NREL
Transforming ENERGY

4.2.1.31 Integrated Life Cycle Sustainability Analysis

March 11, 2021
Data, Modeling & Analysis
Dr. Patrick Lamers
National Renewable Energy Laboratory

Project Overview

Goal

Develop a coherent methodology and consistent model framework to quantify the net effects of an expanding US bioeconomy.

Inform BETO's strategic decision making.

Outcome

Economy-wide assessment of environmental and socio-economic **effects** of individual BETO pathways or **portfolios** thereof **at industry-scale**.

Scientific input to multilateral activities that assess bioeconomy effects.

Relevance

BETO

Complementary

Federal level

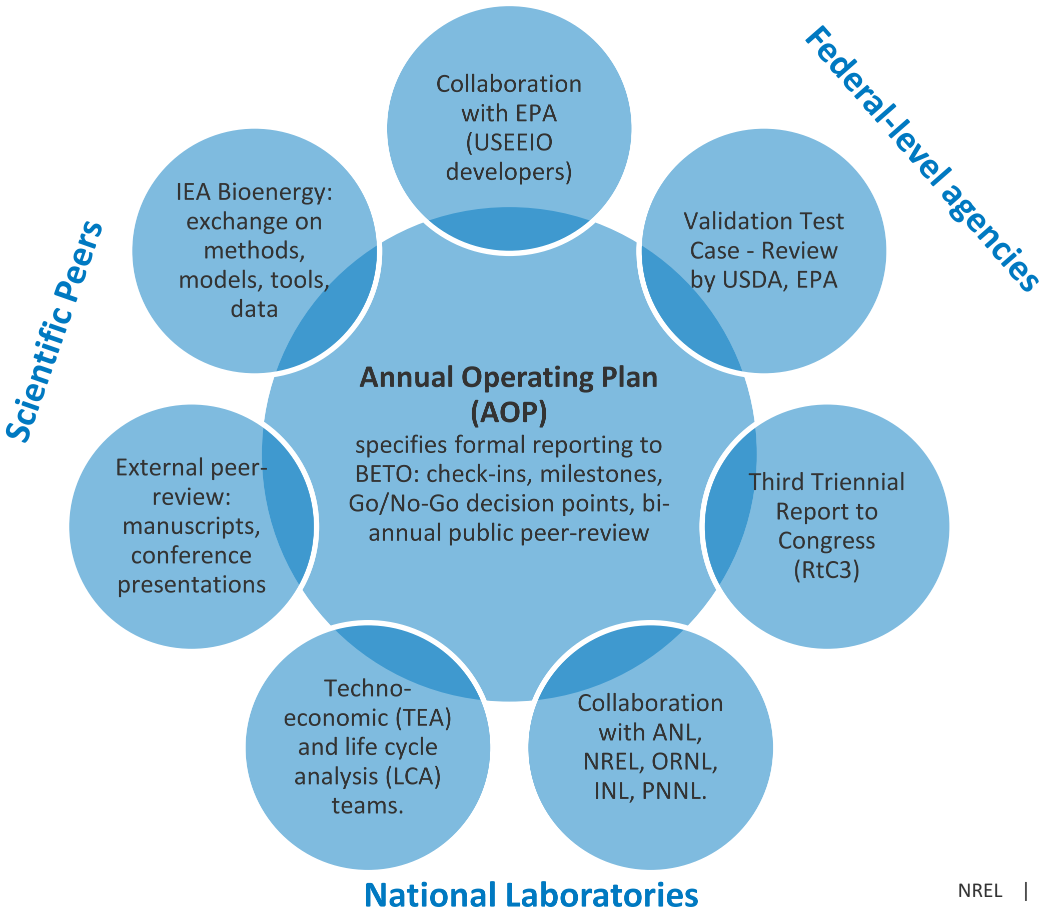
IEA Bioenergy

Technology Collaboration Programme

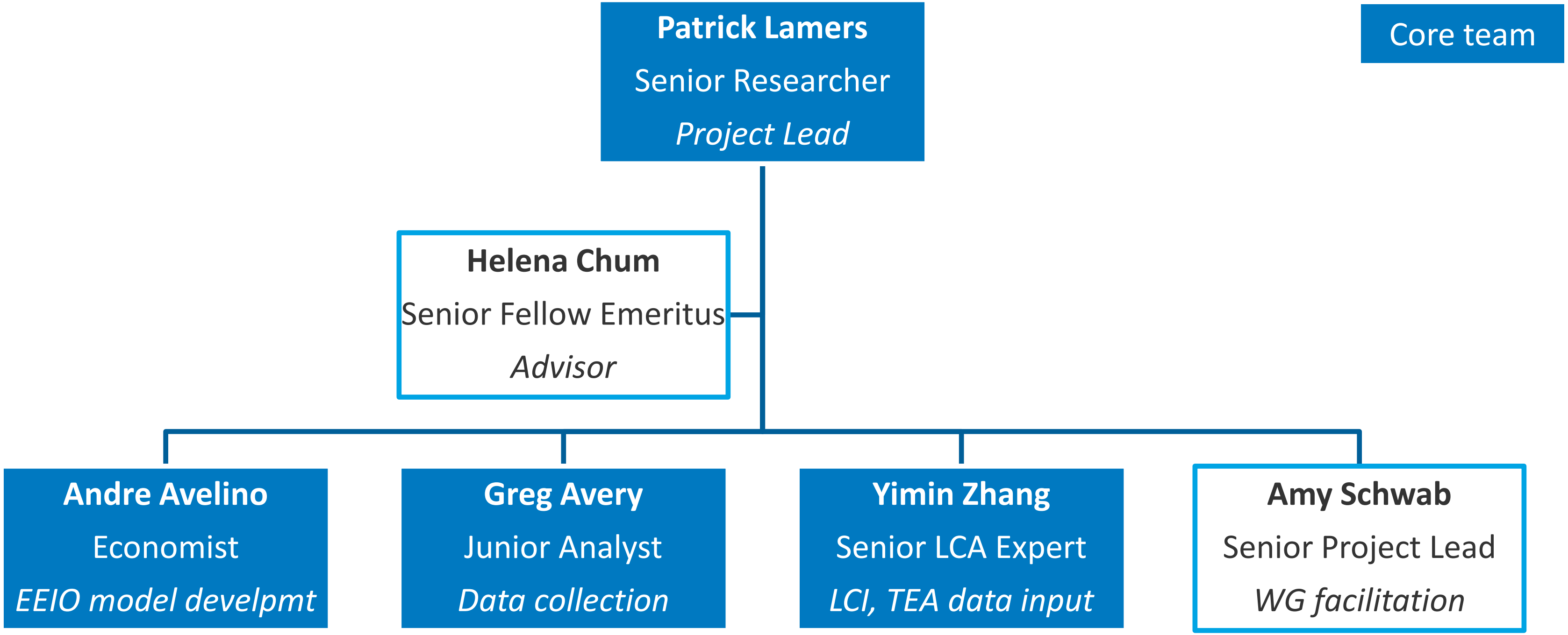
Working Group

1. Management: Plan and Implementation Strategy

- **Annual Operating Plan** (AOP): agreement with BETO that defines objectives, tasks, milestones, monitoring and reporting requirements.
- **Leveraging existing efforts**, e.g., the U.S. Environmentally-Extended Input-Output (USEEIO) model development at EPA.
- **Active outreach** to federal agencies (e.g., EPA, USDA as part of the RtC3) and national lab collaborators to validate data inputs, methods, and results.
- **Step-wise model build-out** and review by scientific peers via manuscript and conference submissions.
- **Planned activity meetings** or workshops (IEA Bioenergy).
- **Facilitation and coordination** of the Working Group on Sustainable Land Management (input to IEA Bioenergy).



1. Management: Project Team – roles and expertise

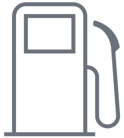


EEIO: Environmentally-Extended Input-Output
LCA: Life Cycle Assessment
LCI: Life Cycle Inventory
TEA: Techno-Economic Analysis
WG: Working Group (on Sustainable Land Management)

1. Management: Risks & Mitigation Strategies

Key challenge: The bioeconomy overlaps many economic sectors. Thus, measurements of its effects are confounded by differences in methodologies and definitions (boundaries).

- Life cycle-based EEIO framework covering the whole US economy.
- Eliminates cut-off points and allows methodological consistency across metrics.



Risk Identification

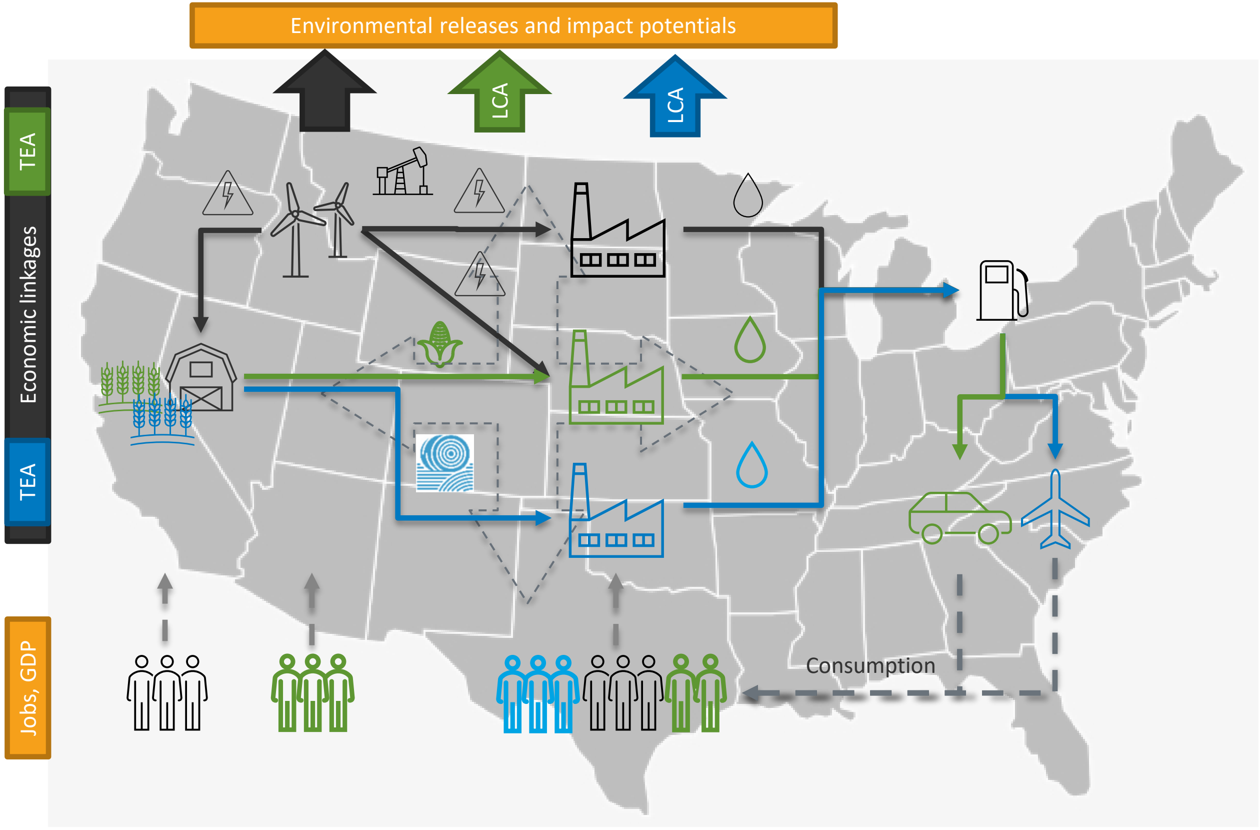
– Complexity: integrating new bioeconomy products in established industry-commodity relationships (US economy),
– Data intensity: economic and life cycle inventory data required,
– Data heterogeneity: creation of time-series requires harmonization to create coherency,
– Results not verifiable by measurement (at the level of aggregation),
– Confidence in results.

Mitigation Strategies

✓ Stepwise build-out (by pathway),
✓ Structured, continued reviews from practitioners to validate the method development and results for additional pathways,
✓ Collaboration with EEIO, TEA and LCA practitioners on method and data,
✓ Linking to existing efforts at federal level,
✓ Follow Federal LCA Commons standards: ensure data transfer and reproducibility.

2. Approach: Model framework

- **Established methodology** to assess impacts of products, businesses (e.g., Amazon), etc.
- **Uses national-level datasets** from US federal agencies (e.g., BEA, EPA, USDA, USGS), and
- **Process-level TEA and LCA**,
- Traces structural changes in the economy, and **analyzes sector interactions**,
- Has **no system cut-offs** (within US economic boundaries),
- Includes **feedback effects** (e.g., consumption within the industry or its supply chain),
- Calculates **impacts on industry-scale** for individual products or **portfolios** thereof.

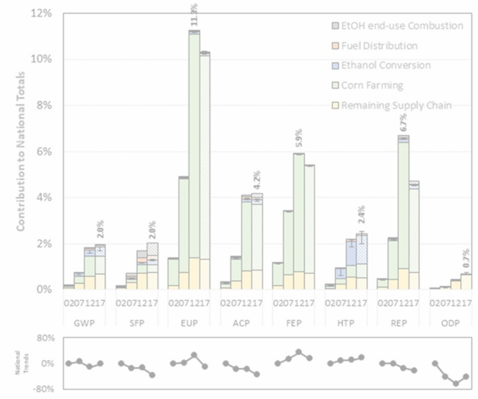


Legend
- US Economy
- US Bioeconomy (current): retrospective, historic trend analysis
- US Bioeconomy (emerging): prospective, scenario analysis

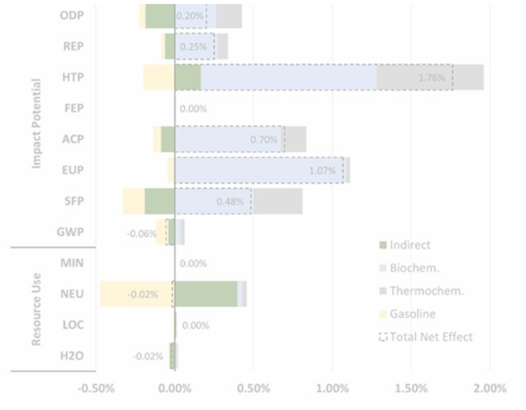
2. Approach: Model capabilities

Analyses

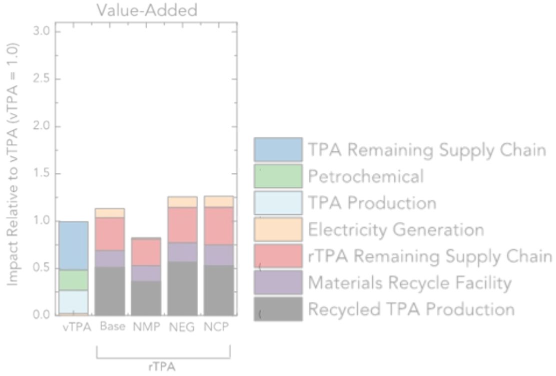
Technology evolution



Portfolio/scenario net effects

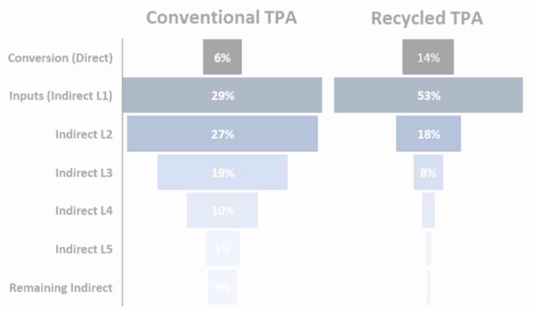


Emerging pathways at-scale

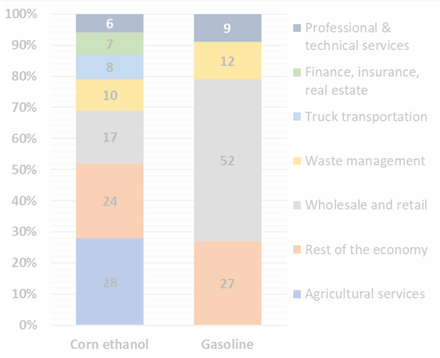


Output details

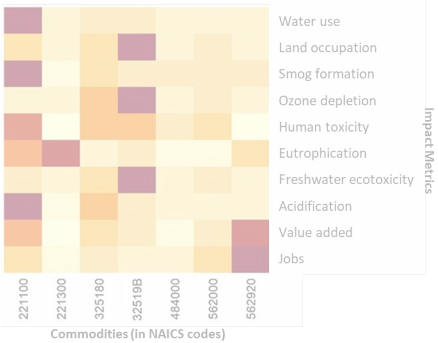
Direct *vs.* indirect effects



Contributions per sector



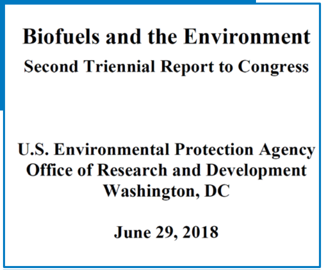
Contributions per commodity



3. Impact: Federal-level decision making

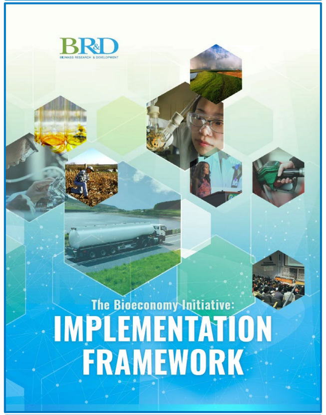
- **Supports Congressional and agency level strategic decision making**
  - EPA's *Third Triennial Report to Congress* (RtC3) on the environmental effects of the Renewable Fuel Standard (RFS2),
  - Biomass R&D Board *Bioeconomy Initiative Implementation Framework:* need for macroeconomic analyses of the entire bioeconomy to allow adequate evaluation of its benefits and tradeoffs,
  - Intra- and interagency discussion on methods, metrics, tools to quantify the impacts of the (US) bioeconomy (e.g., USDA, DOE, IEA Bioenergy).

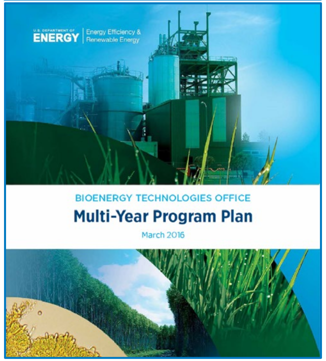
- **Supports BETO goals and Multi-Year Plan (MYP) objectives**
  - By 2019, complete a framework to support multidimensional analyses on specific economic, environmental, and other benefits of an expanding bioeconomy.
  - By 2025, understand and quantify environmental, economic, and social effects associated with emerging biofuel and bioproduct technology pathways and identify R&D needs to enhance benefits, reduce risk, and enable BETO's 2030 performance goal.
  - Addresses several BETO Program Barriers (e.g., At-E: Quantification of Economic, Environmental, and Other Benefits and Costs)


Biofuels and the Environment
Second Triennial Report to Congress

U.S. Environmental Protection Agency
Office of Research and Development
Washington, DC

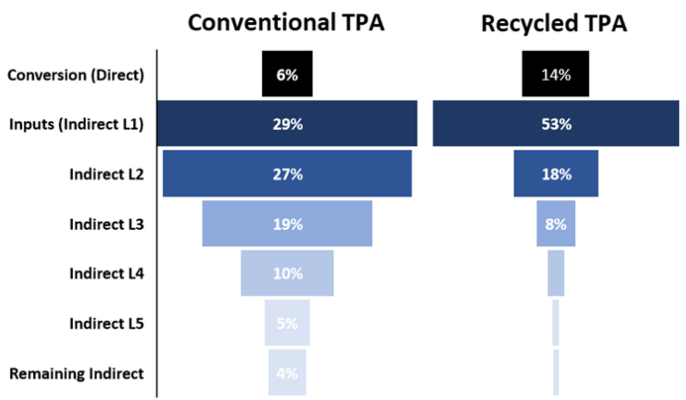
June 29, 2018

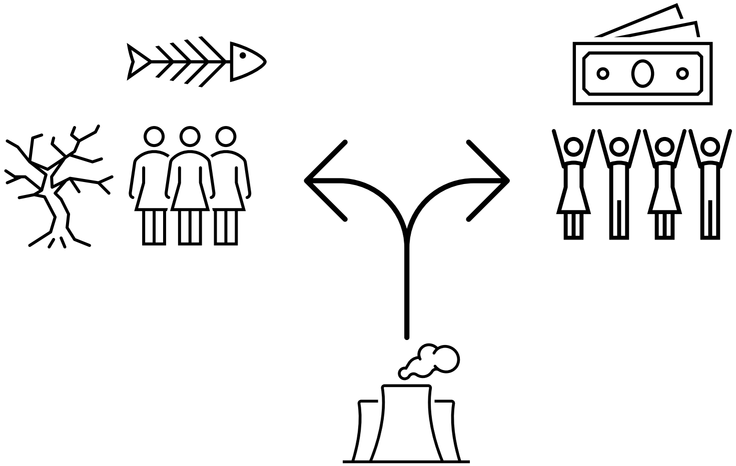




3. Impact: Social and environmental equity

- **Transitioning** towards a bioeconomy will involve **urban and rural communities**.
- Expanding the bioeconomy will involve **investment decisions.**
- **Geographical tradeoff** analysis can benefit regional and federal level decision making:
  - E.g., particulate matter emissions from farming are largely rural while air quality benefits from ethanol are mainly urban.
  - E.g., socio-economic benefits are not distributed equally along the supply chains for all technologies.
- Framework can inform **social and environmental equity** decision making.

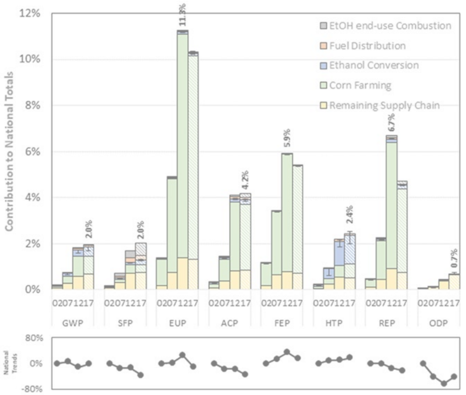




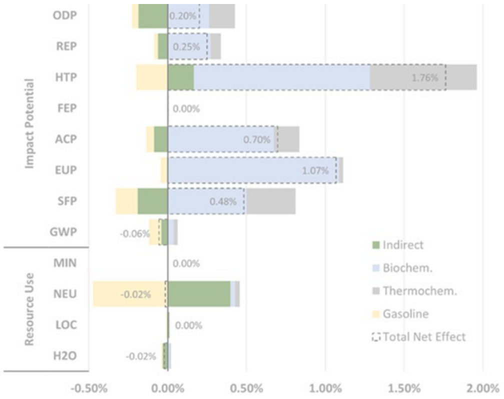
4. Progress & Outcome

Analyses

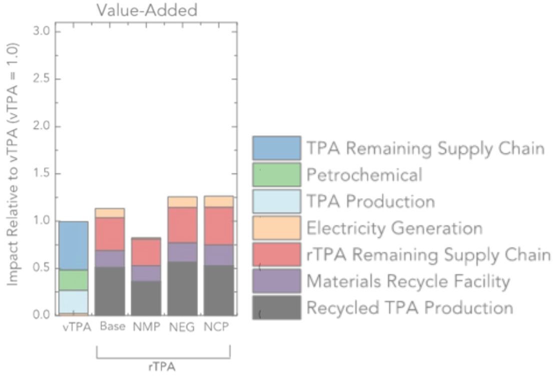
(Bio)Economy, RtC3



Biofuel portfolio net effects

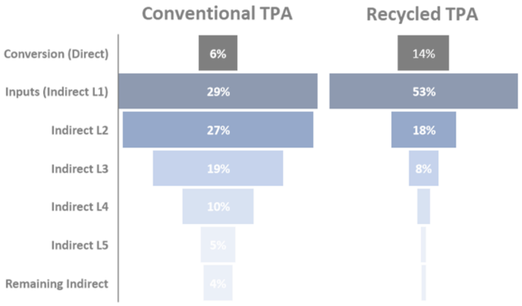


Plastics upcycling

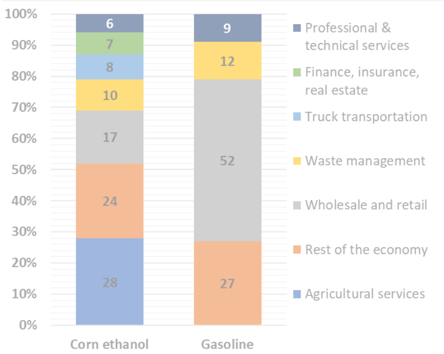


Output details

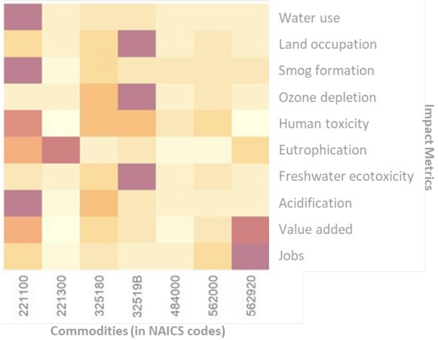
Example: jobs - bioplastics



Example: jobs - biofuels



Example: various - bioplastics



Time-series: Evolution of the US (bio)economy

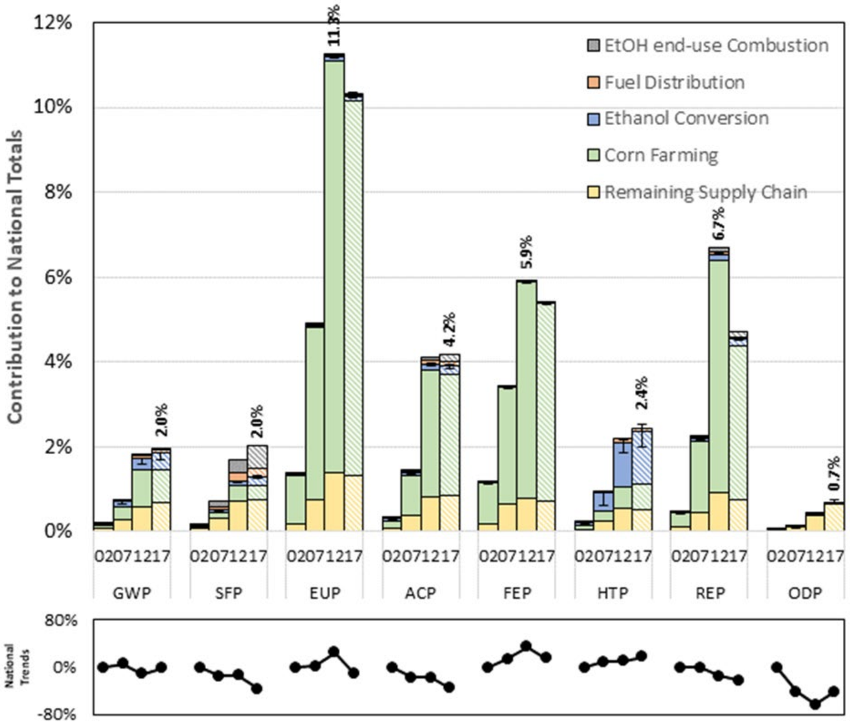
Creation of a novel time-series of harmonized economic and environmental datasets shows the evolution of technologies and structural changes in the US (bio)economy.

Results: *Economy*: Decline in resource intensity and environmental effects (per $GDP) except freshwater ecotoxicity and human toxicity potentials (which increased).

Bioeconomy: Expanding corn ethanol production increases total effects but effects per energy unit generally decline (maturation, scaling, etc.).

Establishment of the Bio-based circular carbon economy Environmentally-extended Input-Output Model (*BEIOM*).

Avelino *et al*. (in review). *Journal of Cleaner Production*



EtOH: Ethanol
GWP: Global warming potential
SFP: Smog formation potential
EUP: Eutrophication potential
ACP: Acidification potential
FEP: Freshwater ecotoxicity potential
HTP: Human toxicity potential
REP: Respiratory effects potential
ODP: Ozone depletion potential
GDP: Gross domestic product

Input to EPA's Third Triennial Report to Congress (RtC3)

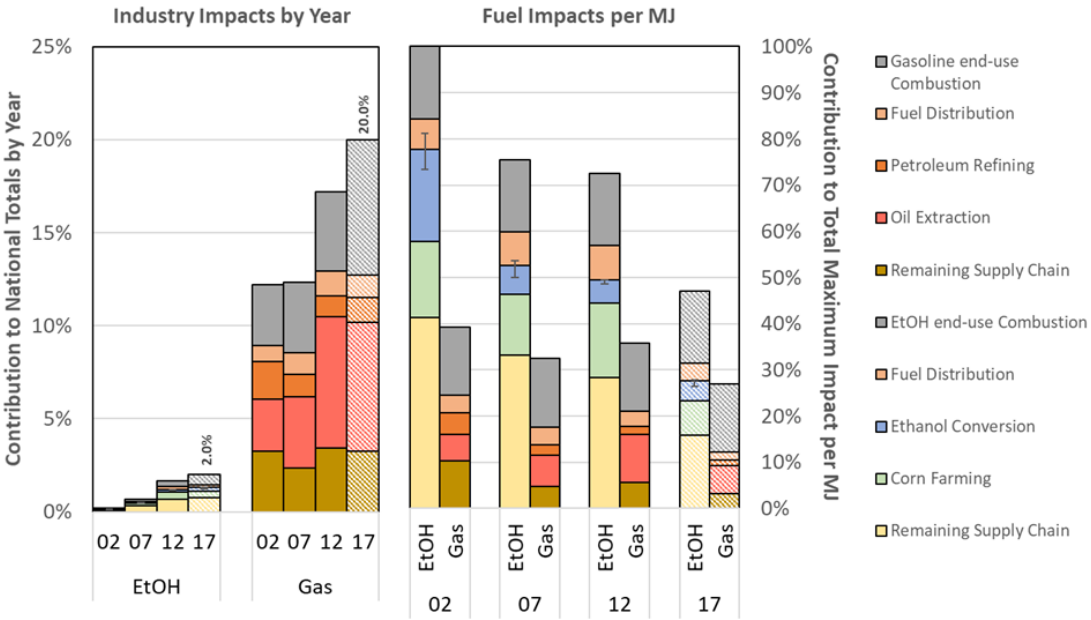
Historic well-to-wheel analysis of US corn ethanol and soybean biodiesel as input to the RtC3 on the effects of the Renewable Fuel Standard (RFS2).

Input to Air Quality, Water Quality, and Water Availability Chapters, plus Synthesis and Executive Summary.

Comparison against incumbent fuels (gasoline, diesel) and detailed across supply chain steps.

Several **briefings** to EPA, USDA, DOE.

Continuation to RtC4 expected.



Graphic: Industry level (left) and MJ impacts (right).
Metric: Smog formation potential [kg O_{3eq}]
Fuels: Corn ethanol (EtOH), gasoline (Gas)
Time series: 2002, 2007, 2012, 2017

Economy-wide net effects of biofuel portfolios

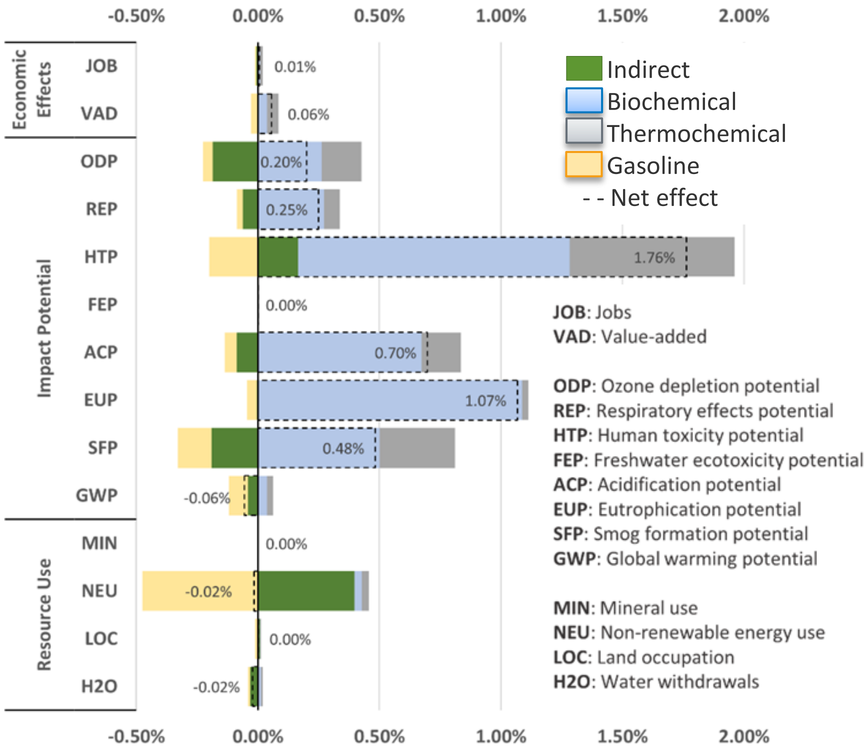
BEIOM can evaluate the net effects of bioeconomy scenarios as biofuel or -product portfolios replacing incumbent technologies.

- It presently uses existing inter-industrial linkages (static US economy context),
- Dynamic inter-industrial linkages (prospective capability) under development.

Case study: Energy Independence and Security Act (EISA) prescribed second generation biofuel production levels (in addition to corn ethanol).

Results: Socio-economic net benefits. Net increases in environmental effects except GWP. Net reductions in energy and water use.

Lamers *et al*. (in print). *Environmental Science and Technology*



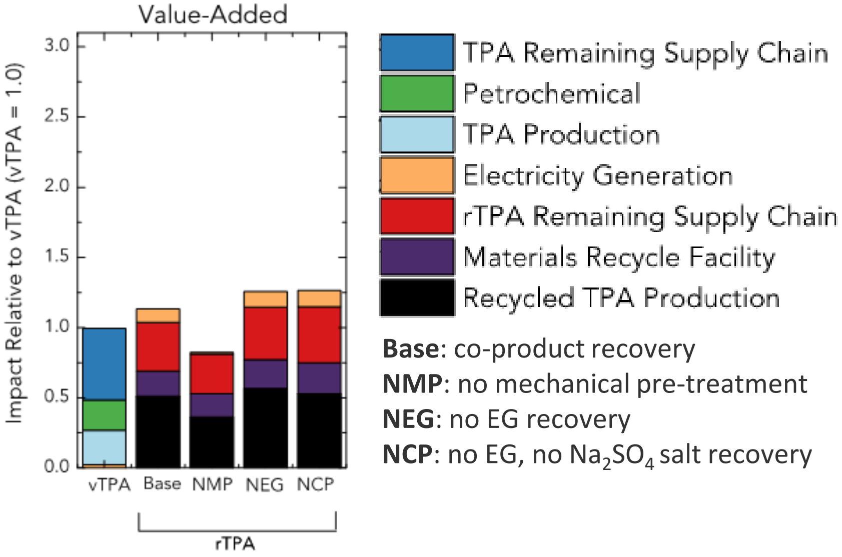
Net effects as percent change from a baseline (gasoline) to a hypothetical bioeconomy scenario (containing biochemical and thermochemical ethanol) across 14 metrics.

Emerging pathway analysis: plastics upcycling

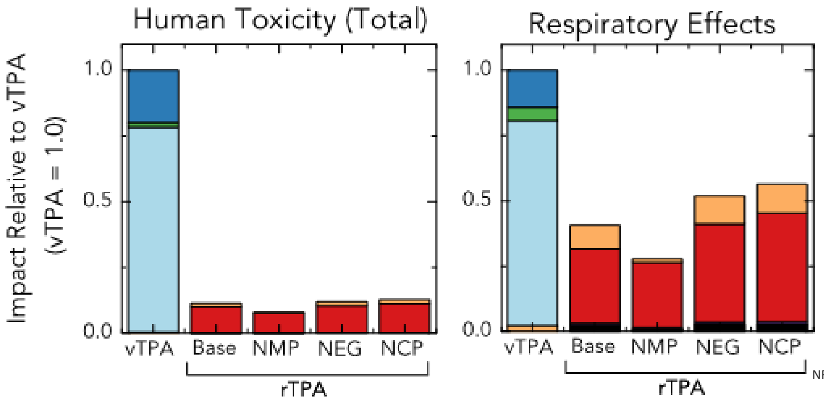
Evaluating R&D-level technologies at-scale shows potential sustainability tradeoffs, which can inform process design alterations.*

Case study: Evaluation of terephthalic acid (TPA) production from virgin (vTPA) or recycled (rTPA) material including co-product recovery of ethylene glycol (EG) and/or sodium sulfate salts.

Results: rTPA provides socio-economic benefits and reduces environmental effects compared to vTPA. Water use increases for rTPA except in the NMP process design. Co-product recovery generally reduces environmental effects.



Base: co-product recovery
NMP: no mechanical pre-treatment
NEG: no EG recovery
NCP: no EG, no Na_2SO_4 salt recovery



Singh *et al.* (in review). *Joule*

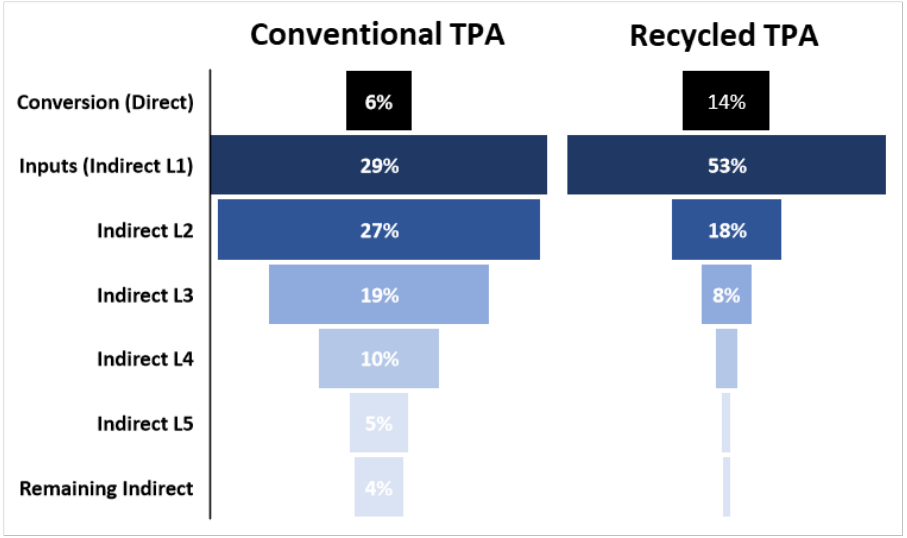
* Capability to support the 2025 MYP objective.

Direct vs. indirect effect distributions

Supply chain tier analysis specifies *where* the effects are 'located' along the supply chain, i.e., within the facility, its direct supply chain (regional), or the broader economy.

Example: recycled terephthalic acid (rTPA).

Results: *Employment* benefits for *rTPA* occur mainly in the *facility itself* and its *direct suppliers*, e.g., material recovery facilities, whereas *virgin TPA* effects occur largely in the *broader economy* and are thus not necessarily regional.



Distribution of employment effects per kg of virgin or recycled terephthalic acid (TPA) by supply chain tier (spending round) in the US economy.

Direct effects: direct effects from TPA facilities
Indirect effects: L1 are those related to the first round of input purchases (e.g., p-Xylene, PET flakes) from material recovery facilities, L2 effects are related to inputs to L1, etc.

Singh *et al*. (in review). *Joule*
Lamers *et al*. (in print). *Environmental Science and Technology*

Effect contributions per economic sector

The total (direct and indirect) effect contributions can be distinguished per sector of the US economy for a specific metric-product-year combination.

Example: *Employment* contributions per MJ of corn ethanol *vs*. gasoline (2017).

Results: *Gasoline* benefits are mainly in retail sectors, i.e., *fuel distribution.*
Corn ethanol benefits *agricultural service* sectors the most.

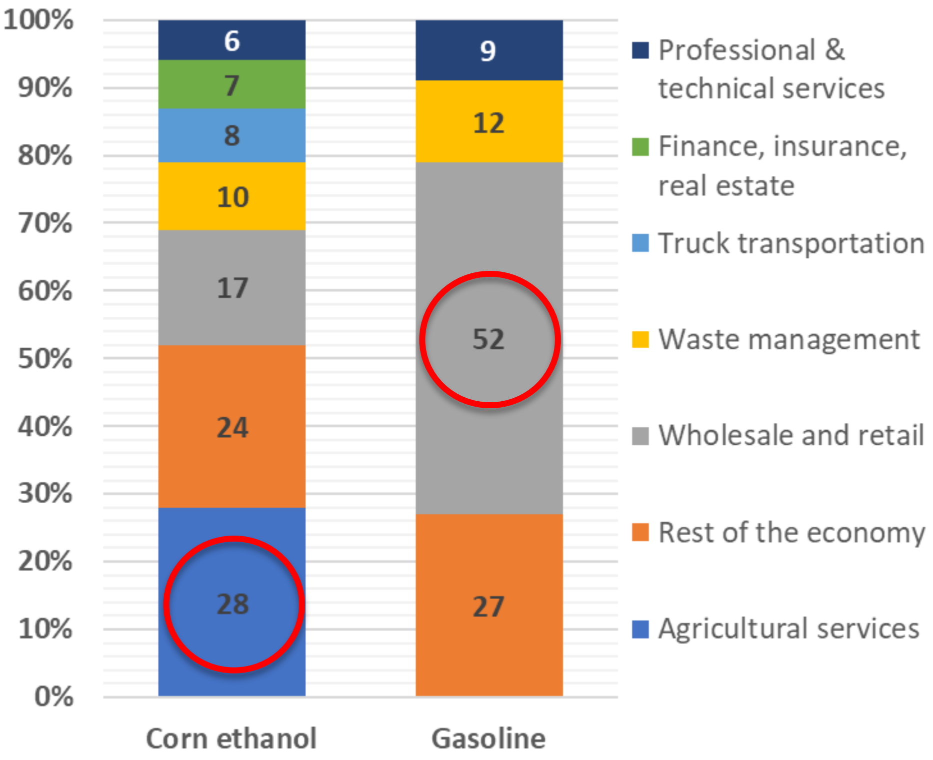


Figure. Sectoral contribution to employment.
Note: "Rest of the economy" encompasses all other sectors whose contribution is less than 5%.

Lamers *et al*. (in print). *Environmental Science and Technology*

Effect contributions per commodity inputs

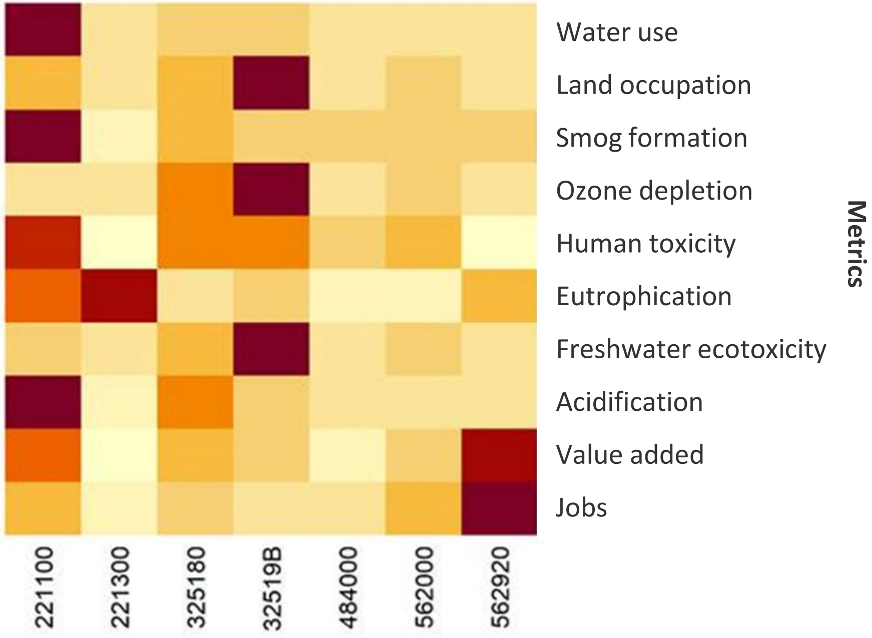
A Field of Influence Analysis shows which commodity inputs drive the effects of the product or portfolio per metric.

Example: recycled terephthalic acid (rTPA).

Results: Most of the *environmental* effects are sensitive to *electricity consumption* (NAICS: 221100).

Socio-economic effects (jobs and value added) are sensitive to the set-up of *material recovery facilities* (NAICS: 562920).

Darker colors indicate higher influence



Commodities (in NAICS codes)

221100 - Electric power generation, transmission, and distribution
221300 - Water, sewage and other systems
325180 - Other basic inorganic chemical manufacturing
32519B - Other basic organic chemical manufacturing
484000 - Truck transportation
562000 - Waste management and remediation services
562920 - Materials recovery facilities

NAICS: North American Industry Classification Standard

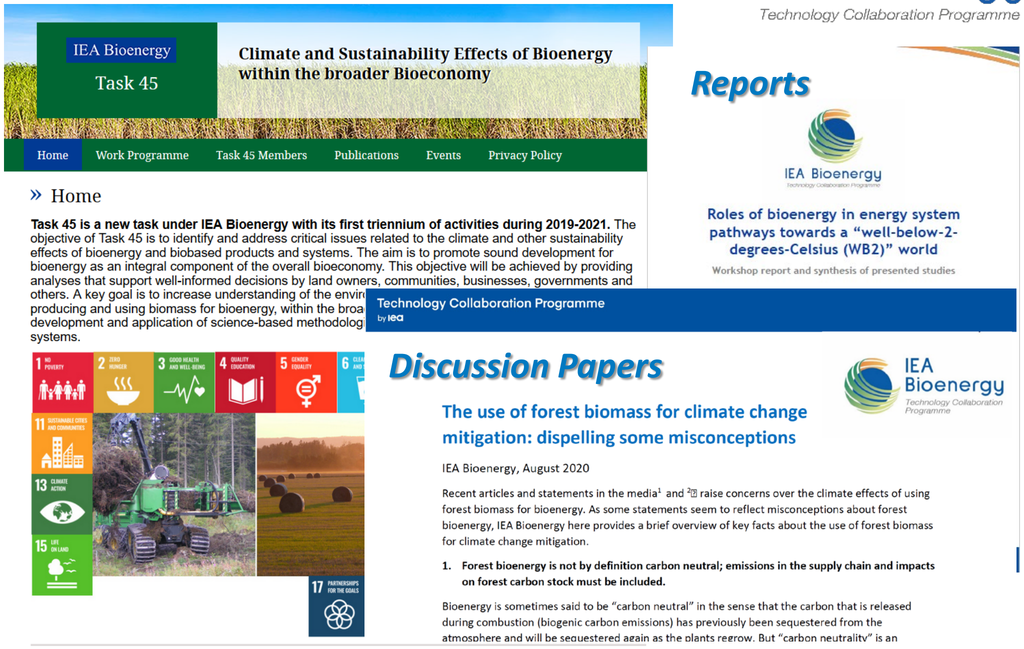
Singh *et al*. (in review). *Joule*

Engaging in and synthesizing key multilateral activities

IEA Bioenergy
Technology Collaboration Programme

- NREL and BETO function as **US leads for** IEA Bioenergy Task 45 (**Sustainability**).
- Multilateral engagement to compare metrics, methods, and tools to quantify sustainability effects and **ensure the sound development of the bioeconomy**.
- **Comparative studies, joint outreach activities:** 7 scientific papers since 2019, 2 workshops (limited due to COVID-19).
- **NREL provides scientific expertise and coordinates national lab involvement**, e.g.: LCA comparison (ANL), Trade-offs and synergies from energy cropping systems (ANL, ORNL, INL, PNNL),
- NREL leads a BETO **Working Group** on Sustainable Land Management (ecosystem service inclusion in top-down models).

https://task45.ieabioenergy.com



Outreach events: Workshops, conference sessions

» IEA Bioenergy T45 WS 13-14 May 2020

IEA Bioenergy Task 45 workshop on forests and the climate, 13-14 May 2020 on Zoom

Summary

1. Management

- **Step-wise model build-out** and review through **active outreach** to federal agencies and national laboratories,
- **Planned activity meetings** in multilateral initiatives and **formalized reporting** to BETO.

2. Approach

- **Economy-wide** framework using a **vetted methodology** and official federal datasets in conjunction with
- **Complementary process-level TEA and LCA** to calculate product and **portfolio effects at industry-scale**.

3. Impact

- **Federal level** decision support: **US Congress** (RtC3), federal agencies & initiatives (Biomass R&D Board),
- **Regional** decision support: **social and environmental equity tradeoffs** for US bioeconomy expansion scenarios.

4. Progress & Outcome

- BEIOM: **Methodological advancements** and **impact analyses for multiple pathways** (**3 scientific papers**),
- IEA Bioenergy: comparative studies & joint outreach activities (**7 scientific papers** & **2 workshops** since 2019),
- Working Group: National laboratory collaboration to **advance** top-down/bottom-up **sustainability analyses**.

Thank you

www.nrel.gov

PR-6A20-79185

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Transforming ENERGY

Quad Chart Overview

Timeline

- Start date 10/01/2017
- Active project period: 10/01/2019 - 09/30/2022

	FY20	Active Project
DOE Funding	$400,000	$1,200,000

Project Partners (in-kind)

- Environmental Protection Agency (EPA),
- International collaborators (IEA Bioenergy Task 45),
- National laboratories: ANL, INL, ORNL, PNNL.

Barriers addressed

At-E: Quantification of Economic, Environmental, and Other Benefits and Costs

At-A: Analysis to Inform Strategic Direction

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

Project Goals

- Develop a model framework to consistently assess the environmental and socio-economic effects of an expanding US bioeconomy.
- Inform BETO's strategic decision making by engaging in, evaluating, and synthesizing selected global, multilateral activities that develop, compare, or apply metrics, methods, and tools to quantify sustainability effects of specific bioeconomy products.

End of Project Milestone

Delivery of a state-of-the-art environmentally-extended input-output model capable of determining the net effects of an expanding US bioeconomy across multiple economic and environmental dimensions. Application of the model to US bioeconomy projections relevant to strategic BETO needs. Submission of a draft manuscript to BETO (for publication approval).

Funding Mechanism

AOP

Additional Slides

Responses to Previous Reviewers' Comments

- Overall, this is a unique project among the other BETO projects we've reviewed, and offers value in improving harmonization and capturing of indirect impacts related to the sustainability of bioenergy.
- Weakness: What is the "gap in BETO sustainability efforts" identified through peer review and international efforts? Is it being filled here?
  The "gap identified" related to previous BETO Peer Review comments from the panel that stated BETO would benefit from an integrated sustainability analysis framework. This project specifically addresses this gap.
- Weakness: I would like to have seen the PIs commit to examining the other major biofuel in the U.S. (soy biodiesel), that is a significant shortcoming.
  Following the peer-review the team discussed this extension with DOE and EPA and was able to expand the modeling to include soybean biodiesel. The respective results are now included in EPA's RtC3.
- Weakness: Interesting results on some parameters, though I am not convinced that all evaluated criteria are as easily addressed or that this can be done at a similar rigor in the remaining year. Similarly, corn ethanol test case has been studied extensively. Can this be done for more obscure bioeconomy pathways?
  The model and its pathway analyses have since been reviewed by external scientific peer-reviewers, and additional efforts undertaken to align and harmonize input data sources (a related submission is presently with the Journal of Cleaner Production). Further, since the peer-review, multiple additional pathways beyond corn ethanol have been included in the model and a respective journal paper published showcasing the framework's capability to assess the net effects of a hypothetical bioeconomy (in a static context).

Publications, Patents, Presentations, Awards, and Commercialization

Lamers, P., A. Avelino, Y. Zhang, E. Tan, B. Young, J. Vendries and H. Chum (accepted). "The potential socio-economic and environmental effects of an expanding US bioeconomy: an assessment of near-commercial cellulosic biofuel pathways." Environmental Science & Technology.

Avelino, A., P. Lamers, Y. Zhang and H. Chum (submitted). "Using a harmonized time series of environmentally-extended input-output tables to evaluate the effects of an expanding US bioeconomy." Journal of Cleaner Production.

Singh, A., N. A. Rorrer, S. R. Nicholson, E. Erickson, J. DesVeaux, A. F. T. Avelino, P. Lamers, A. Bhatt, Y. Zhang, C. Wu, G. Avery, L. Tao, A. R. Pickford, J. E. McGeehan, A. C. Carpenter and G. T. Beckham (submitted). "Analysis of the enzymatic recycling of poly(ethylene terephthalate)." Joule.

Contributions to the Third Triennial Report to Congress (RtC3) on the impacts of the Renewable Fuel Standard (RFS2): Chapters 8 (Air Quality), 10 (Water Quality), 11 (Water Availability), 17 (Synthesis), Executive Summary.

IEA Bioenergy related publications

IEA Bioenergy
Technology Collaboration Programme

Peer-reviewed articles since 2019

Prisley, S. *et al.* Comment on Sterman, et al. (2018) “Does replacing coal with wood lower CO2 emissions? Dynamic lifecycle analysis of wood bioenergy”. *Environmental Research Letters*, (2018).

Roni, M. S., Lamers, P. & Hoefnagels, R. Analyzing the Potential Resource Distribution in Global Competitive Feedstock Markets for Industrial Grade Wood Pellets. *Biofuels*, (2018).

Junginger, H. M. *et al.* The future of biomass and bioenergy deployment and trade: a synthesis of 15 years IEA Bioenergy Task 40 on sustainable bioenergy trade. *Biofuels Bioprod Bior* **13**, 247-266, (2019).

Thrän, D. *et al.* The dynamics of the global wood pellet markets and trade – key regions, developments and impact factors. *Biofuels Bioprod Bior* **13**, 267-280, (2019).

Daioglou, V. *et al.* Implications of climate change mitigation strategies on international bioenergy trade. *Clim. Change*, (2020).

Schipfer, F., Kranzl, L., Olsson, O. & Lamers, P. The European wood pellets for heating market - Price developments, trade and market efficiency. *Energy* **212**, 118636, (2020).

Schipfer, F., Kranzl, L., Olsson, O. & Lamers, P. European residential wood pellet trade and prices dataset. *Data in Brief* **32**, 106254, (2020).

Most recent submission: 29 authors across 24 institutions and 14 countries

Cowie, A., G. Berndes, N. Bentsen, M. Brandão, F. Cherubini, G. Egnell, B. George, L. Gustavsson, M. Hanewinkel, Z. Harris, F. Johnsson, H. Junginger, K. Kline, K. Koponen, J. Koppejan, F. Kraxner, P. Lamers, S. Majer, E. Marland, R. Monaghan, G. Nabuurs, L. Pelkmans, R. Sathre, M. Schaub, C. Smith, S. Soimakallio, F. V. D. Hilst, J. Woods and F. Ximenes (submitted). "Applying a science-based systems perspective to dispel misconceptions about forest bioenergy." *GCB Bioenergy*.

Historical perspective

By 2019, complete a framework to support multidimensional analyses on specific economic, environmental, and other benefits of an expanding bioeconomy.

FY18

- Practitioner workshop (scope)
- Prototype (based on USEEIO)
- Test case (corn ethanol)
- <u>**Go**</u>/No-Go Decision Point (Q4)

FY19

- External review of the test case
- Harmonization of economic and environmental datasets
- Extension with several 'near-commercial' pathways
- **2019 MYP objective**

FY20

- Compilation of **three manuscripts** for external peer-review: methodology, bioeconomy, plastics upcycling.
- Contribution to the **Third Triennial Report to Congress.**

FY21

- Model extension to *prospective* analysis capability: **Go/No-Go Decision Point** 3/21.
- Bioeconomy scenario analyses (**external review** via manuscript).

FY22

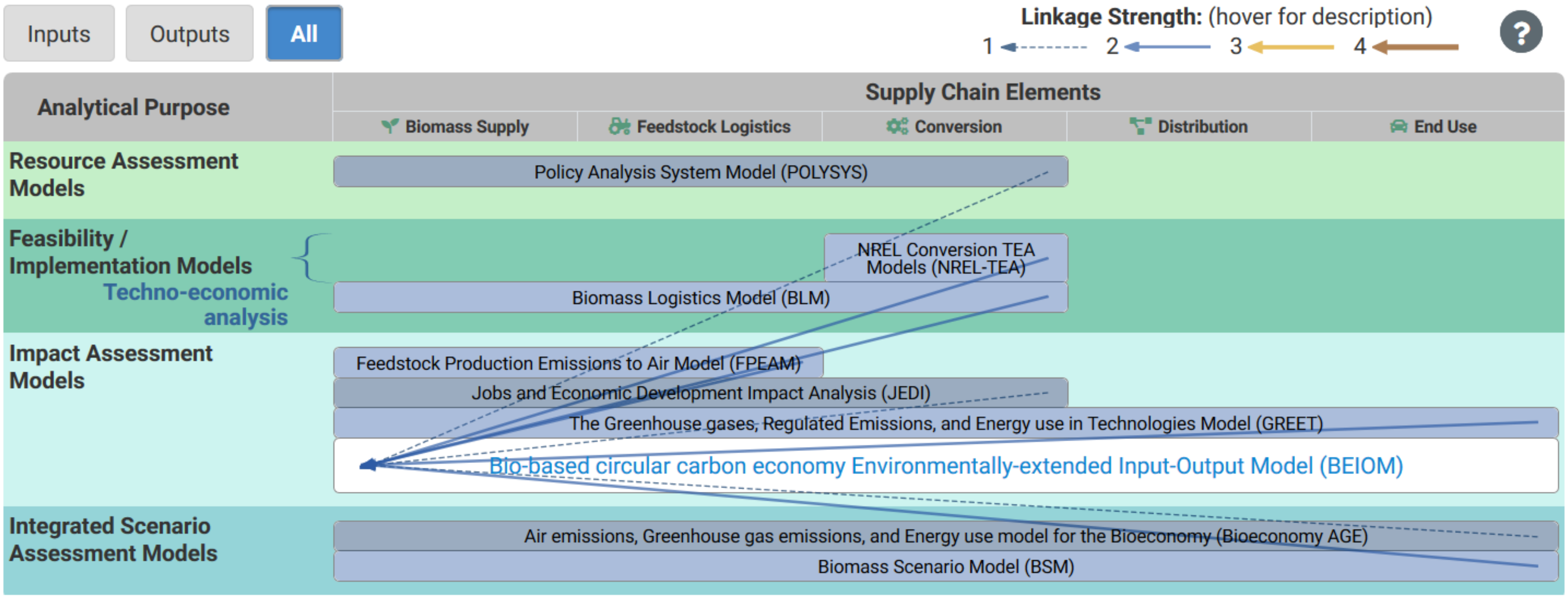
- Extension to *regional* analysis capability.
- US bioeconomy scenarios at national and regional levels (with additional pathways).
- **External review** (manuscript).

Specific model scope as of 1/2021

- **US Bioeconomy**
  - 2 *commercial* pathways: corn ethanol, soybean biodiesel,
  - 2 *near-commercial* pathways: cellulosic biochemical and thermochemical ethanol,
  - 1 *emerging* pathway: polyethylene terephthalate (TPA),
  - 3 *incumbent* technologies.
- **Metrics**
  - 2 *socio-economic*,
  - 14 *environmental*.
- **Effects**
  - *Relative* effects per functional unit (MJ, kg),
  - *Absolute* effects per industry at scale.
- **Time series**
  - Historical: 2002, 2007, 2012, 2017,
  - Current.

Metrics	Unit	Media
Value Added (GDP)	US$	
Jobs (Employment)	persons	
Freshwater Withdrawals	m^3	
Land Occupation	m^2	
(Non-Renewable) Energy Use	MJ	
Mineral Use	kg	
Global Warming Potential	kg CO_2 eq	Air
Smog Formation Potential	kg O_3 eq	Air
Eutrophication Potential	kg N eq	Air, water
Acidification Potential	kg SO_2 eq	Air
Freshwater Ecotoxicity Potential	CTU e	Air, soil, water
Human Toxicity Potential	CTU h	Air, soil, water
Respiratory Effects Potential	kg $PM_{2.5}$ eq	Air
Ozone Depletion Potential	kg CFC-11 eq	Air

BETO Model Map: BEIOM



As a top-down, economy-wide analysis tool of BETO pathways or portfolios thereof, BEIOM is an explicit *user* of data and scenarios from other BETO analyses and tools. Exchanges and links to those models are manual with data manipulation (Level 2) or serve calibration and validation purposes (Level 1).