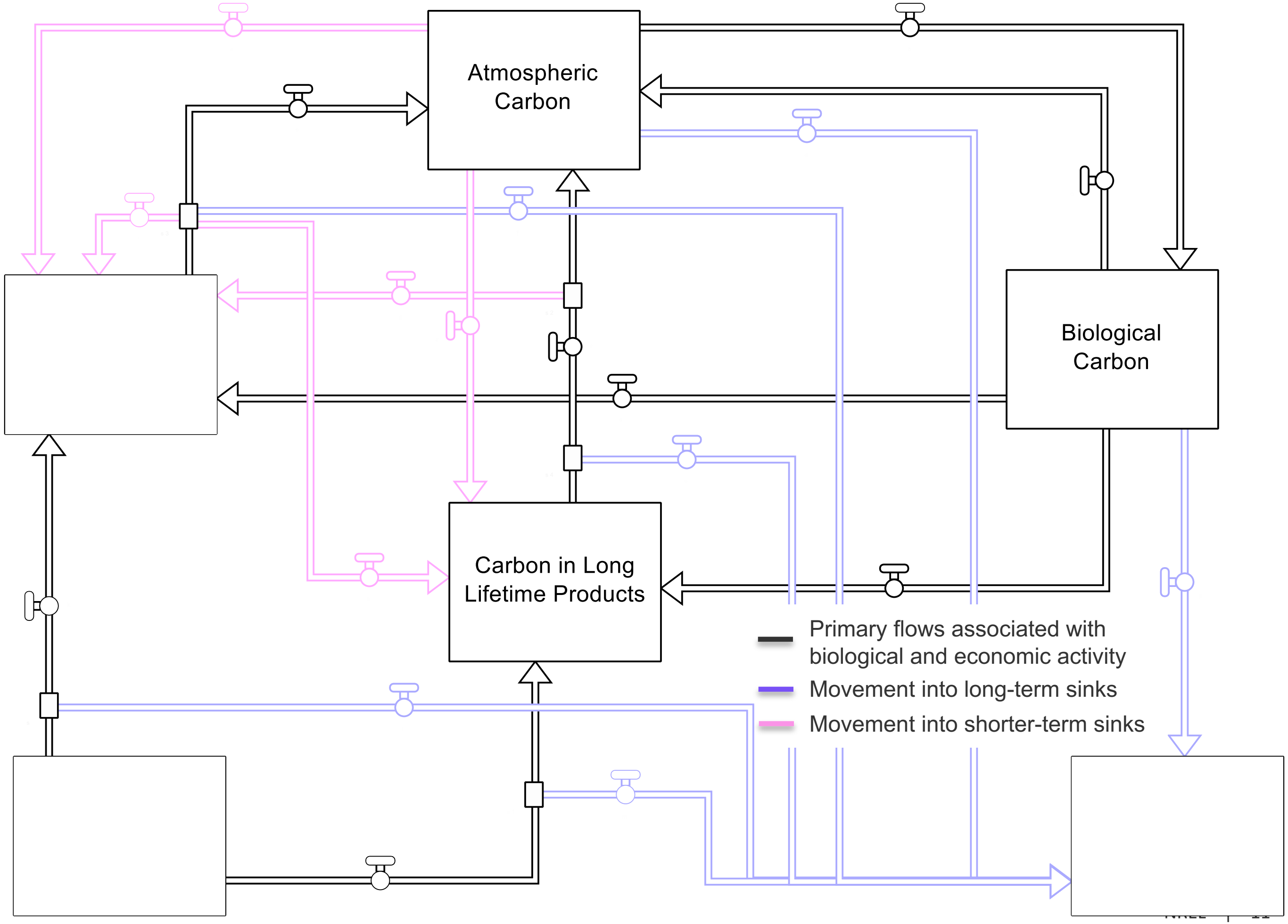


Approach

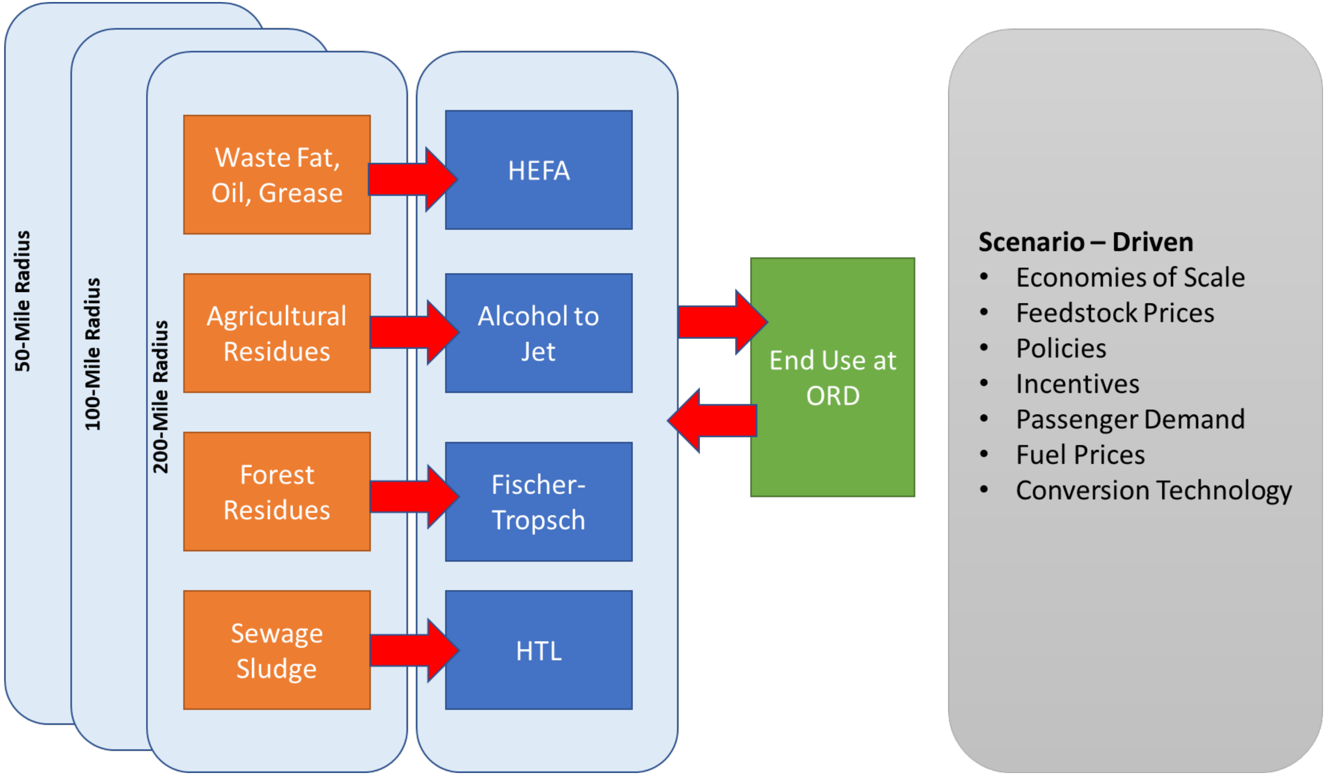
High-level View of Carbon Flows

Work Now Funded Outside BETO

- Supply chain dynamics
- Feedbacks among systems of systems
- Challenge and opportunity identification
- Value of carbon content in biomass



The Regional BioEconomy Model (RBEM) simulates regional supply chains.



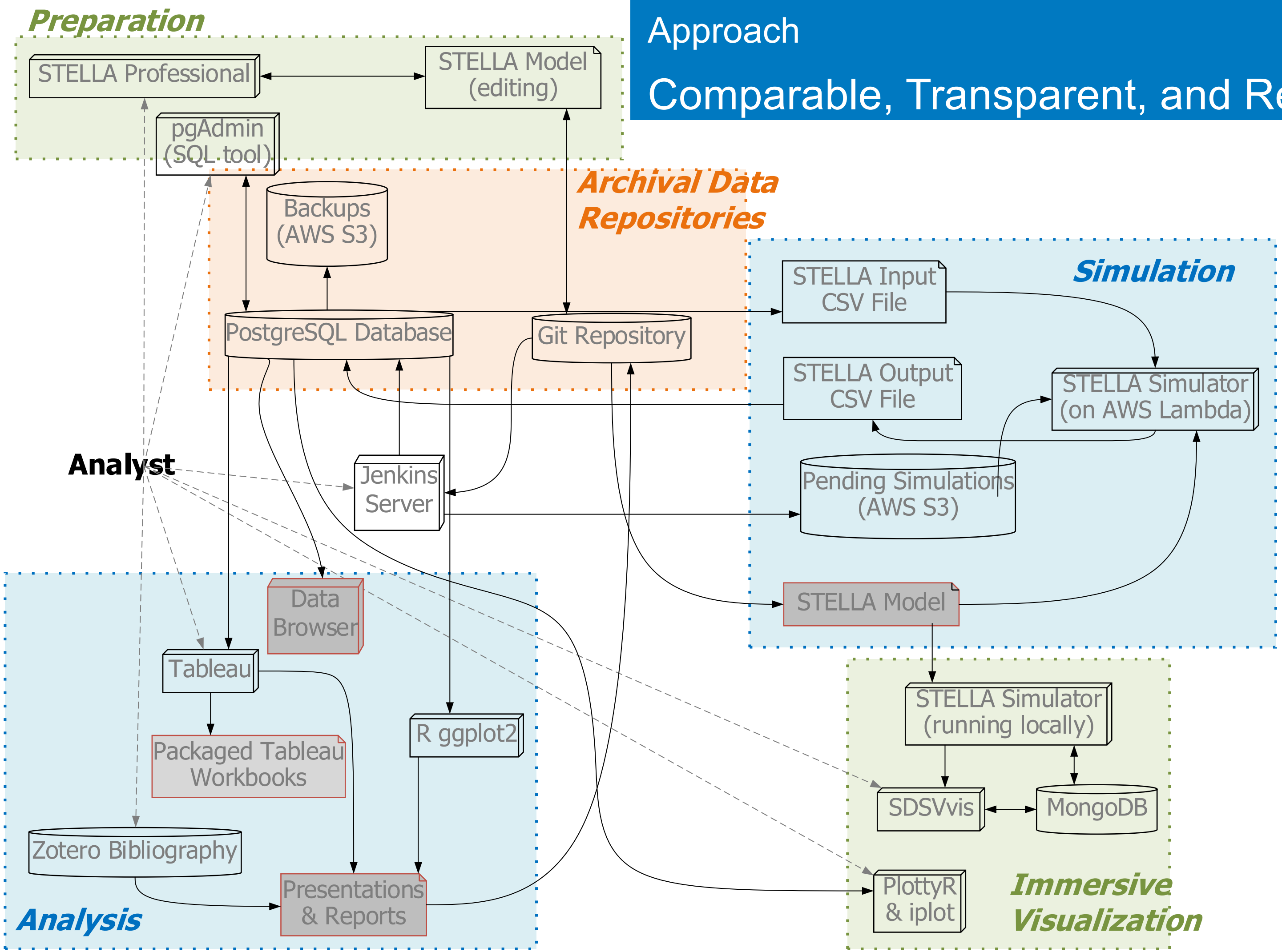
Schematic of RBEM. Modules and key attributes are shown for reference. ORD =O'Hare International Airport (Chicago); HTL = hydrothermal liquefaction; HEFA = hydrotreated esters and fatty acids.

Regional BioEconomy Model (RBEM) Analysis

- Can be used to assess scenarios of targeted industry and associated markets
- Produces insights into the development potential of biofuel within a defined region (Which conditions are necessary and sufficient for investment?)
- Creates a better understanding of the implications of existing and potential policies and incentives

Approach

Comparable, Transparent, and Reproducible Analysis



Comparable

Robust visualization and quality control

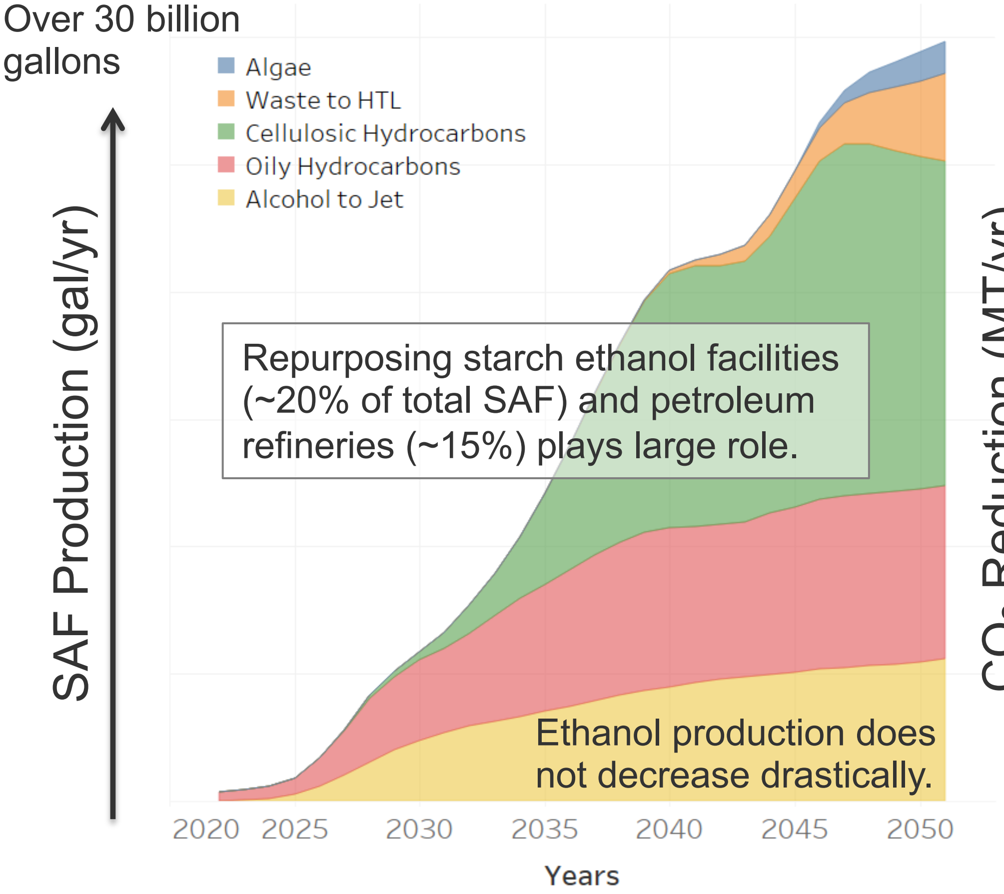
Transparent

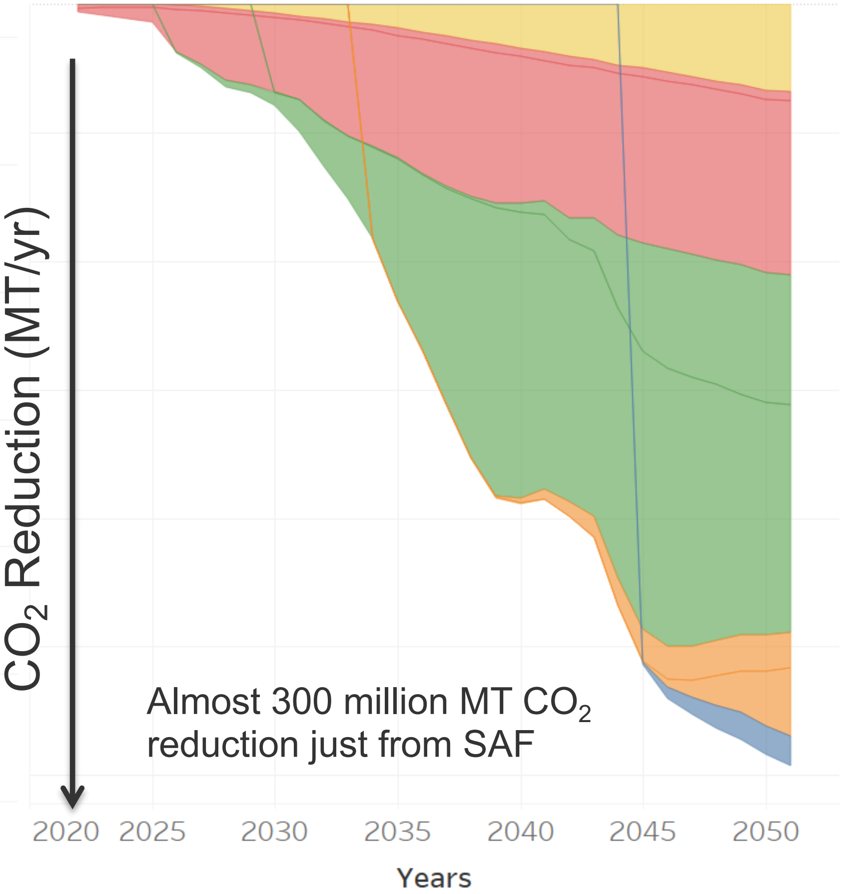
Documentation embedded in model variables

Reproducible

Sophisticated information architecture to enable inventorying and mining of results

BSM Analysis Supports SAF Grand Challenge





Brandt and Newes et al. (analysis being run currently)

PRELIMINARY RESULTS - DO NOT DISTRIBUTE, QUOTE, OR CITE

Will material supply support SAF expansion?

Cement Production

United States

- Current: 92 Mt
- Future: 175.6 Mt

Global

- Current: 4.4 Gt
- Future: 4.7 Gt

Steel Production

United States

- Current: 85.8 Mt
- Future: 80 Mt

Global

- Current: 1.951 Gt
  Future: 1.887 Gt

Source: Beck and Newes (forthcoming)

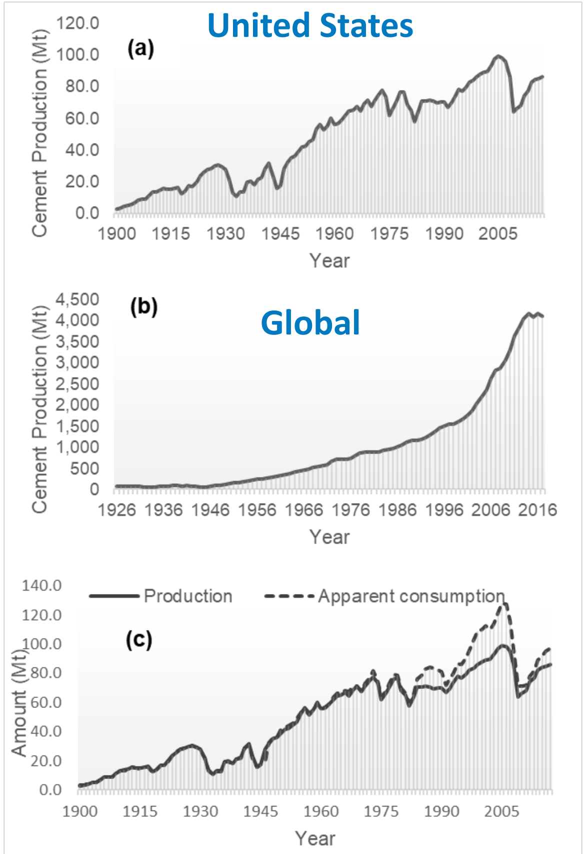


Figure 3. *Historical annual production of cement in the United States (a) and globally (b). Comparison of domestic annual production to consumption (c).*

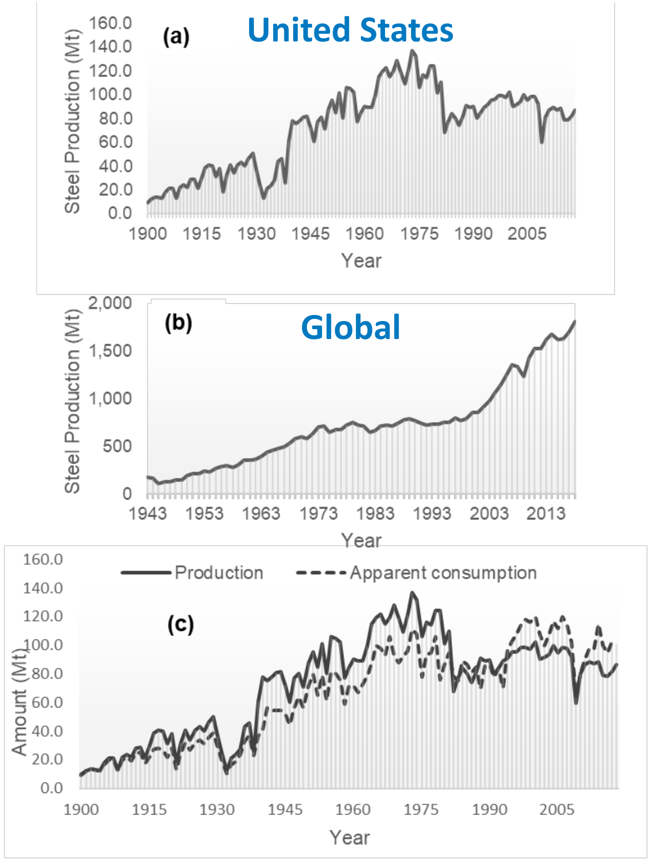
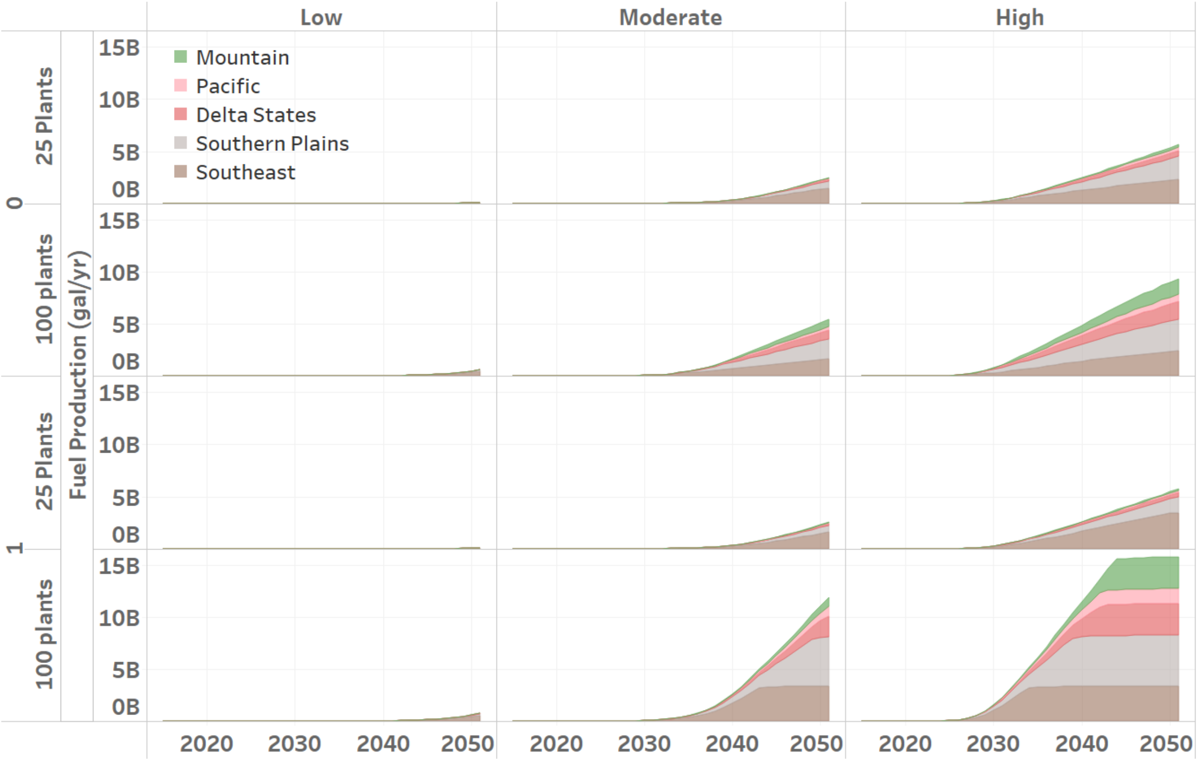


Figure 4. *Historical annual production of steel in the United States (a) and globally (b). Comparison of domestic annual production to consumption (c).*

Algae-to-HEFA could produce over 15 bgal/yr.



Algal fuel production by the HEFA pathway in the United States shown by scenario component (2015–2050). The columns show results for economic policy incentives (low, moderate, high). The rows show results for the initial fractional availability (0 or 1) of sites for algae production and annual maximum plant construction capacity (25 plants/year or 100 plants/year).

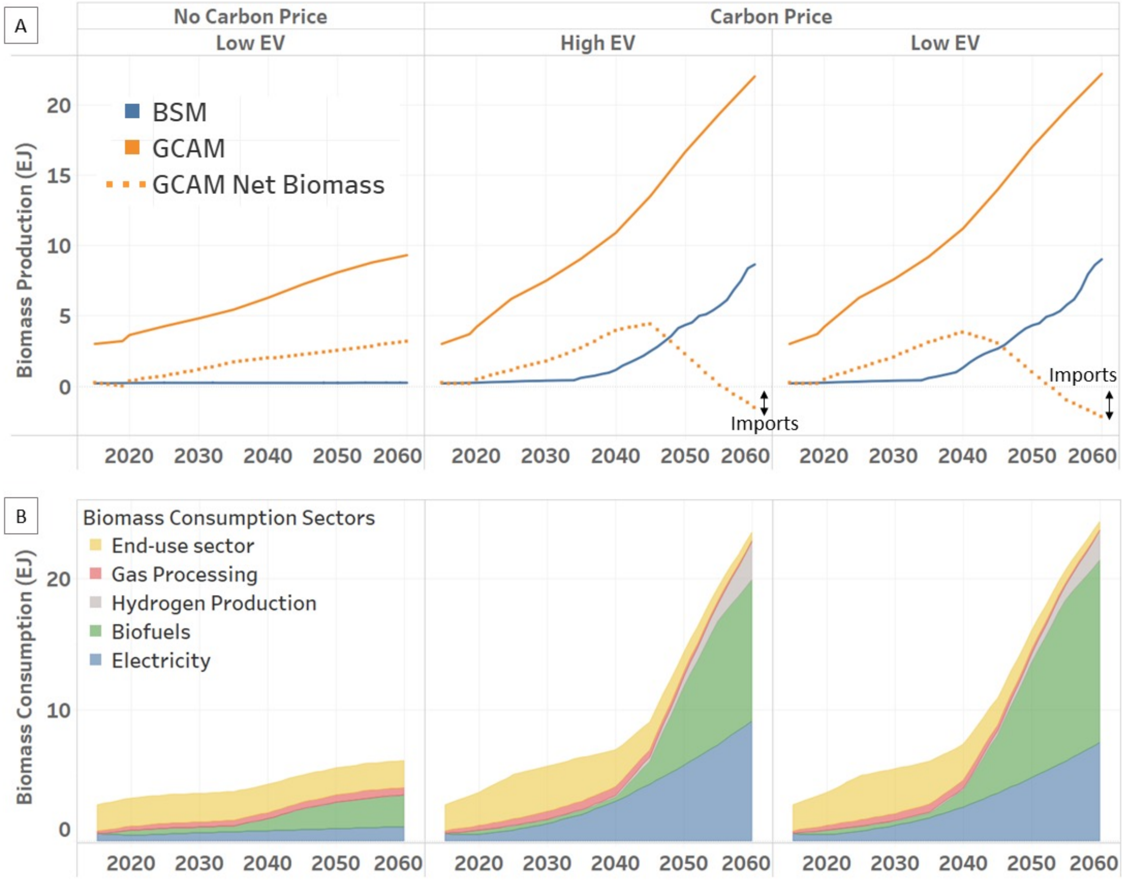
A set of moderate to high incentives (PTCs, RINs, LCFS) is essential to increasing fuel production from algae.

A limit of 25 new plant constructions per year is constraining for biofuel production, but at 100 plants per year, the availability of algal sites is constraining.

Regions with lower MBSP are developed earlier than regions with higher MBSP.

Source: Atnoorkar and Wiatrowski et al. (forthcoming)

Systems Analysis Enhancing Integrated Assessment Modeling



- Biomass production increases with carbon price.
- GCAM biomass > BSM
  - Includes biopower
  - More biofuel
- EVs → More biopower and less total biomass
- Carbon price → U.S transitions to biomass importing

Vimmerstedt et al. (forthcoming)

Progress and Outcomes

All Milestones Completed on Time

Milestone	End Date
Provide BETO with a draft journal article for review on insights gained from carbon analysis using an integrated assessment model (GCAM) integrated with a detailed bioenergy supply chain model (BSM).	Q3 FY21
Complete analysis using the RBEM—with one or two examples from BETO-funded conversion strategies on sustainable aviation fuel production—that will provide insights on sustainable aviation fuel.	Q4 FY21
In support of analysis around a near-term deployable algal biofuel option, deliver a draft journal article on deployment scenarios associated with the algae-to-HEFA pathway.	Q1 FY22
Increase outside awareness of analysis results by presenting GCAM/BSM analysis results at a conference or an Energy Modeling Forum meeting as another avenue for disseminating BETO-funded work. Deliberately select venue with opportunities to connect with the IAM community.	Q2 FY22

Milestone	End Date
Conduct an external model input review of RBEM with 6–10 subject matter experts. The review will focus on two aspects of the model: (1) the SD methodological approach—structure, feedback, and detail complexity and (2) the data quality and representativeness—data sufficiently representing the system being modeled.	Q3 FY22
Illuminate a potential barrier to large-scale SAF biorefinery deployment by delivering a literature review and analysis on potential construction capacity constraints.	Q4 FY22
Brief BETO on completed global sensitivity analysis on the BSM. This analysis will focus on all model inputs and all included modules in the BSM framework. The model outputs upon which the sensitivity analysis will be performed will be prioritized based on input from BETO. Results from this analysis will be used to create ranges on BSM results and will be used to inform model reduction work proposed for FY24.	Q4 FY23

Go/No Go on whether to continue development of BSA models. Assess level of external feedback needed to continue model development, given current BETO objectives and progress in R&D.

- Technical Review Committee reviewed RBEM and provided guidance regarding model improvements, potential analyses, and use cases.
- Increased interest in running scenario analyses using the BSM.

Summary of Accomplishments (2021–2023)

- **Impactful Analyses**
  - Starch ethanol retrospective analysis for EPA's *Biofuels and the Environment: Third Triennial Report to Congress**
  - Industry request for policy analysis of sustainable aviation fuels
  - Response to requests from U.S. Congress, United States Department of the Treasury, and industry for analysis of four proposed bills
  - Collaboration with GCAM team to investigate policy implications on carbon emissions and the associated industry build-out
  - Exploration of converting a nascent feedstock (algae) to SAF using a mature technology (HEFA)
  - Investigation of potential material and labor constraints in the bioeconomy build-out
  - Analysis of potential supply chain constraints in supplying SAF to O'Hare International Airport
  - Biodiesel retrospective analysis with EPA
- **Publications**
  - Two published journal articles on BSM data process, and starch ethanol
  - Four pending journal articles on sensitivity analysis, algae-to-HEFA, and GCAM/BSM, construction constraints analysis
  - One pending technical report on RBEM.

*U.S. EPA. *Biofuels and the Environment: Third Triennial Report to Congress (External Review Draft)*. EPA/600/R-22/273, 2022.

Summary of Accomplishments (2021–2023)

- **Model Development to Meet Analysis Needs**
  - Incorporated waste to HTL—including sludge, manure, and food waste—as feedstocks
  - Added bolt-on alcohol-to-jet technology
  - Added coprocessing at petroleum refineries
  - Modified the BSM for joint analysis with GCAM
  - Updated techno-economics, feedstock logistics, and other data
  - Continued development of two additional models (RBEM and Carbon Dynamics) to be able to explore future pressing bioeconomy questions
- **Annual Update of Public Version of the BSM**
  - Annual model calibration
  - Metadata release update
- **Presentations**
  - BETO 2021 Project Peer Review
  - Industrial Energy-Related Energy Technologies and Systems, International Energy Agency Webinar in May 2021
  - Potential impacts of two policies (ITC and PTC) on SAF production with ASTM-certified pathways
  - Poster at Integrated Assessment Modeling Conference for BSM/GCAM analysis

Support Analysis across Bioenergy Community

GHG emissions are increasing.

Bioeconomy can decrease emissions, especially in aviation and marine, but markets are likely to be driven by policy.

Economies are complex.

Policymakers need tools for developing and evaluating policy options.

Our analysis approach delineates opportunities in this complex, nonlinear environment at every stage in the bioeconomy process.

Pictures from stock images

Models from this project—and links to other impact-oriented models (GREET, BEIOM)—can show benefits of bioeconomy and ensure no unintended consequences for emerging technologies.

Contribute to SAF Grand Challenge

- Work recognized by DOE Secretary’s Achievement Award
- Performed policy analysis for industry stakeholders and U.S. Congress
- Identified potential barriers to reaching SAF goals
- Collaborating with WSU on joint analysis (to be published)
- Serving as SAF Subcommittee Chair for Transportation Research Board (National Academy of Sciences)

Source: DOE (2022)

Stakeholder Outreach and Engagement

Starch Ethanol/Biodiesel Retrospective Analysis

- EPA relied on the system dynamics expertise of NREL to explore potential impact of different policy mechanisms.

Carbon Market Analysis

- NREL investigated potential deployment of biofuels and BECCS under different carbon policy scenarios (with Pacific Northwest National Laboratory [GCAM]).

BETO Program Analysis

- BSM was used in analysis of the decarbonization potential of the BETO program in coordination with VTO and HFTO.

Co-Optima Fuel Pathways Analysis

- NREL assessed feasibility, economics, and logistics of adopting Co-Optima by drivers, vehicle makers, fuel retailers, and fuel producers.

Summary

Value Proposition

- Support design of bioeconomy strategies
- Identify opportunities and challenges for creation of a bioenergy industry

Key Accomplishments

- Contributed to the EPA's *Third Triennial Report to Congress*
- Supported analysis of proposed policies in Congress
- Participated in multiple collaborations on critical strategic topics: biofuels for aviation, bioeconomy for carbon mitigation, and benefits of BETO program
- Developed new models to explore emerging questions
- Contributed to many journal articles, presentations, posters, technical reports

Quad Chart Overview

	FY22 Costed	Total Award
DOE Funding		

Funding Mechanism

Lab Call: Data, Modeling, and Analysis

April 2021

Note: This project was formerly part of WBS 4.1.2.1. The project directly supports Co-Optima.

Project Goals

- **Provide bioeconomy scenarios analysis support** to BETO and the broader bioeconomy stakeholders
- Analysis informs **the creation of a bioenergy industry**.

End of Project Milestone

Brief BETO on completed global sensitivity analysis on the BSM; focused on all model inputs and included modules in the BSM framework. Results from this analysis will be used to (1) create ranges on BSM results and (2) inform model reduction work proposed for FY24.

Abbreviations and Acronyms

AWS	Amazon Web Services
BECCS	bioenergy with carbon capture and storage
bgal	billion gallons
CSV	comma-separated values
BEIOM	Bio-based circular carbon economy Environmentally-extended Input-Output Model
BETO	Bioenergy Technologies Office
BSM	Bioenergy Scenario Model
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
EV	electric vehicle
FOG	fats, oils, and greases
FY	fiscal year
GCAM	Global Change Analysis Model
GE	General Electric
GM	General Motors
Gt	gigaton
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Transportation
HEFA	hydrotreated esters and fatty acids
HFTO	Hydrogen and Fuel Cell Technologies Office
HTL	hydrothermal liquefaction
IAM	integrated assessment modelling
ITC	investment tax credit
LCFS	low-carbon fuel standard
MBSP	minimum biomass selling price
MIT	Massachusetts Institute of Technology
MT	metric tons
MYPP	multiyear program plan
ORD	O’Hare International Airport
PTC	production tax credit
RIN	renewable identification numbers
SAF	sustainable aviation fuel
SD	system dynamics
VEETC	volumetric ethanol excise tax credit
VTO	Vehicle Technologies Office
WSU	Washington State University

References

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Beck, J., and E. Newes. Forthcoming. “Material and Labor Impacts on Future Sustainable Aviation Fuel Deployment.”

Dartmouth College.2013. *The Role of Biomass in America's Energy Future (RBAEF)*. https://rbaef.engineering.dartmouth.edu/index.html

DOE (U.S. Department of Energy). 2022. *SAF Grand Challenge Roadmap: Flight Plan for Sustainable Aviation Fuel*. Prepared by the U.S. Department of Energy, U.S. Department of Transportation, and U.S. Department of Agriculture, in collaboration with the U.S. Environmental Protection Agency. https://www.energy.gov/sites/default/files/2022-09/beto-saf-gc-roadmap-report-sept-2022.pdf.

DOE. 2016. *Multi-Year Program Plan*. https://www.energy.gov/eere/bioenergy/articles/bioenergy-technologies-office-multi-year-program-plan-march-2016

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Newes, Emily, Christopher M. Clark, Laura Vimmerstedt, Steve Peterson, Dallas Burkholder, David Korotney, and Daniel Inman. 2022. “Ethanol Production in the United States: The Roles of Policy, Price, and Demand.” *Energy Policy* 161: 112713. https://doi.org/10.1016/j.enpol.2021.112713.

Newes, Emily, Laura Vimmerstedt, Zia Haq, and Alicia Lindauer. 2021. *PTC and ITC for Aviation Fuel: Analysis Using the Biomass Scenario Model*. National Renewable Energy Laboratory. https://www.nrel.gov/docs/fy21osti/79356.pdf.

Thank you!

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NREL Transforming ENERGY

Additional Slides

Responses to Previous Reviewers' Comments

- It would be good to see more clarity about who target policy audiences are and strategy for how to reach them and influence their decisions.
  - We have continued to network with academia and industry to build more relationships and increase the impact and reach of our work. We were asked by industry to publish a presentation on two policies (ITC and PTC) on SAF production with ASTM-certified pathways and responded to requests from U.S. Congress and the U.S. Treasury for analysis of four proposed bills.
- In such a complex model, how is the team quantifying, addressing, and communicating uncertainty?
  - We have completed extensive sensitivity analyses of the BSM, upon which uncertainty analyses may be performed. An updated sensitivity analysis is currently being completed.
  - Pervasive uncertainties regarding many aspects of the biomass-to-bioenergy supply chain persist. The strategies around calibration and validation of our models described in the project approach build confidence in but cannot dispel these uncertainties. We are limited by data availability because we are looking into the future for processes that do not fully exist today. To address this challenge, studies with the BSM routinely test hundreds to thousands of unique conditions, based on combinations or statistical samples of inputs, and we develop and improve the computational infrastructure to perform and track large numbers of simulations.

Publications, Presentations, Awards

Journal Articles

Bush, Brian, Dana Stright, Jay Huggins, and Emily Newes. 2022. "Simulation Process and Data Flow for a Large System Dynamics Model." *SIMULATION* 98(9): 823–833. https://doi.org/10.1177/00375497221093381.

Newes, Emily, Christopher M. Clark, Laura Vimmerstedt, Steve Peterson, Dallas Burkholder, David Korotney, and Daniel Inman. 2022. "Ethanol Production in the United States: The Roles of Policy, Price, and Demand." *Energy Policy* 161: 112713. https://doi.org/10.1016/j.enpol.2021.112713.

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Beck, J., and E. Newes. Forthcoming. "Material and Labor Impacts on Future Sustainable Aviation Fuel Deployment."

Vimmerstedt, L., B. Bush, D. Inman, E. Newes, D. Stright, and S. Peterson. Forthcoming. "Pathways to Biofuels Industry Growth."

Vimmerstedt, L., S. Atnoorkar, C. Bergero, D. Inman, E. Newes, S. Peterson, and M. Wise. Forthcoming. "Deep Decarbonization and U.S. Biofuels Production: A Coordinated Analysis With a Detailed Structural Model and an Integrated Multisectoral Model."

Technical Reports

Inman, D., S. Peterson, and E. Newes. Forthcoming. *Overview of the Regional BioEconomy Model (RBEM)*. National Renewable Energy Laboratory.

U.S. Environmental Protection Agency. 2022. *Biofuels and the Environment Third Triennial Report to Congress External Review Draft (ERD)*. https://cfpub.epa.gov/ncea/biofuels/recordisplay.cfm?deid=353055#:~:text=This%20Third%20Triennial%20Report%20to,imported%20ethanol%20from%20Brazilian%20sugarcane.

Presentations and Posters

Atnoorkar, Swaroop, Laura Vimmerstedt, Emily Newes, Steve Peterson, Marshall Wise, Candelaria Bergero, and Daniel Inman. 2022. *Decarbonization Scenarios in the United States: Comparing Biofuels Growth in Two Models: GCAM and BSM*. College Park, MD. National Renewable Energy Laboratory. NREL/PO-6A20-84601. https://www.nrel.gov/docs/fy23osti/84601.pdf.

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Newes, Emily. 2021. *Bioeconomy Scenario Analysis*. Presented at the IETS-IEA Workshop Series: Future Scenarios and Strategic Decision-Making for Industry, Virtual, May 6, 2021. National Renewable Energy Laboratory. NREL/PR-6A20-79900. https://www.nrel.gov/docs/fy21osti/79900.pdf.

Awards

U.S. Department of Energy Secretary's Achievement Award as part of the Sustainable Aviation Fuels Grand Challenge Team, 2023.

Proposed Future Work

- Complete BSM sensitivity analysis
- Complete and submit five journal article manuscripts
- Create reduced form version of the BSM
- Release updated BSM with user-friendly interface
- Examine issues surrounding the debate of renewable diesel versus SAF

Support BETO with Crosscutting Analysis

BETO Feedstock Supply and Logistics

“develop technologies to provide a sustainable, secure, reliable, and affordable biomass feedstock supply”

- Analysis of feedstock supply chain issues on a local scale
- Algae-to-HEFA analysis

BETO Conversion

“develop commercially viable technologies for converting biomass feedstocks”

- Algae-to-HEFA analysis
- BECCS and carbon policy analysis

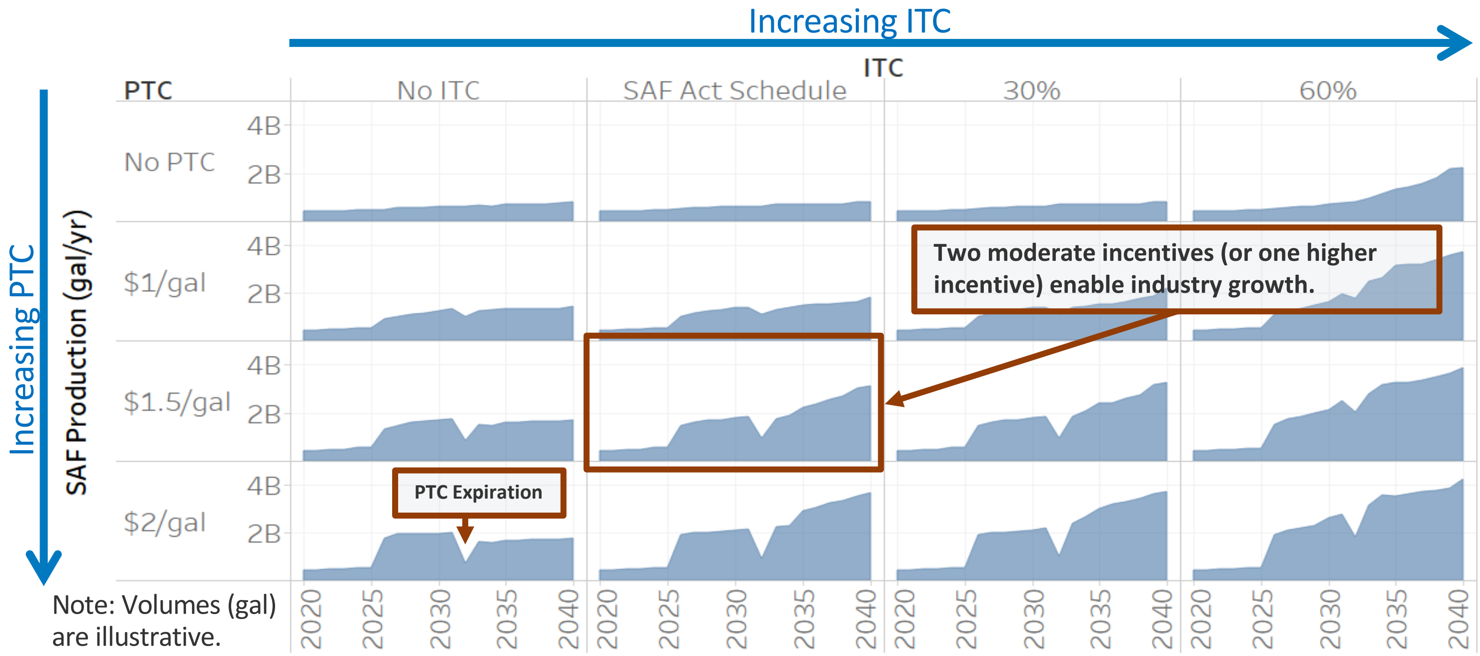
BETO Advanced Development and Optimization

“develop commercially viable biomass utilization technologies that build and validate integrated biorefineries; develop supporting infrastructure to enable a biomass-to-bioenergy value chain”

- Analysis of impacts of a transition to high octane fuel
- Study on potential material and labor constraints

Source: BETO MYPP

BSM Provides Policy Insights for Sustainable Aviation Fuel (SAF)



Note: Volumes (gal) are illustrative.

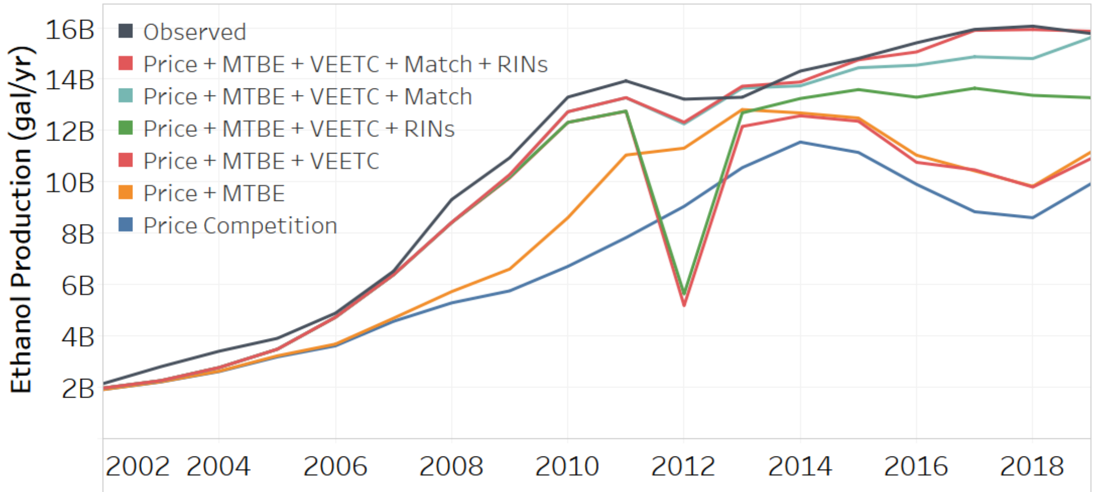
- Production tax credits and investment tax credits—individually or in combination—enable SAF industry growth.
- Because FOG supply is limited, cellulosic feedstock supply grows to meet industry demand.

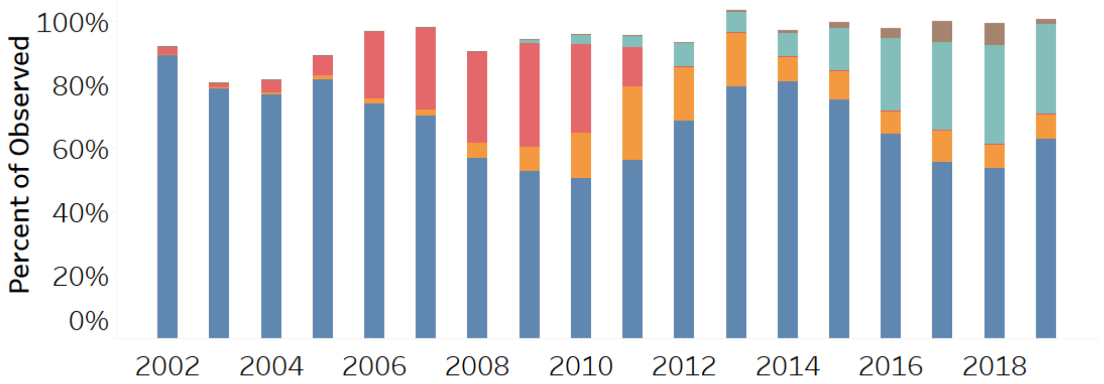
SAF production levels decrease after PTC expiration and then may rebound to a lower level, compared to an unlimited PTC. The dip is deeper (30%–60%) with higher PTC values.

Source: Newes et al. (2021)

**** Because the study scope includes only commercial technologies, these results do not estimate the potential for technology innovation to reach higher production levels.****

BSM-retro Model Used in EPA Report to Congress





Starch Ethanol Retrospective Model

- Provides original, dynamic policy analysis
- Informs EPA's *Third Triennial Report to Congress*
- Ethanol price competitiveness with gasoline may have been responsible for up to 50% of ethanol production.
- Effect of volumetric ethanol excise tax credit (VEETC) expiration and drought could have been more impactful without match blending.

Source: Newes et al. (2022)