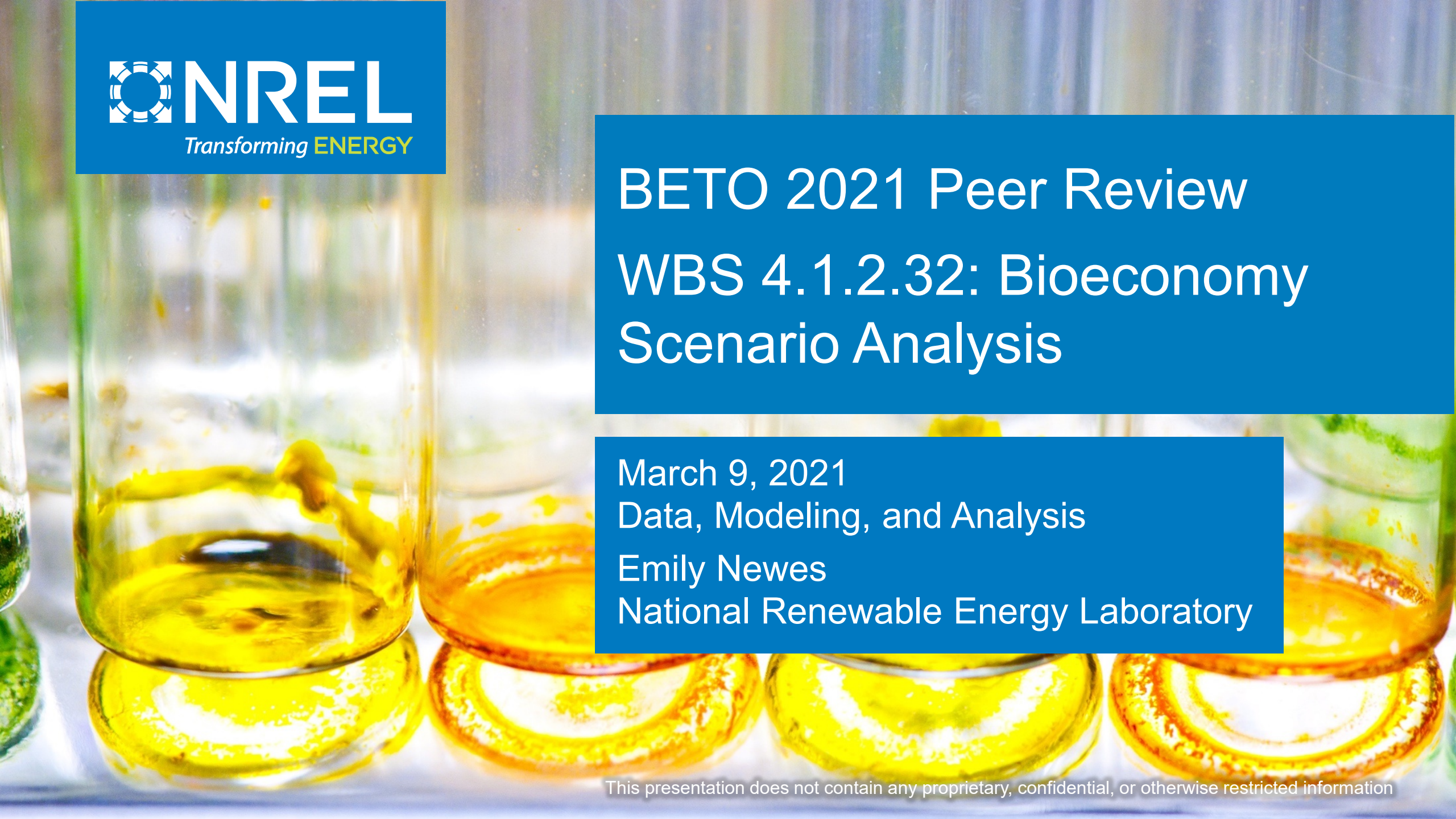


BETO 2021 Peer Review

WBS 4.1.2.32: Bioeconomy Scenario Analysis

March 9, 2021
Data, Modeling, and Analysis

Emily Newes
National Renewable Energy Laboratory

Bioeconomy Scenario Analysis Project

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., Biomass Scenario Model) along with peer-reviewed data to model the bioeconomy, representing system-level feedbacks in the integrated supply chain.

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 and what are the limits?

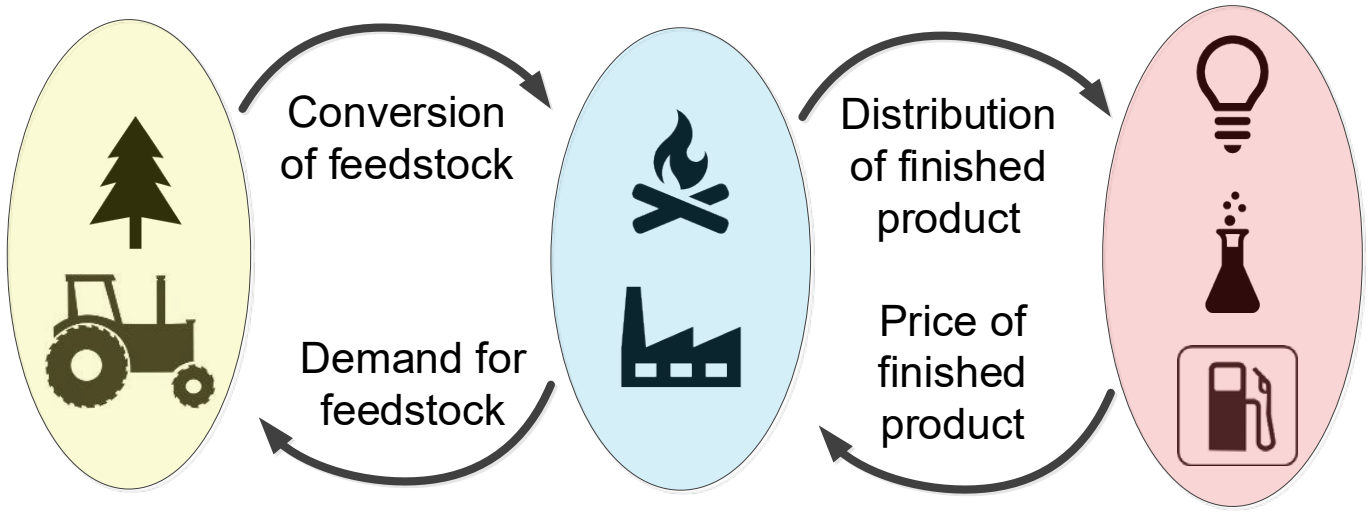
- Provide standard for bioeconomy scenario exploration through system dynamics modeling
- Limiting factor is data.

What are the risks?

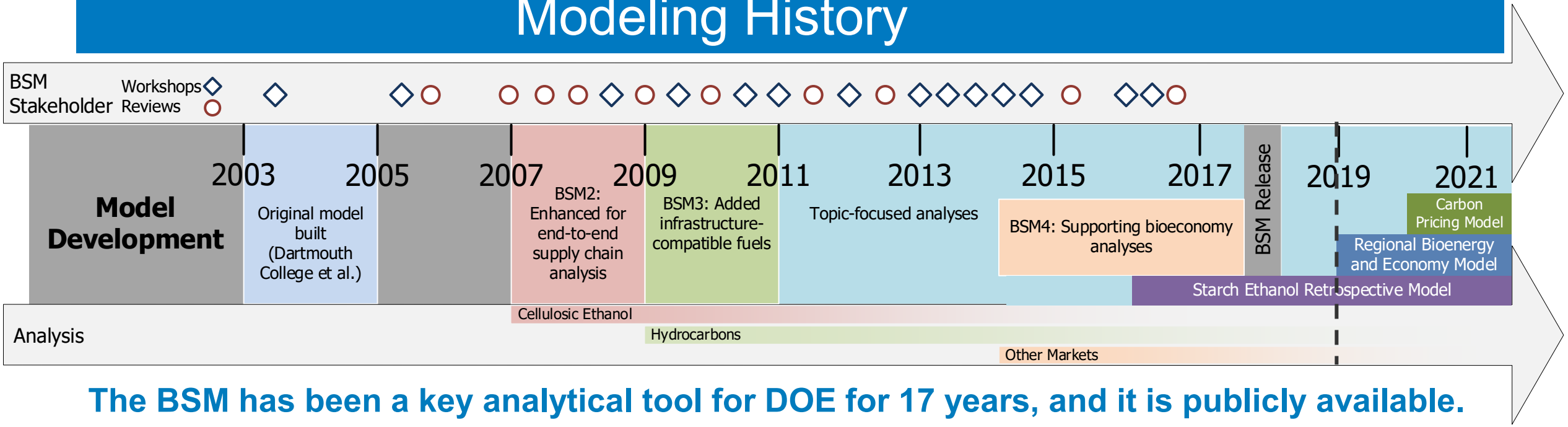
- Over fitting, excessive complexity, and lack of institutional knowledge
- Ensuring collaborators are engaged
- Avoiding scope creep and answering questions appropriate to methodology

Why is it important?

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



Modeling History



The BSM has been a key analytical tool for DOE for 17 years, and it is publicly available.

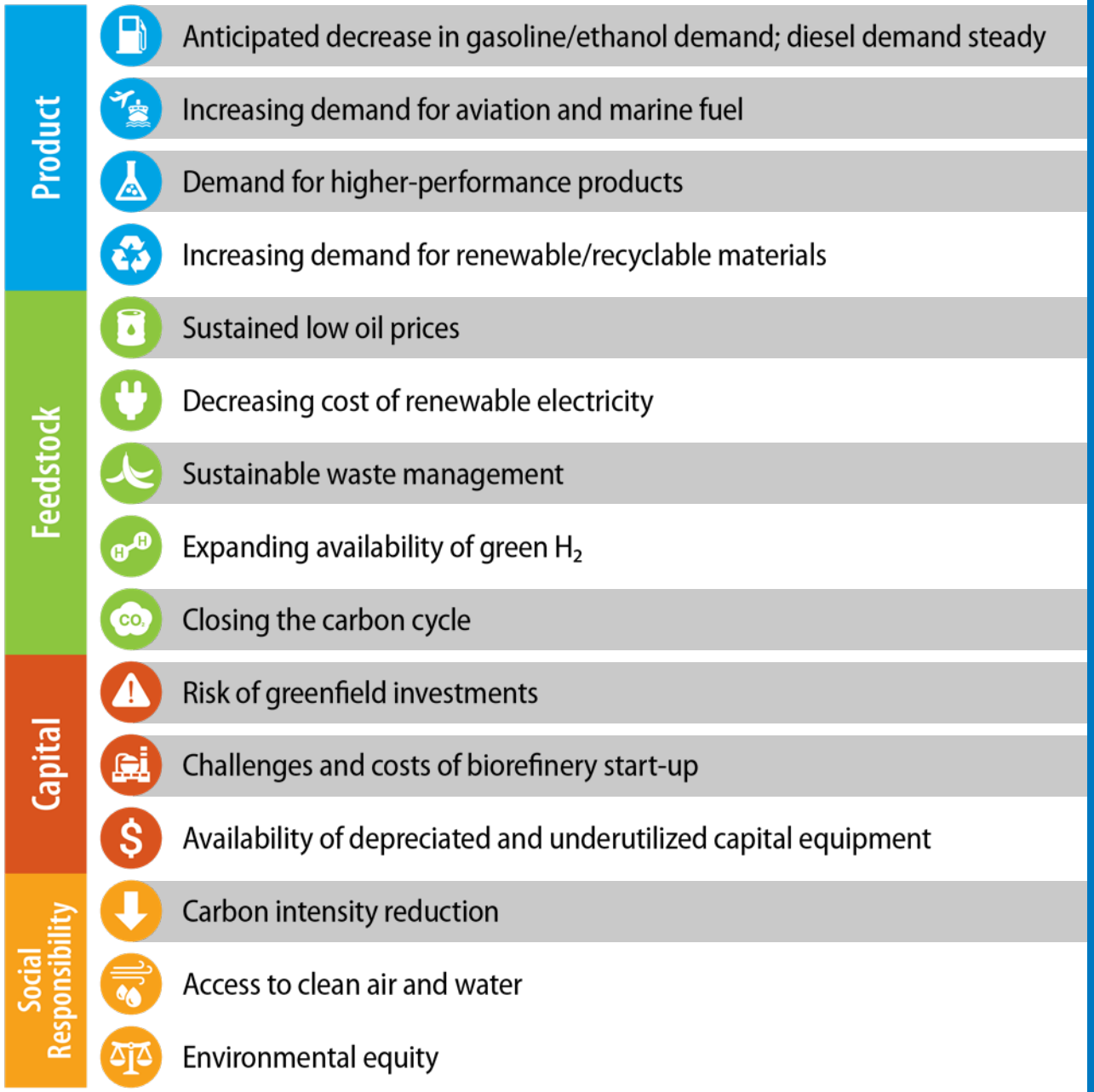
The BSM is:

- 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.

Market Trends



NREL's bioenergy program is enabling a sustainable energy future by responding to key market needs.

Value Proposition

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

Key Differentiators

- Shows potential challenges and opportunities in the bioeconomy supply chain for accelerated development
- Modeling that evolves with market needs
- Relied upon by decision makers in government and industry

Multidisciplinary Team

Ling Tao
PhD chemical engineer with 10+ years of experience in advanced conversion technologies

Emily Newes
5+ 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

Kristi Moriarty
Expert in the area of infrastructure and biofuel testing and compatibility requirements

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

Steve Peterson
Principal BSM model architect; teaches System Dynamics at Dartmouth College

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

Modeling and Analysis to Explore Pressing Questions

Reliance system-dynamics modeling framework

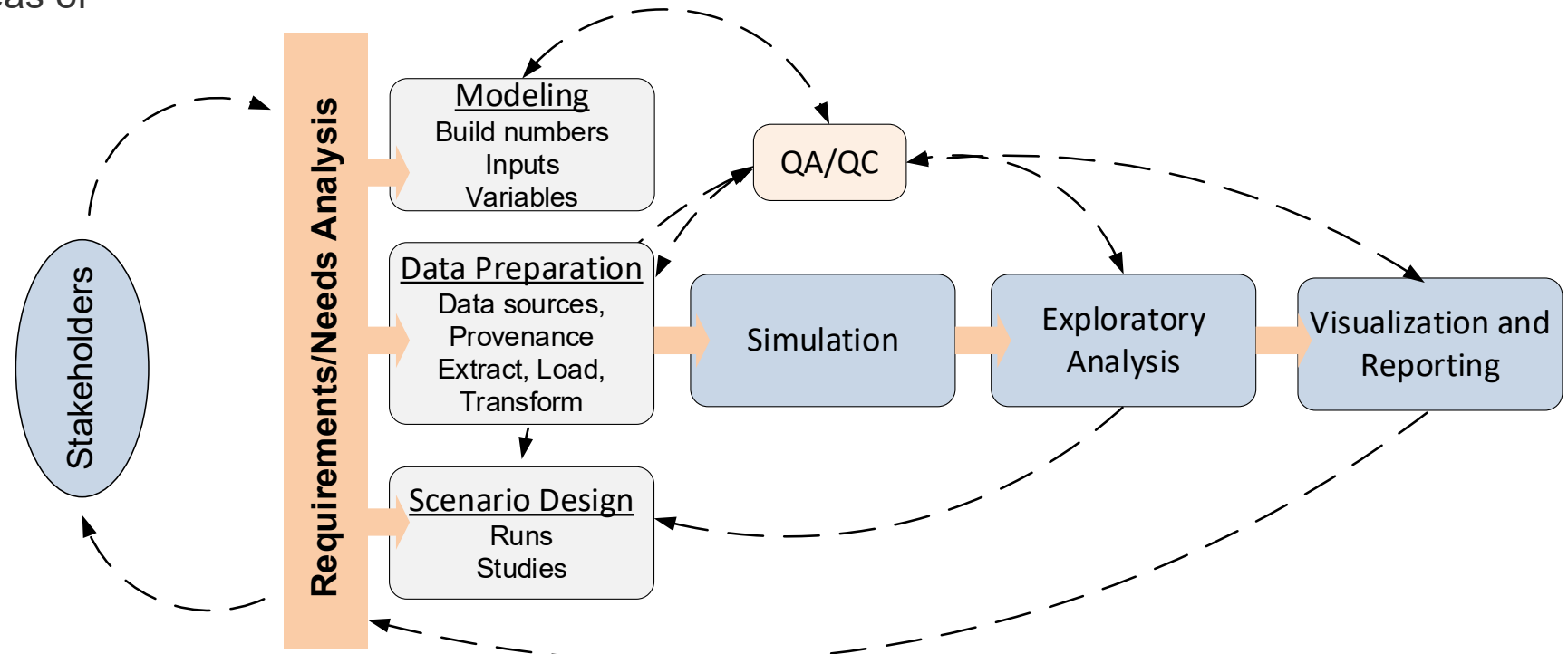
- Appropriate and well-established
- Robust methodology for analyzing behavior of complex real-world feedback systems over time

Frequent communication and reporting to BETO

- Team members with specialized areas of expertise
- Collaboration with external subject matter experts
- Adaptive adjustment of analysis plans
- Flexible, modular modeling architecture
- Exploration of collaborative results with stakeholders using interactive web browser (bsm-viewer.nrel.gov)

State-of-the-art approach to reproducibility and quality

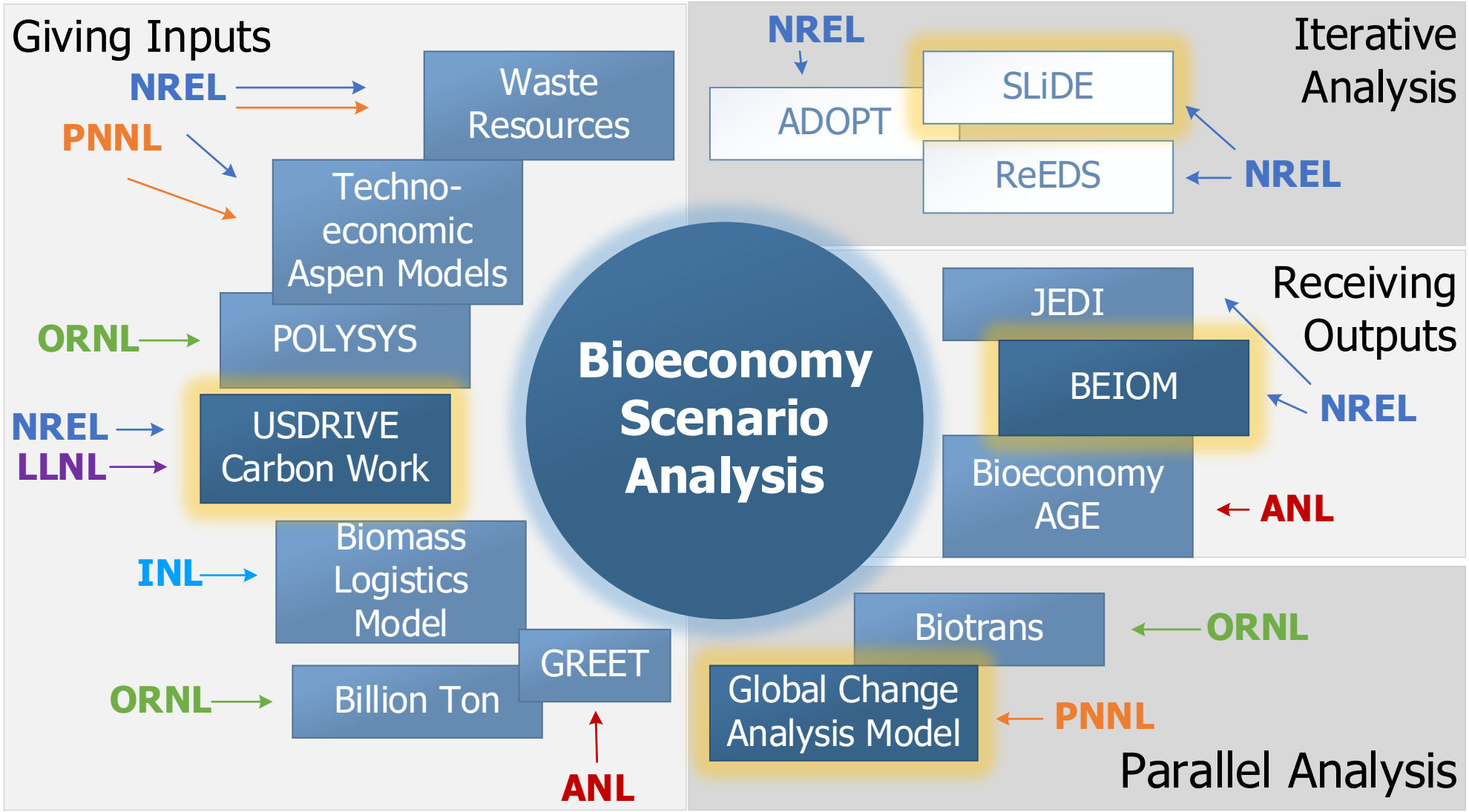
- Defensible and traceable inputs, with metadata
- Full archives of analysis results
- Configuration management and issue tracking systems



Deep Connections with BETO Models

White boxes signify models not funded by BETO.

Yellow highlighting signifies expansion of current capability.



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

- Confirming modeling represents best available information
- Establishing collaboration with meaningful information exchange
- Ensuring mathematics is appropriate to represent the system

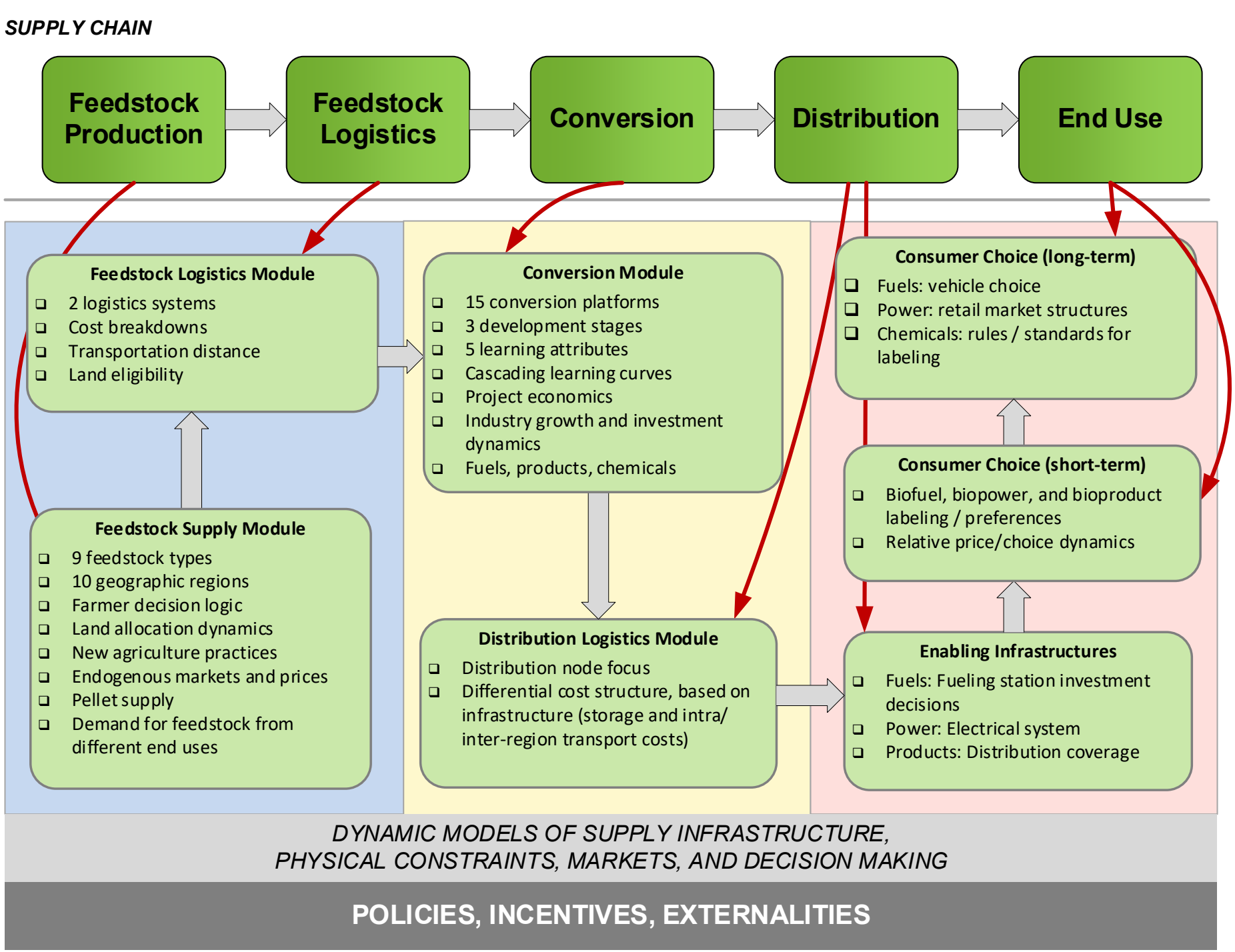
Mitigation Strategies

- Avoiding over fitting, excessive complexity, and lack of institutional knowledge
- Ensuring collaborators are engaged
- Preventing scope creep, answering questions appropriate to methodology

Approach

The BSM Models the Bioeconomy

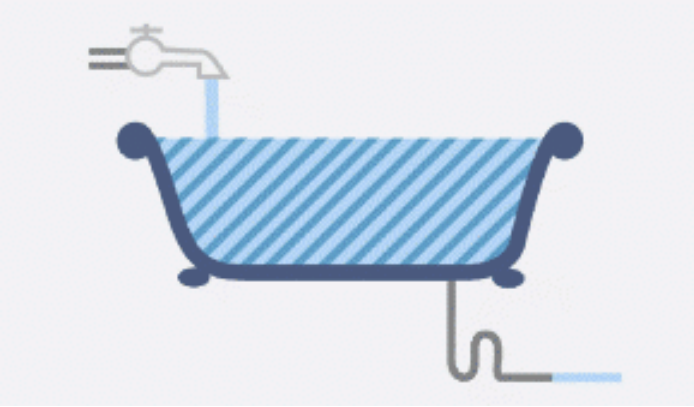
- Supply chain dynamics
- Feedbacks among systems of systems
- Challenge and opportunity identification

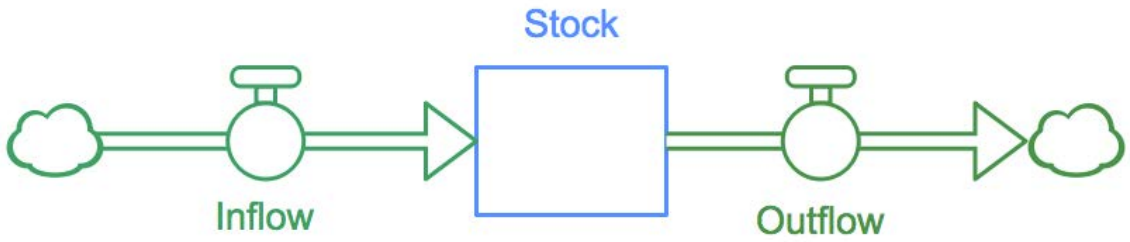


Source: MYPP 2016

System Dynamics: Complex Nonlinear Systems

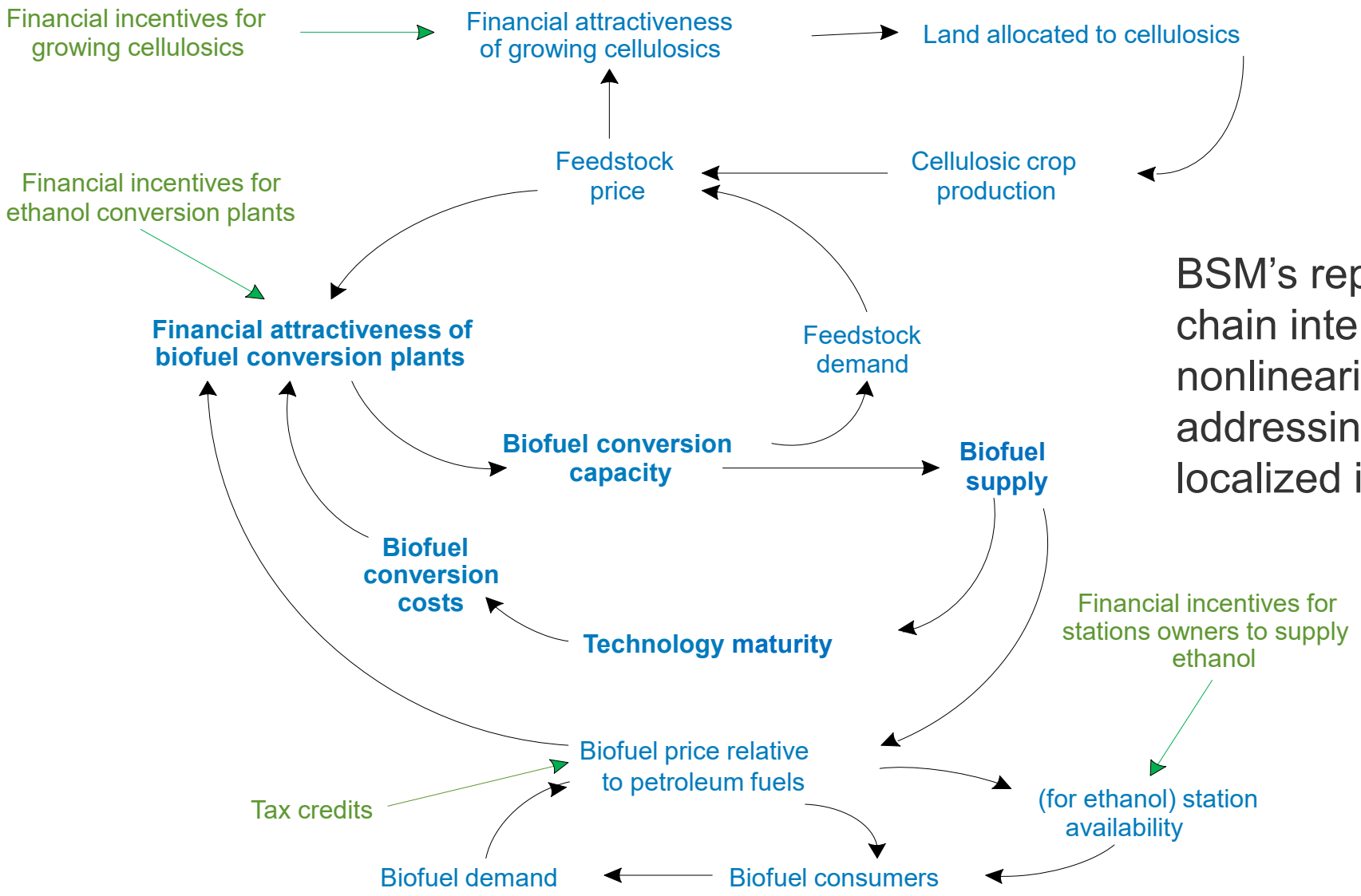
- System dynamics (SD) modeling is grounded in the theory of nonlinear dynamics and feedback control systems. SD uses coupled ordinary differential equations to represent complex (nonlinear) systems.
- SD was originally developed in 1950s at MIT. It originally focused on supply chain dynamics and has subsequently been used by wide range of organizations (e.g., GE, GM, DOE, and DOD) in a broad set of application areas.
- Key concepts include accumulation, flow, feedback, and nonlinearity.
- Visual languages create 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.





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

System Insights Show Potential Barriers and Leverage Points

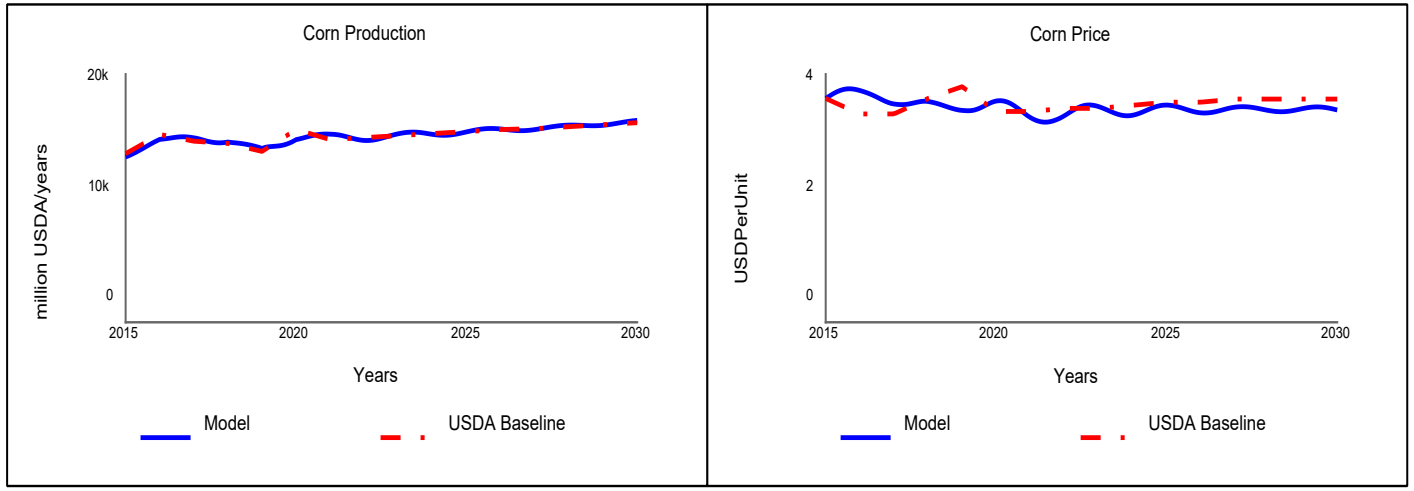


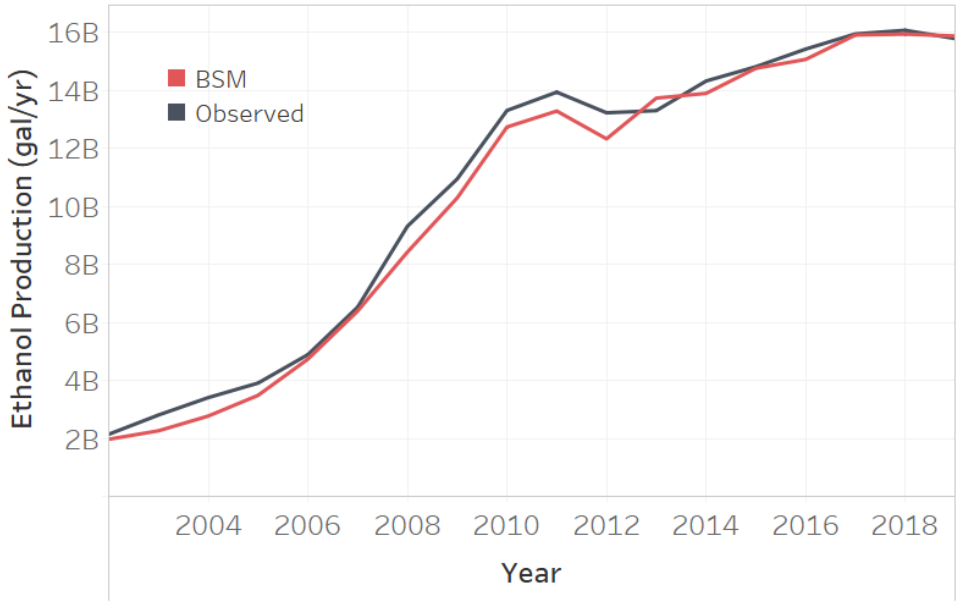
BSM's representation of supply chain interactions captures nonlinearities and evolving markets, addressing systemic implications of localized initiatives and decisions.

Model Calibration and Validation

Calibration Example: BSM Simulated Corn Production vs. 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 USDA long-term forecast each year.



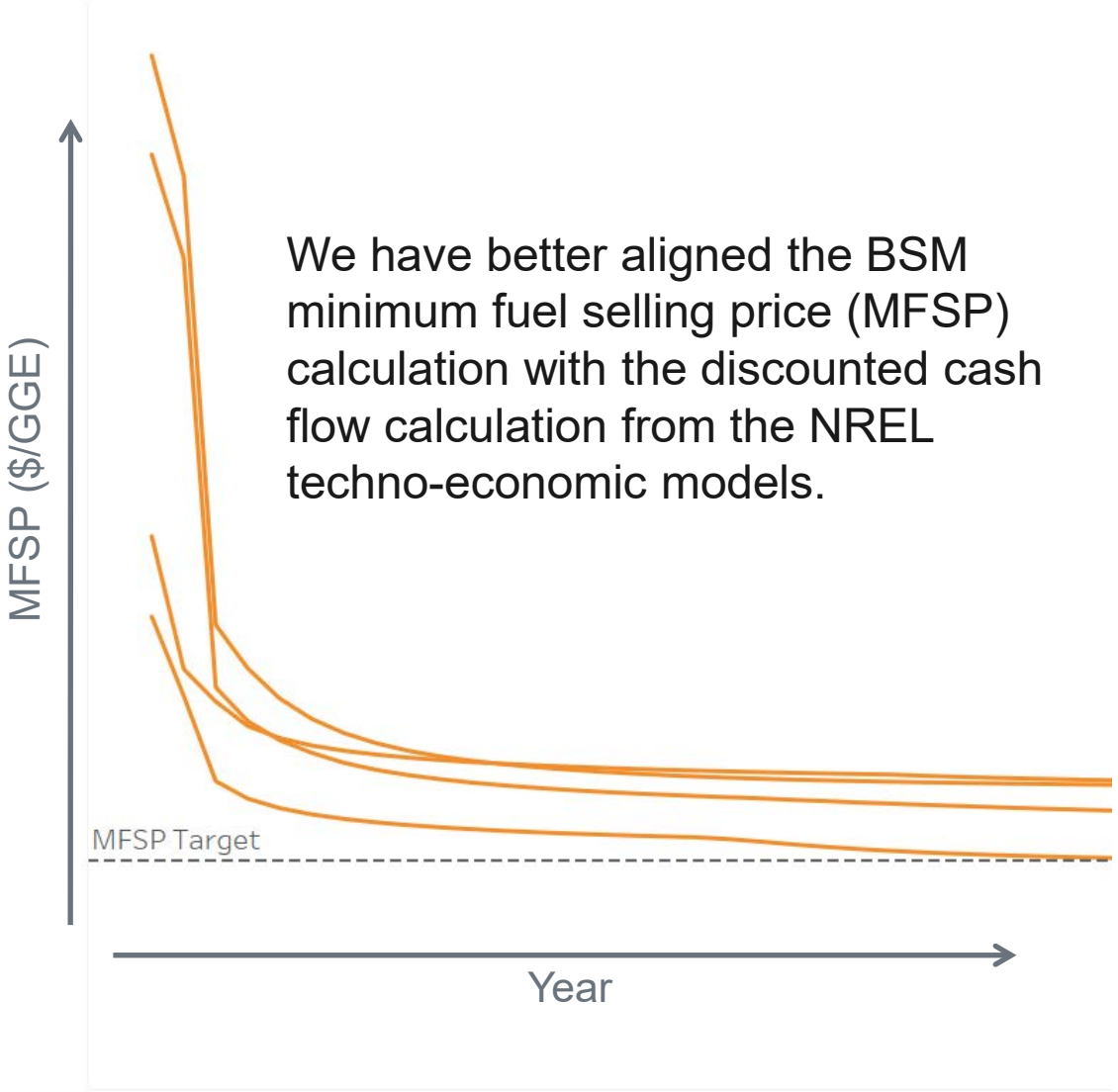


Validation Example: BSM-Simulated Starch Ethanol Production vs. Historical Data

- Production levels, installed capacity, and timing of simulated results match observed production levels, installed capacity, and timing.
- 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, $p < 0.001$

Model Calibration and Validation

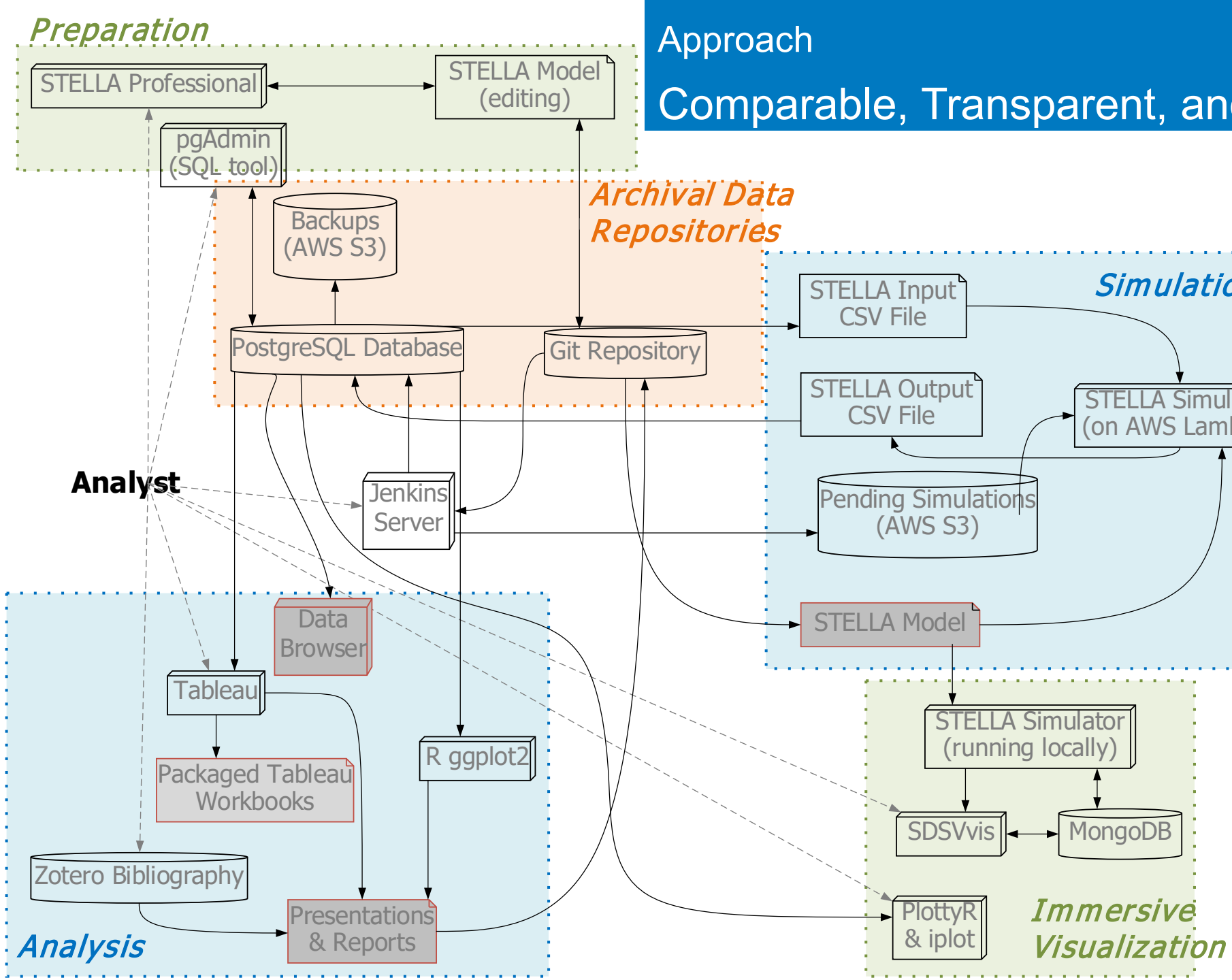


We have better aligned the BSM minimum fuel selling price (MFSP) calculation with the discounted cash flow calculation from the NREL techno-economic models.

TECHNOLOGY PATHWAY	Units	Biological Sugar Upgrading - ACID	Biological Sugar Upgrading - BDO	High-Octane Gasoline	Ex Situ Catalytic Fast Pyrolysis
SOURCE		Davis et al. 2020 (FY19SOT)	Davis et al. 2020 (FY19SOT)	Tan et al. 2020 (FY19SOT)	Dutta et al. 2020 (FY19SOT)
Throughput Capacity	dt/day	2205	2205	2205	2205
Feedstock Type	—	herbaceous	herbaceous	woody	woody
Fixed Capital Investment	$	705,100,000	649,900,000	369,300,000	519,600,000
Fixed Operating Cost	$/yr	19,400,000	17,700,000	19,000,000	25,400,000
Other (non-feedstock) Variable Operating Cost	$/yr	84,300,000	93,400,000	16,60,000	14,700,000
Coproducts Sales Revenue	$/yr	171,900,000	176,900,000	—	22,500,000
Power Sales Revenue	$/yr	—	—	—	9,100,000
MFSP	$/GGE	2.40	2.40	3.21	2.91
Feedstock Cost (+ handling)	$/GGE	1.54	1.60	1.09	1.12
Feedstock Cost	$/dt	82.05	82.05	58.82	68.31

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

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.

U.S. carbon emissions increased in 2018, even as coal plants closed.

Picture: Dennis Schroeder, NREL (2018)
Analysis: Rhodian Group (2019)*
Quéré, Corinne Le, Robbie M. Andrew, Pierre Friedlingstein, Stephen Sitch, Judith Hauck, Julia Pongratz, Penelope A. Pickers, et al. "Global Carbon Budget 2018." *Earth System Science Data* 10, no. 4 (December 5, 2018): 2141–94. https://doi.org/10.5194/essd-10-2141-2018.

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

Stakeholder Outreach and Engagement

Co-Optima Fuel Pathways Analysis
- Assessed feasibility, economics, and logistics of adopting Co-Optima by drivers, vehicle makers, fuel retailers, and fuel producers

Alternative Jet Fuel Analysis
- Informed airports on infrastructure options for biofuel (through ACI-NA)
- Performed policy analysis for industry stakeholders

Starch Ethanol Retrospective Analysis
- EPA relied on system dynamics expertise to explore potential impact of different policy mechanisms.

Carbon Market Analysis
- Investigated potential deployment of biofuels and BECCS under different carbon policy scenarios (with Pacific Northwest National Laboratory [GCAM])

Bioenergy Technologies Office (BETO) Program Analysis
- BSM used in analysis of the potential benefits of the BETO program in coordination with VTO and HFTO

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

BETO Conversion

"develop commercially viable technologies for converting biomass feedstocks"

- Analysis of effects of industrial learning
- BECCS and carbon policy

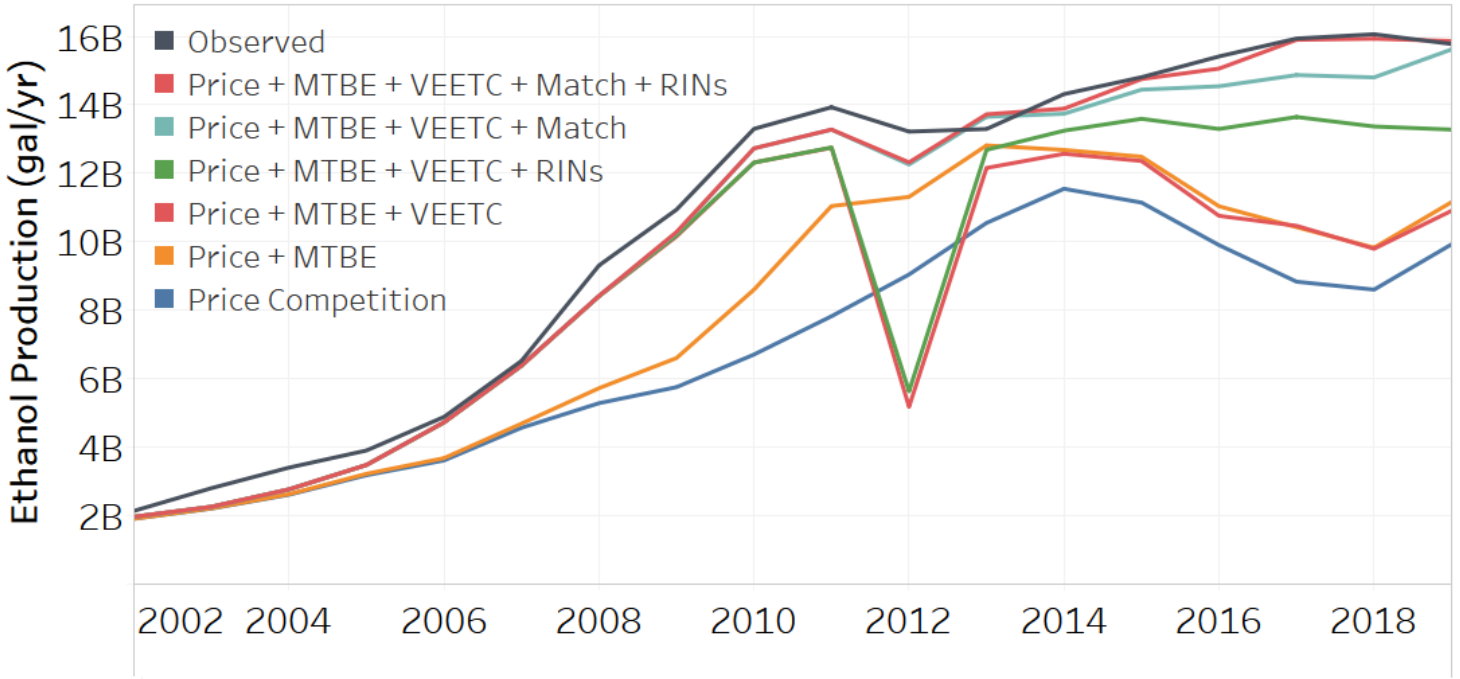
BETO Advanced Development and Optimization

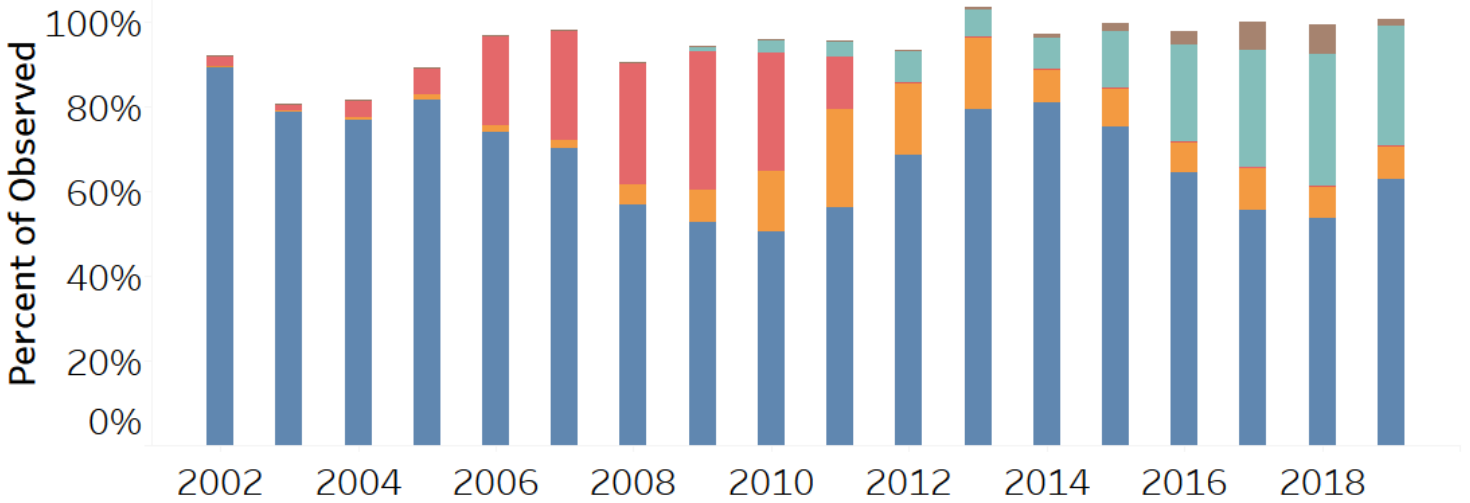
"develop commercially viable biomass utilization technologies that build and validate integrated biorefineries; develop supporting infrastructure to enable a biomass-to-bioenergy value chain"

- Analysis of impacts of a transition to high octane fuel
- Studies of airport infrastructure to enable biofuel integration

Source: BETO MYPP

BSM-retro Model Used in EPA Report to Congress





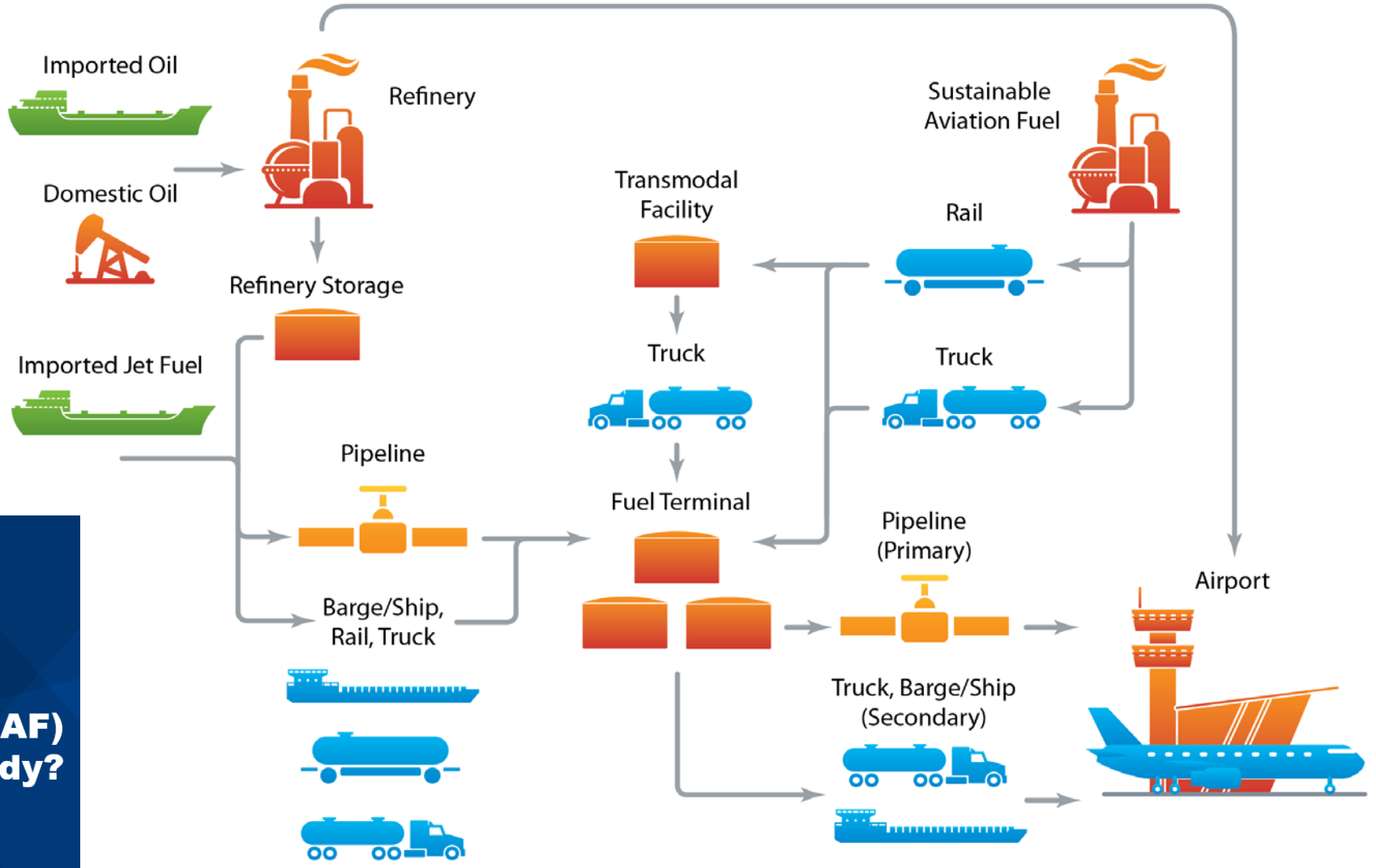
Starch Ethanol Retrospective Model

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

Preliminary graphic from related pending journal article with EPA

Scenario Analysis of Aviation Biofuel Deployment at Airports

Technical report provides airports with critical information on different infrastructure scenarios and potential biofuel integration, depending on infrastructure components and regulations.



2019 AIRPORTS @ WORK

Sustainable Aviation Fuel (SAF) – Is Your Infrastructure Ready?

Grand Ballroom A

https://www.nrel.gov/docs/fy21osti/78368.pdf

Systems Analysis Enhancing Integrated Assessment Modeling

BSM Scope / Results

- Production of Bioenergy in United States with Multiple Feedstocks, Pathways, and Incentive Options
- Biofuel Capacity Growth Dynamics
- Detailed Biofuel Conversion Technologies
- Bioenergy Logistics and Learning
- U.S. Bio Feedstock, Agricultural Production, and Land Use
- Transportation Sector Fuel Demands

Biofuel Conversion Pathway TEAs
Technology Dynamics and Logistics
Technology Learning and Costs

Energy, Fuel, Crop, and Carbon Prices
U.S. Crop Production/Demands/Yield
Multisector Bioenergy Demands

GCAM Scope/Results

- U.S. and Global, Multisector, Energy Production, Demands, and Prices
- International Energy Trade
- U.S. and Global Agricultural Production, Demand, and Prices
- International Agricultural Trade
- Commercial and other Land Uses
- Carbon Emissions from Energy and Land Use

Parallel Results for United States

- Bioenergy Production by Feedstock
- Bioenergy Crop Land Use
- Transportation Biofuel Demands
- Production by Conversion Pathways

Future Work: Regional Bioenergy and Economy Model

Goal

RBEM development will focus on an initial regional economic impact case study of the effects of sustainable aviation fuel, it will endeavor to ***complement R&D efforts*** by identifying potential barriers and opportunities within the supply chain and during end use, supporting effective industry development and ***enhancing FOAs***.

Inputs

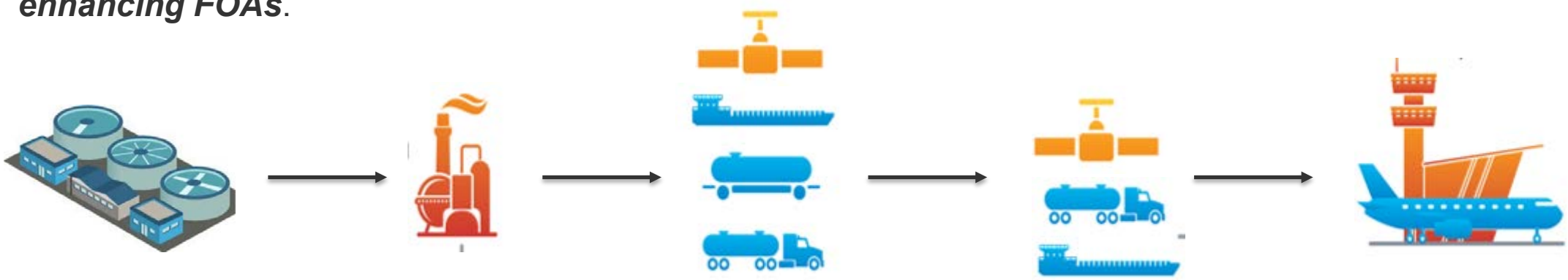
- Process techno-economics
- Oil/aviation fuel price scenarios
- Potential aviation fuel demand for the region
- Offtake agreement parameters

Outputs

- Industry maturity
- Fuel production/price
- Variability in fuel production
- Feedstock consumption/price
- Emissions
- Incremental effect of the investment on the economy of the region

Sample Questions

- What are regional differences in barriers to waste-to-jet development?
- What are the potential sensitivities of the elements included in offtake agreements or feedstock supply agreements?



Future Work: Carbon Dynamics Model

Carbon Dynamics Model development will focus on carbon utilization for production of methane and key chemical intermediates, within the broader context of the carbon cycle in the economy, especially agriculture.

Inputs

- Carbon price
- Carbon content
- Techno-economics for key technologies

Outputs

- Carbon utilization technology output
- Carbon sequestration amount
- Carbon emissions reductions

Sample Questions

- How can biofuels R&D maximize the potential co-benefits through carbon markets while we ensure the best use of resources (e.g., biomass, land, and water) for the bioeconomy (biopower, biofuels, biochemicals)?
- What are the implications of different policy approaches, prices of conventional fuels and carbon, and their timing for development and siting of technologies that differ in cost and effectiveness of carbon utilization?

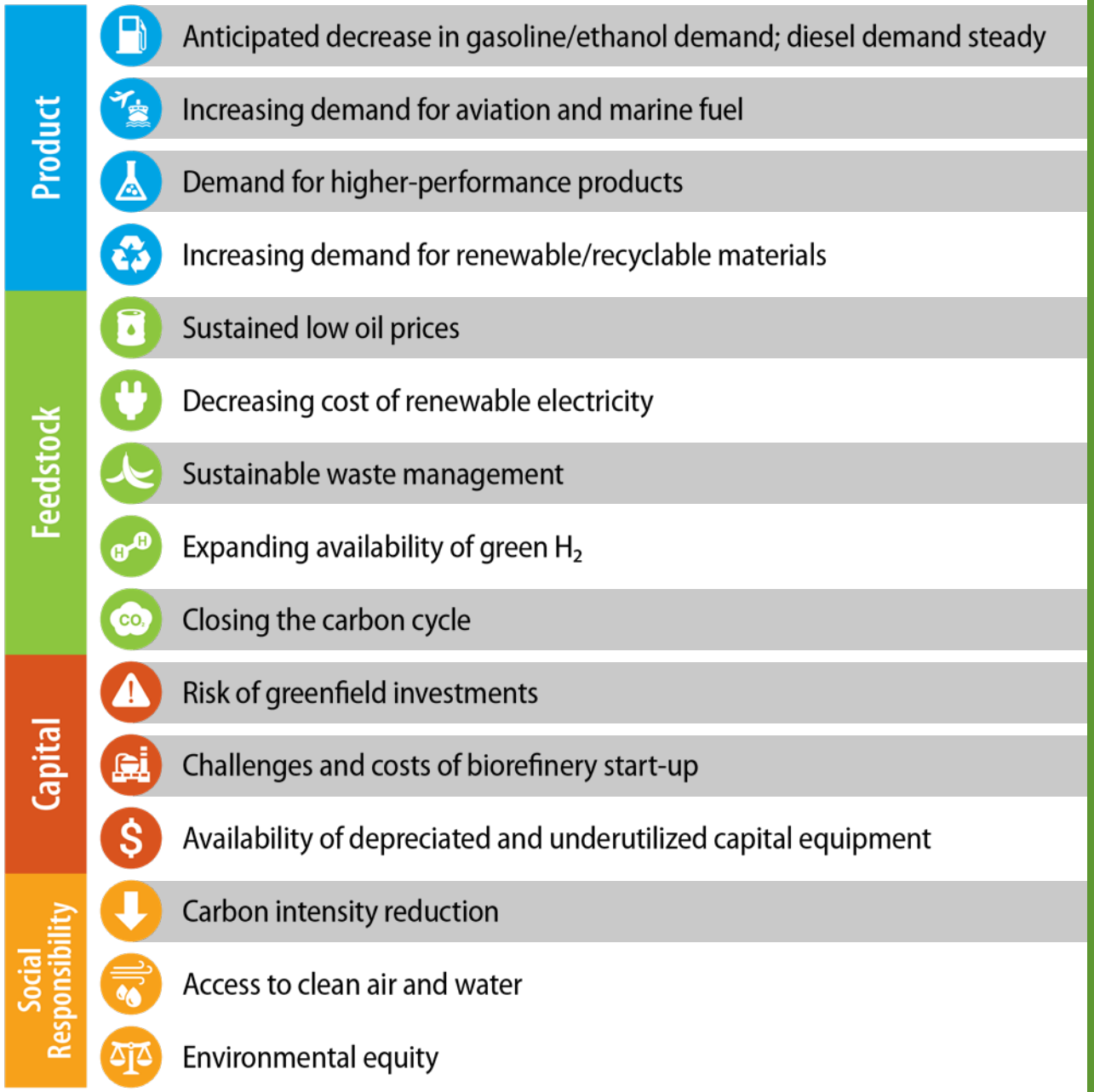
Summary of Accomplishments (2019–2021)

- **Impactful analyses**
  - Starch ethanol retrospective analysis for the Third Triennial Report to Congress
  - Industry request for policy analysis around sustainable aviation fuels
  - Explored potential impact of CORSIA framework
  - Airport infrastructure scenario analysis in coordination with ACI-NA and multiple airports
  - Collaboration with GCAM team to investigate policy implications on carbon emissions and the associated industry buildout
  - Analysis of the potential benefits of the BETO Program versus if no program existed
- **Publications**
  - Three published journal articles on BSM insights and system dynamics applications
  - Three pending journal articles on sensitivity analysis, data process, and starch ethanol industry retrospective
  - Published book chapter on system aspects of feedstock logistics
  - Published technical report on integrating biofuels into airport infrastructure

Summary of Accomplishments (2019–2021)

- **Model development to meet analysis needs**
  - Incorporated waste to HTL, updated MFSP calculation, and added exports
  - Established dynamic interaction with the ADOPT Heavy Duty model, allowing co-optimization of fuels (in the BSM) and engines (in ADOPT)
  - Improved accounting structure for infrastructure costs
  - Vehicle module update and calibration
  - Modifications for joint analysis with GCAM
  - Starch ethanol retrospective model design and execution
  - Created heavy-duty vehicle module
  - Updated techno-economics, feedstock logistics, and other data
  - Began 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 2019 Project Peer Review
  - ACI-NA meeting 2019
  - Invited to present at Industrial Energy-Related Energy Technologies and Systems, International Energy Agency Webinar in March 2021

Summary



NREL's bioenergy program is enabling a sustainable energy future by responding to key market needs

Value Proposition

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

Key Accomplishments

- Contribution to the EPA's Third Triennial Report to Congress
- Multiple collaborations on critical strategic topics: biofuels for aviation, bioeconomy for carbon mitigation, and benefits of BETO program
- Development of new models to explore emerging questions
- Many journal articles, presentations, posters, technical reports

Quad Chart Overview

Timeline

- Start: FY2018 (*See Note*)
- Merit review cycle: FY2021-2023

	FY20	Active Project
DOE Funding	$450,000	$1.35 million (FY21–23)

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

Barriers Addressed

- Analysis to Inform Strategic Direction [MYP At-A]
- Analytical Tools and Capabilities for System-Level Analysis [MYP At-B]
- Identifying New Market Opportunities for Bioenergy and Bioproducts [MYP At-D]

Project Goal

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

End of Project Milestone

Perform joint analysis with external collaborator using the Carbon System Model of the effects of bioenergy technology and product assumptions, carbon reduction goals, and carbon capture assumptions in determining carbon utilization; This will result in a draft conference paper, technical report, and/or journal article.

Funding Mechanism

FY2021 Lab Call: Data, Modeling, and Analysis

Thank You

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NREL/PR-6A20-79169

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Acronyms and Abbreviations

ACI-NA	Airports Council International - North America
ADOPT	Automotive Deployment Options Projection Tool
AGE	Air emissions, Greenhouse gases, and Energy consumption
ANL	Argonne National Laboratory
AWS	Amazon Web Services
BECCS	Bio-energy with carbon capture and storage
BEIOM	Bio-based circular carbon economy Environmentally extended Input-Output Model
BETO	Bioenergy Technologies Office
BSA	Bioeconomy Scenario Analysis
BSM	Biomass Scenario Model
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DOD	U.S. Department of Defense
DOE	U.S. Department of Energy
EPA	U.S. Environmental Protection Agency
FY	fiscal year
GCAM	Global Change Analysis Model
GHG	greenhouse gas
GREET	Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies
HEFA	hydroprocessed esters and fatty acids
HFTO	DOE Hydrogen and Fuel Cell Technologies Office
HTL	hydrothermal liquefaction
INL	Idaho National Laboratory
JEDI	Jobs and Economic Development Impact
LLNL	Lawrence Livermore National Laboratory
MFSP	minimum fuel-selling price
MIT	Massachusetts Institute of Technology
MYP	Multiyear Plan
MYPP	Multi-Year Program Plan
MTBE	Methyl tert-butyl ether
NREL	National Renewable Energy Laboratory
ORNL	Oak Ridge National Laboratory
PNNL	Pacific Northwest National Laboratory
POLYSYS	Policy Analysis System
ReEDS	Regional Energy Deployment System
RBEM	Regional Bioenergy and Economy Model
SD	system dynamics
SLiDE	Scalable Linked Dynamic Equilibrium Model
SQL	Structured Query Language
USDA	U.S. Department of Agriculture
VEETC	volumetric ethanol excise tax credit
VTO	Vehicle Technologies Office
WBS	work breakdown structure

Response to Reviewers' Comments 2017

Given the novelty, it's not clear to me that we can be confident in the assumptions in the cellulosics space—despite the fact that the model is very sensitive to those assumptions.

- We update the BSM on an annual basis and engage with experts in cellulosics to make sure the model is using the most up-to-date information.

The spatial scale of the BSM is still rather coarse, I'd like to see it go to the state scale or smaller eventually, many of the revenue and use issues are locally determined.

- We are developing the RBEM to be able to address more local-scale questions.

Given that the focus of A&S is analysis and sustainability, I'd like to see the BSM team venture more into the sustainability implications of different BSM scenario runs. Currently, they steer clear of many of the aspects relevant to A&S.

- We continue to develop relationships to other models (Bioeconomy AGE, BEIOM, JEDI) that focus on environmental and economic aspects.
- We have developed GHG estimates in the BSM-based on GREET carbon intensities.

Publications (2019-2021)

Journal Articles

Dunn, Jennifer B., Emily Newes, Hao Cai, Yimin Zhang, Aaron Brooker, Longwen Ou, Nicole Mundt, Arpit Bhatt, Steve Peterson, and Mary Biddy. 2020. "Energy, Economic, and Environmental Benefits Assessment of Co-Optimized Engines and Bio-Blendstocks." *Energy & Environmental Science* 13 (June 18, 2020). https://doi.org/10.1039/D0EE00716A.

Inman, Daniel, Brian Bush, Emily Newes, Corey Peck, and Steven Peterson. 2020. "A Technique for Generating Supply and Demand Curves from System Dynamics Models." *System Dynamics Review* 36 (3): 373–84. https://doi.org/10.1002/sdr.1663.

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Forthcoming

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Milestone/Deliverable History and Status

Period	Milestone/Deliverable	Status
FY19	Q1: Select one analysis question to explore for Q4 milestone.	Completed on schedule
	Q2: Provide briefing on at least two modeling options for completing the Q4 milestone.	Completed on schedule
	Q3: Document updates made to the BSM. This will serve as a living document that will accompany each public release.	Completed on schedule
	Q4: Complete analysis as defined in Q1 and document in a draft conference paper, technical report, and/or journal article.	Completed on schedule
FY20	Q1: Provide technical documentation on the Regional Bioenergy and Economy Model (RBEM).	Completed on schedule
	Q2: Briefing for annual update on cross-lab meetings, external engagements, current collaborations, and actual/potential outputs.	Completed on schedule
	Q3: Document updates made to the BSM. The document will serve as a living document that will be provided to the public with each public release.	Completed on schedule
	Q4: Complete analysis on the potential deployment of sustainable aviation fuel in the United States, including imports/exports, given the upcoming CORSIA scheme that will become binding in 2027.	Completed on schedule
FY21	Q1: Provide briefing on how the work being completed by the Ecosystem Services Working Group could be incorporated into BSA project models.	Completed on schedule
	Q2: Calibrate the Biomass Scenario Model (BSM) with the most current data on biodiesel and renewable diesel (HEFA) to be able to support updated diesel and jet fuel analyses with increased model fidelity. These updates will be included in a public release of BSM.	On schedule
	Q3: 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).	On schedule
	Q4: 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 waste-to-jet.	On schedule

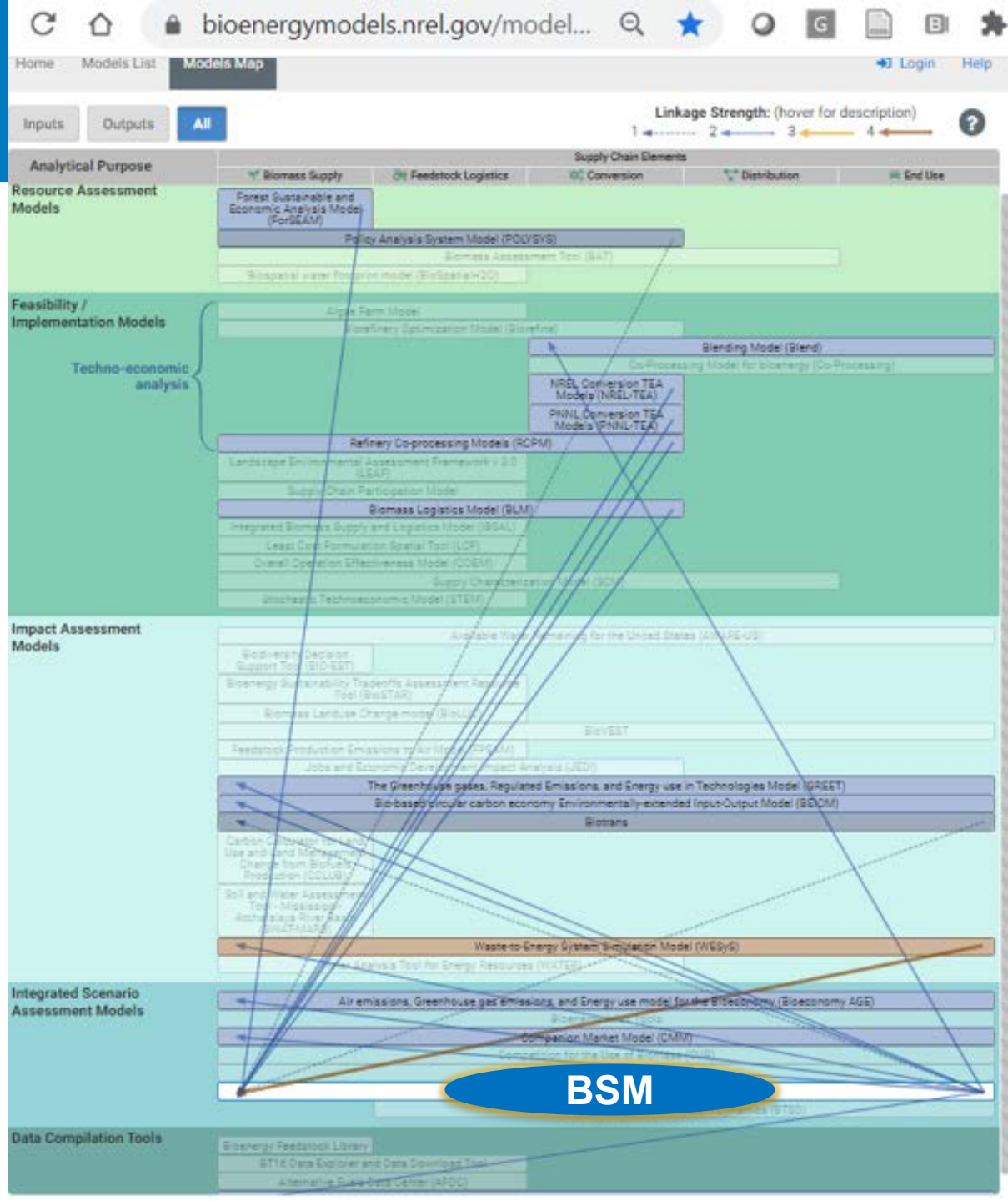
Management

Deep Connections with BETO Models

The BETO model mapping website shows BETO-funded models and tools and their interaction levels with one another.

The BSM (our flagship model) is well connected with other BETO-funded efforts.

bioenergymodels.nrel.gov/models/map



BSM Helps BETO Attain Goals and Objectives

Collaboration and stakeholder outreach helps expand these goals outside BETO.

Goals	BSA Support
BETO	
Enable sustainable, nationwide production of biofuels that are compatible with today's transportation infrastructure, can reduce greenhouse gas emissions relative to petroleum-derived fuels, and can displace a share of petroleum-derived fuels to reduce U.S. dependence on foreign oil. Encourage the **creation of a new domestic bioenergy** and bioproduct industry.	Allows BETO to explore the evolution of impacts due to bioenergy development by: • **Generating plausible scenarios** for bioenergy market penetration. • Understanding the dynamics of the transition to a bioeconomy. • Analyzing local effects of prospective policies, incentives, investments, R&D impacts, and strategies. • Identifying high-impact drivers, points of leverage, and bottlenecks.
Strategic Analysis	
Provide context and justification for decisions at all levels by establishing the basis of quantitative metrics, tracking progress toward goals, and informing portfolio planning and management.	Demonstrates the potential **impacts of different BETO strategic directions** and synergies.
Convey the results of analytical activities to a wide audience, including DOE management, Congress, the White House, industry, other researchers, other agencies, and the general public.	**Enables facilitation and collaboration for high-priority MOUs and multiagency efforts**
Develop and maintain analytical tools, models, methods, and datasets to **advance the understanding of bioenergy** and its related impacts.	Provides high Impact and reproducible analysis: • **Data infrastructure for study reproducibility** • Proven track record of team commitment to quality work.