DOE Bioenergy Technologies Office (BETO) 2023 Project Peer Review

Argonne NATIONAL LABORATORY

Life Cycle Analysis of Biofuels and Bioproducts and GREET Development

Michael Wang, Thathiana Benavides, Hao Cai, Troy Hawkins, Hoyoung Kwon, Uisung Lee

Systems Assessment Center, Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory

WBS 4.1.1.10
Data, Modeling, and Analysis (DMA) Program
April 4, 2023

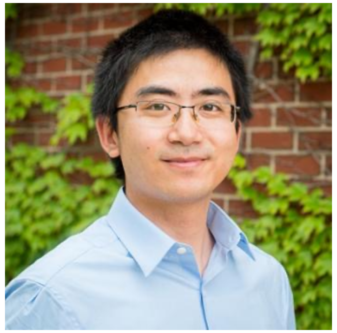
Acronyms

ABF	Agile bio foundry
ACC	American Chemistry Council
AD	Anaerobic digestion
AFTF	Alternative Fuel Task Force
ANL	Argonne National Laboratory
AOP	Annual Operation Plan
ARPA-E	Advanced Research Projects Agency–Energy
AWARE US	Available Water Remaining Model for the United States
BAU	Business as usual
BECCS	Bioenergy with carbon capture and sequestration
BETO	U.S. Department of Energy Bioenergy Technologies Office
CAP	Combined algae processing
CAMPD	Clean Air Markets Program Data
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use Change from Biofuels
CCS	Carbon capture and sequestration
CFP	Catalytic fast pyrolysis
CI	Carbon intensity
CNG/LNG	Compressed/liquefied natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
DECARB	Decarbonization
DGS	Distillers' grain with solubles
DMA	Data, Modeling, and Analysis Program of DOE BETO
DME	dimethyl ether
DOT	Department of Transportation
EERE	Office of Energy Efficiency and Renewable Energy
EIA	Energy Information Administration
EJ	Environmental Justice
EPA	U.S. Environmental Protection Agency
EtOH	Ethanol
FAA	Federal Aviation Administration
FCIC	Feedstock Conversion Interface Consortium
FD-CIC	The Feedstock Carbon Intensity Calculator
FT	Fischer-Tropsch
GCS	Gas collection scenarios
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GREET	GHGs, Regulated Emissions, and Energy use in Transportation
HDPE	High-density polyethylene
HFTO	Hydrogen and Fuel Cells Technologies Office
HTL	Hydrothermal liquefaction
ICAO	International Civil Aviation Organization of UN
IPCC	The Intergovernmental Panel on Climate Change
IDL	Indirect liquefaction
iLUC	Indirect land use change
IMO	International Marine Organization of UN
INL	Idaho National Laboratory
ISATT	Integrated Systems Analysis Tech Team
LCA	Life cycle analysis
LCI	Life cycle inventory
LCFS	Low Carbon Fuel Standard
LMC	Land Management Change
LP	Linear programming
LPG	Liquefied petroleum gas
LUC	Land Use Change
MARAD	Maritime Administration
MJ	Megajoule
MOVES	Motor Vehicle Emission Simulator
MSP	Minimum Selling Price
MSW	Municipal Solid Waste
NERC	The North American Electric Reliability Corporation
NG	Natural gas
NHTSA	National Highway Traffic Safety Administration
N_2O	Nitrous oxide
NOx	Nitrogen oxides
NREL	National Renewable Energy Laboratory
NRMSW	Non-recycled municipal solid waste
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PGM	Platinum Group Metals
PLA	Polylactic Acid
PM	Particulate matter
PNNL	Pacific Northwest National Laboratory
PTW	Pump-to-wheel
R&D	Research & development
RD	Renewable diesel
RFS2	Second Renewable Fuels Standard
RNG	Renewable natural gas
SAF	Sustainable aviation fuel
SCSA	Supply chain sustainability analysis
SMR	Steam methane reforming
SOC	Soil organic carbon
SOT	State of technology
SOx	Sulfur oxides
T&D	Transportation & distribution
TEA	Techno-economic analysis
UN	United Nations
US DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
USDA	U.S. Department of Agriculture
VOC	Volatile organic compound
VTO	Vehicle Technologies Office
WATER	Water Analysis Tool for Energy Resources
WTE	Waste-to-energy
WTP	Well-to-pump
WTW	Well-to-wheels
ZrO_2	Zirconium oxide

PI, Co-PIs, and Team Members

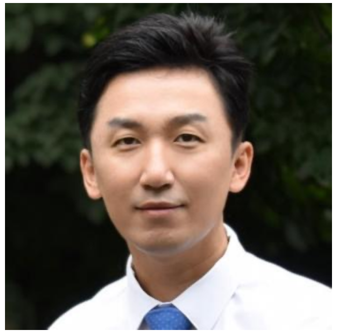

Michael Wang


Thathiana Benavides

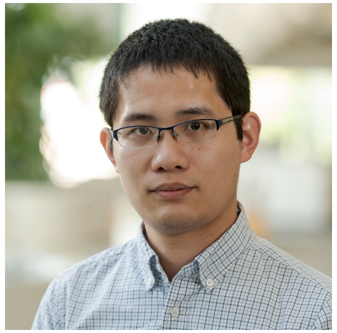

Hao Cai


Troy Hawkins


Hoyoung Kwon


Uisung Lee


Ulises Gracida


Longwen Ou


Xinyu Liu


Taemin Kim

The key to the success of the GREET project is the strength of the team with diversified expertise.

SECTION 1: APPROACH

Project Goals, Outcome, and Impact

Goal	**Quantify life-cycle energy and environmental impacts of biofuels/bioproducts**	• Greenhouse gas emissions • Criteria air pollutant emissions • Water consumption • Energy security via diversified domestic supply
Outcome	**Accurate results about energy and environmental implications of biofuel/bioproduct systems to help policies, R&D directions, and deployment decisions**	• Consistent, transparent LCA energy and environmental results • Benchmarked against other analyses/studies • Rigorous, reliable, and timely responses to key questions from BETO and the bioeconomy community • Peer-reviewed GREET/results and publications for broad dissimilation
Impact	**Address societal value proposition of biofuel/bioproduct technologies**	• Provide LCA results for energy and environmental benefits of bioenergy and for guiding R&D directions • Interact with researchers and industries to examine critical issues for LCA of biofuels/bioproducts • Provide LCA tool to bioeconomy and LCA community

Project Overarching Approach

- Develop GREET® LCA model to address energy and environmental impacts of biofuels and bioproducts (and to compare with conventional fuels and products)
  - Establish LCA methodologies especially to deal with technology advancements, LCA system boundary, co-products, indirect effects, etc.
  - Develop extensive, reliable data for LCAs of biofuel and conventional fuel pathways
  - Maintain model openness and transparency
- Interact with stakeholders (researchers, agencies, industries) to improve understanding and use of LCA results with a consistent modeling platform
- Conduct LCAs of biofuel/bioproduct production pathways
  - Update existing biofuel/bioproduct pathways in GREET
  - Examine and add emerging biofuel/bioproduct pathways (e.g., SAF pathways and CO_2 utilization) to GREET
  - Address emerging LCA issues (e.g., indirect land use change for biomass feedstocks, counterfactual scenarios for waste/residue feedstocks)
  - Publish biofuel LCA studies and review/evaluate relevant studies

Project Is Structured with Three Integral Tasks to Address BETO Research Areas and Key Issues

1. GREET Development and Bioeconomy Community Engagement
- GREET development
- Supply chain sustainability analysis (SCSA) for BETO
- Development of carbon intensities for sustainable aviation fuel (SAF) pathways
- Interaction with international, national, and state agencies

2. Feedstock Analysis for LCA of Biofuels and Bioproducts
- Feedstock production, harvest, and logistics
- Modeling of soil organic carbon and N_2O effects and CCLUB development

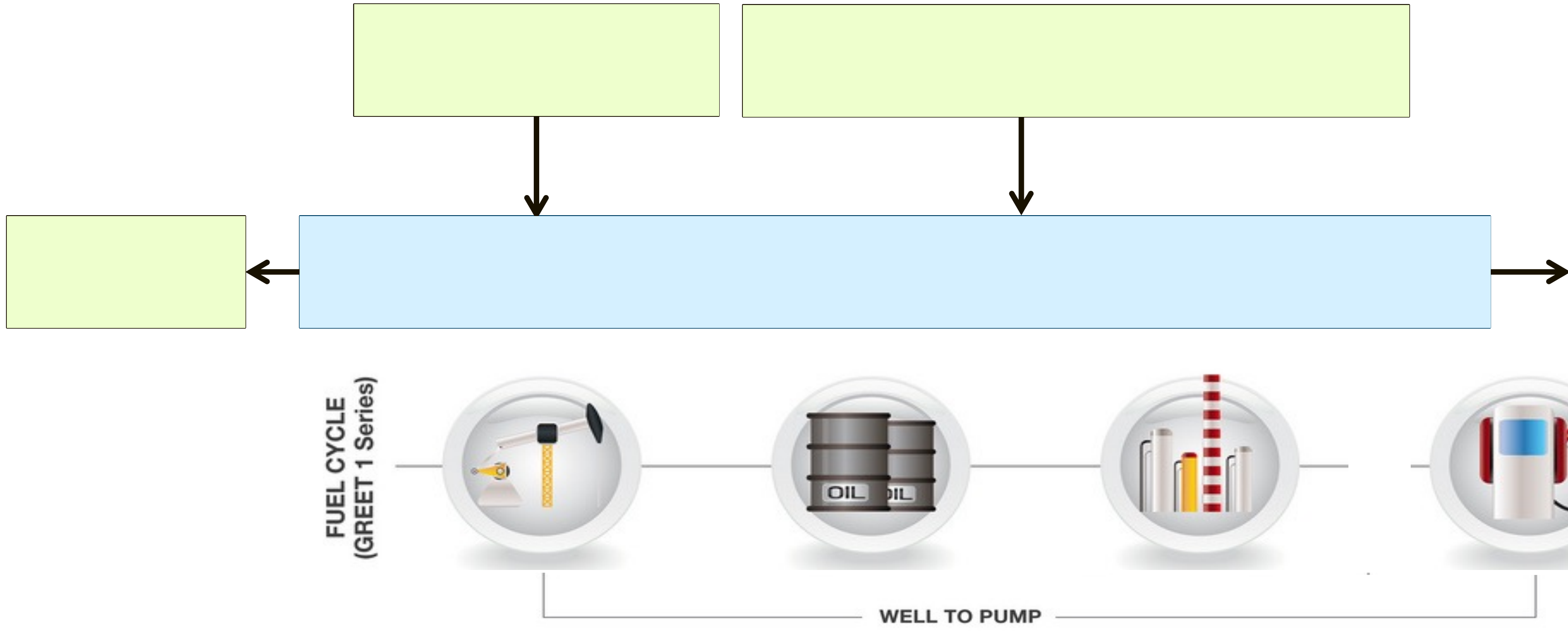
3. Conversion Process Analysis for LCA of Biofuels and Bioproducts
- Waste-to-energy and waste-to-product technologies
- Bioplastic technologies
- Impacts of catalysts and enzymes on biofuel and bioproducts conversion

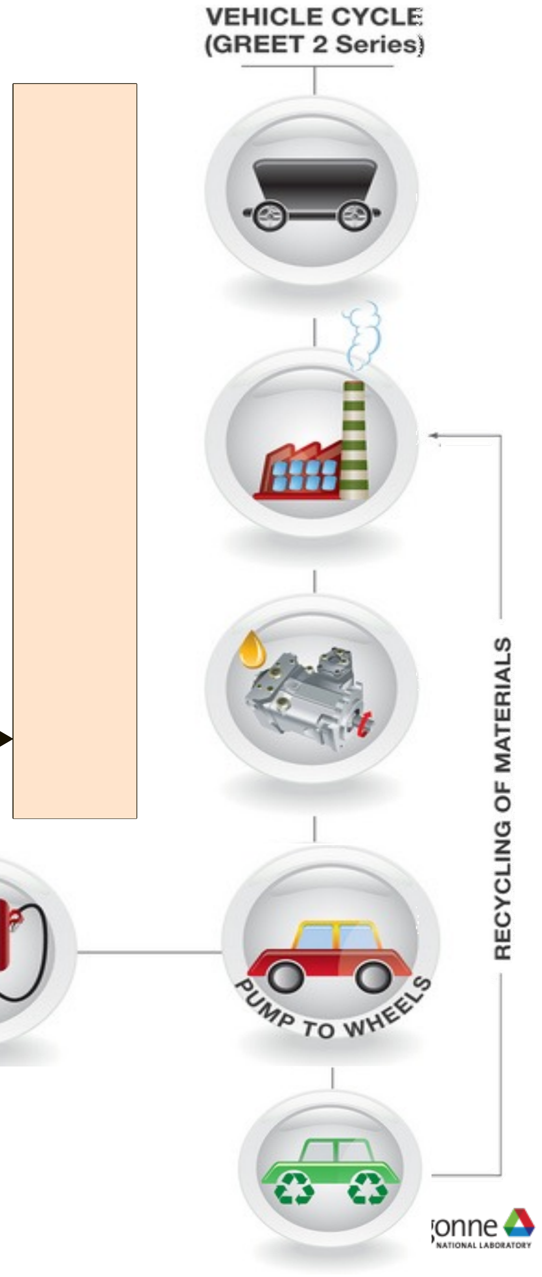
- Project comprised of interacting and well-coordinated tasks.
- Each task interacts with relevant BETO programs and stakeholders to incorporate inputs from them.
- Task deliverables also support other BETO efforts such as Consortia and benchmark reports.

The GREET (Greenhouse gases, Regulated Emissions, and Energy use in Technologies) Model Framework

(Vehicle manufacturing cycle as the example)

- Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- BETO has been a major GREET sponsor since the beginning
- GREET is available at greet.anl.gov
- GREET Outputs: GHG emissions, Criteria Air Pollutant emissions, Energy Use, and Water Consumption





Renewable Fuels Are Important Groups of Energy Systems in GREET

Petroleum Sector:
- Conventional oil
- Shale oil
- Oil Sands

→

Gasoline
Diesel
Jet fuel
Liquefied petroleum gas
Naphtha
Residual oil

Natural Gas Sector:
- Conventional NG
- Shale gas

→

- NG end use in electric, industrial, and residential sectors
- Transportation sector: CNG, LNG
- Alternative fuels: LPG, methanol, DME, FT diesel, FT jet

Hydrogen Economy:
- Gaseous hydrogen
- Liquid hydrogen
- With CCS, if applicable

←

Natural gas
Biomass
Coal
Petroleum coke
Coke oven gas
Electrolysis with electricity
Nuclear energy

Electric Systems:
- Electricity generation at US plant level
- Aggregate to national, NERC, and state level
- With CCS, if applicable

←

Natural gas
Coal
Residual oil
Biomass
Nuclear
Hydro
Wind
Solar

Renewable Energy/Fuels:
- Ethanol
- Biodiesel
- Renewable diesel
- Renewable gasoline
- Renewable jet fuel
- Renewable natural gas

←

1st Gen Feedstocks:
- Corn
- Sorghum
- Soybeans
- Rapeseeds
- Sugarcane
- Palm

2nd Gen Feedstocks:
- Dedicated energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes

Algae

Renewable Hydrogen via electrolysis:
- Wind
- Solar
- Nuclear

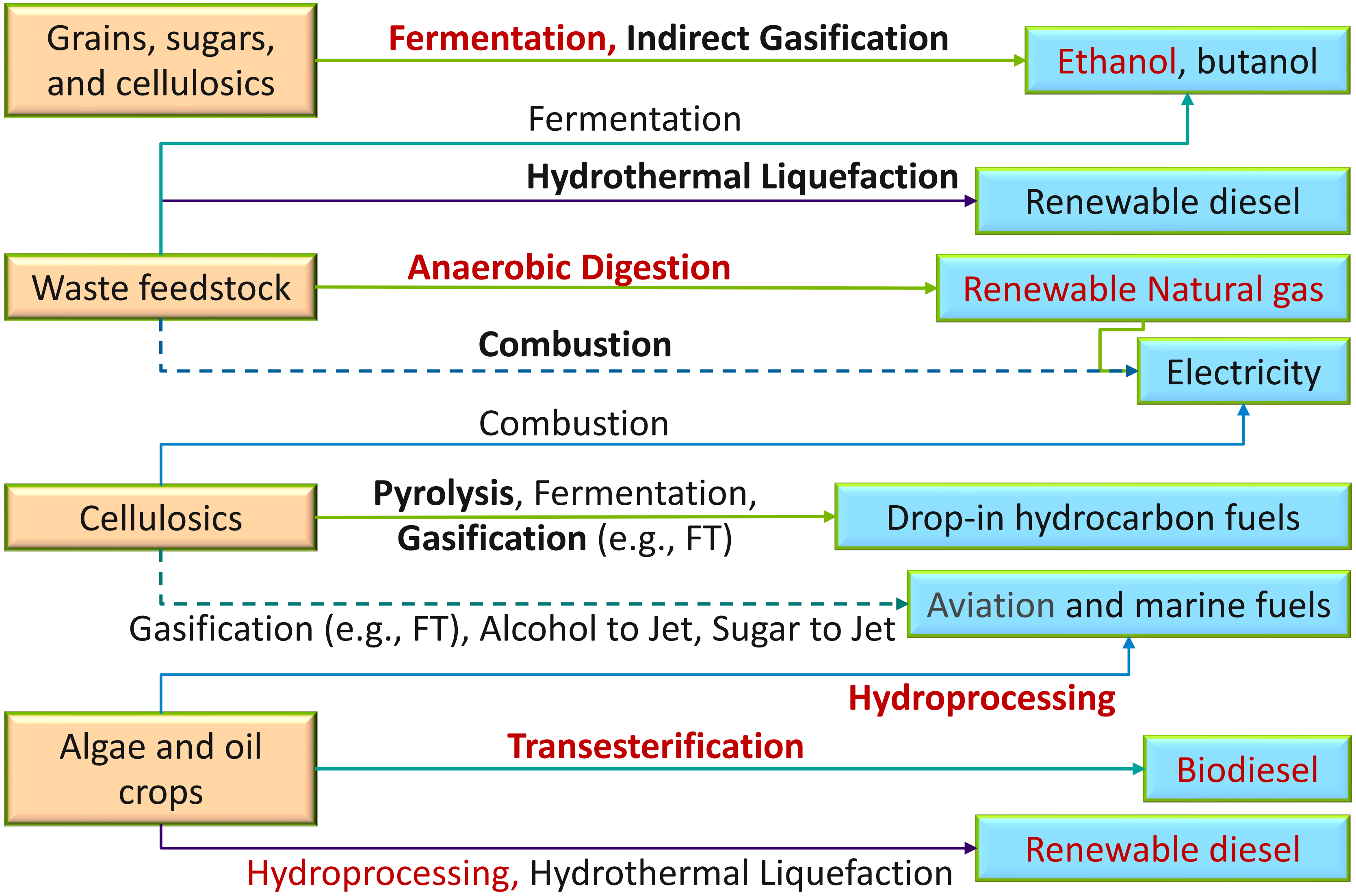
→

Electro-Fuels
- Gasoline
- Diesel
- Jet fuel
- Methanol

←

CO_2 Sources
- Ethanol plants
- NG SMR plants
- Cement plants
- Etc.

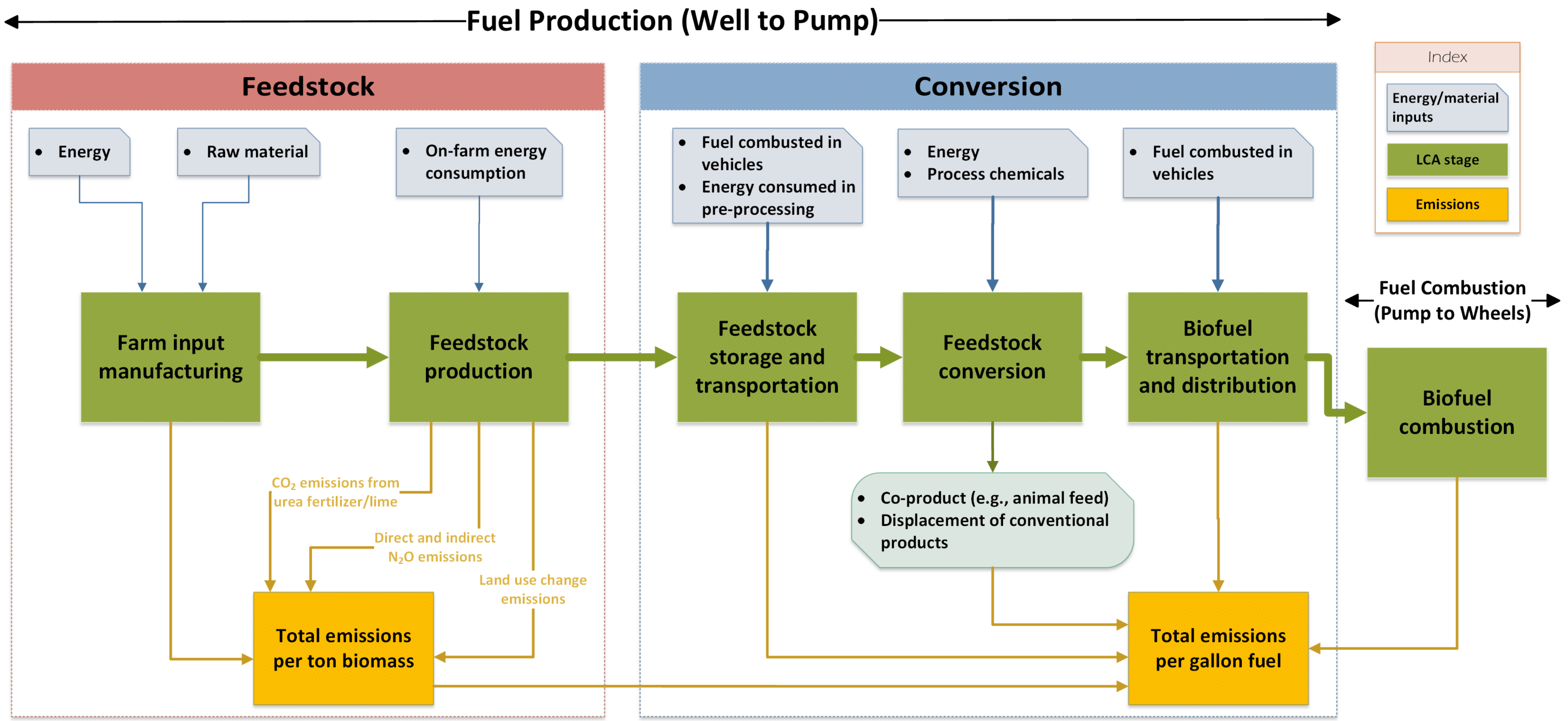
GREET Includes A Variety of Bioenergy Technology Pathways of Interest to BETO and Regulations



Consistent comparison across all relevant technologies key to helping policies and deployment.

- **The highlighted options have significant volumes in LCFS and RFS**
- **Ethanol accounts for >15 billion gallons**
- **Renewable diesel has increased significantly recently**
- **RNG, though still small volume, grew fast**

GREET Biofuel LCA System Boundary Includes Details of Both Feedstock and Conversion



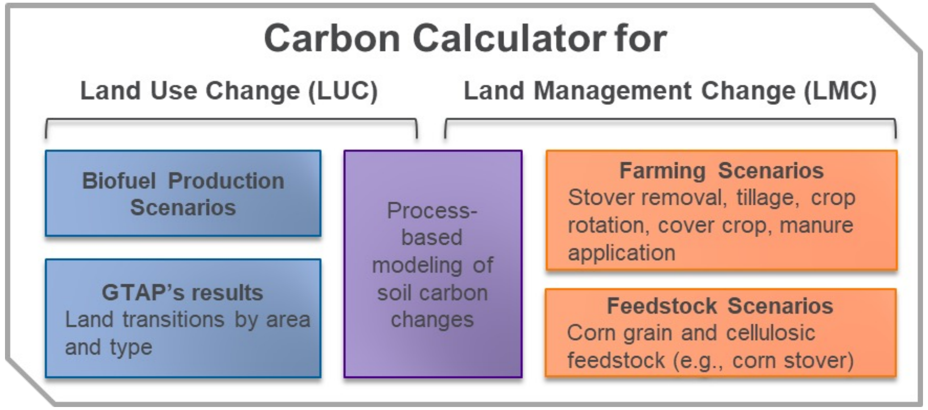
Analyzing a comprehensive system boundary is key for an accurate result.

CCLUB's Soil Carbon Modeling Provides LUC GHG Estimates of Feedstock Production for Biofuel LCA

CCLUB has been updated with new data and observations to address issues in estimating LUC/LMC and associated GHG emissions

N_2O emission factors have been improved with the latest information/database

- Fertilizer-driven N_2O emission factors (Xu et al. 2019b)
- US county-level N input data for corn (Xia et al. 2021)



It accounts for the LMC effects on soil carbon changes during feedstock production, whose consideration in biofuel LCA can help deep carbon reductions by biofuels

Process-based modeling and meta-analysis of field data have been adopted to refine soil carbon emission factors

- Process-based modeling is based on spatiotemporal data of crop productivity, soil and climate conditions for soil carbon modeling
- Meta-analysis of published literature helps the process-based modeling improve emission factors (corn stover harvest; forest residue harvest

LCA of Bioplastics and Bioproducts Include Feedstocks, Conversion, and End-of-Life Treatment

Chemicals and plastics module in GREET

GREET

Chemical & plastic pathways

Environmental and energy metrics

- Feedstocks
- Conversion technologies
- Bioproducts & plastic precursors
- Processing and manufacturing
- End-of-life

GREET LIFE-CYCLE MODEL

Leveraging extensive **GREET background data** for feedstock, chemical inventory and energy inputs

Foreground data for bioplastic technologies based on literature review, public data, experimental data, industry input

Outcomes

- Accurate information of system-wide environmental implications of chemicals and plastics from biobased feedstocks
- Baseline fossil plastics and products are also fully addressed
- Consistent, transparent, and publicly-available models
- Case studies to provide guidance for how to perform rigorous LCA
- Identify key drivers affecting sustainability of bioproducts and bioplastics technologies

Critical Success Factors Identified for GREET Development and Applications

- **Critical LCA issues need to be addressed with science and rigor**
  - LCA system boundary needs to be complete and consistent among fuel pathways
  - Co-products of biofuels need to be handled with reliable and transparent methods
  - LCA output attributes should be relevant to energy and environmental concern
- **GREET (and LCA models) should address technology advancements and technical variability and uncertainties**
  - LCA simulations should be dynamic to consider technology advancements over time
  - Technical variability of pathway parameters is addressed with stochastic simulations in GREET
  - Technical uncertainties are addressed with scenario analysis and a variety of technology paths for a given supply chain with GREET
- **Reliable data and transparent models and analyses**
  - Engage agencies and stakeholders for data sharing and verification
  - Make GREET and data open and transparent
  - Produce high-quality, consistent, and peer-reviewed analyses/publications
  - GREET enables users to input data from their practices/experiments

GREET Relies on A Variety of Data Sources to Address the Challenge of Data Availability and Reliability

Baseline technologies and systems (background data)

- Energy Information Administration's data and its Annual Energy Outlook projections
- EPA eGrid for electric systems
- US Geology Services for water data

Field operation data (primary sources for foreground data)

- Oil sands and shale oil operations
- Ethanol plants energy use
- Farming data from USDA

Simulations with models (secondary sources for foreground data)

- ASPEN Plus for fuel production
- ANL Autonomie for fuel economy
- EPA MOVES for vehicle emissions, EPA CAMPD for stationary emissions
- LP models for petroleum refinery operations
- Electric utility dispatch models for marginal electricity analysis

Collaboration with other national laboratories (primary/secondary sources for foreground data)

Industry inputs (primary sources for foreground data)

- Fuel producers and technology developers on fuels
- Automakers and system components producers on vehicles

Data availability and reliability are always a challenge for LCA.

SECTION 2: PROGRESS AND OUTCOMES

GREET Development: 2021 and 2022 Releases Included Updated and New Biofuel/Bioproduct Pathways and Modules

- New Biofuels/Bioproducts pathways
  - Expanded sustainable aviation fuels from various pathways
  - Gen1/Gen1.5/Gen2 ethanol and upgrading to SAF
  - E-fuel production pathways (CO_2 utilization)
  - Biodiesel and renewable diesel from waste feedstocks
  - Co-processing bio-oils in petroleum refineries
  - Catalysts and bioproducts
  - Biopower pathways
- Updates of baseline fuels and electricity
  - Petroleum production
  - Electricity mix and emission factors
  - Methane leakage of natural gas supply chain
- Other relevant technologies now available in GREET2022
  - Green/blue ammonia
  - Plastic upcycling to lubricant products
  - Poly-alpha olefins
  - Waste to polylactic acid

Argonne NATIONAL LABORATORY

ANL/ESD-21/16

Summary of Expansions and Updates in GREET® 2021

Energy Systems Division

Argonne NATIONAL LABORATORY

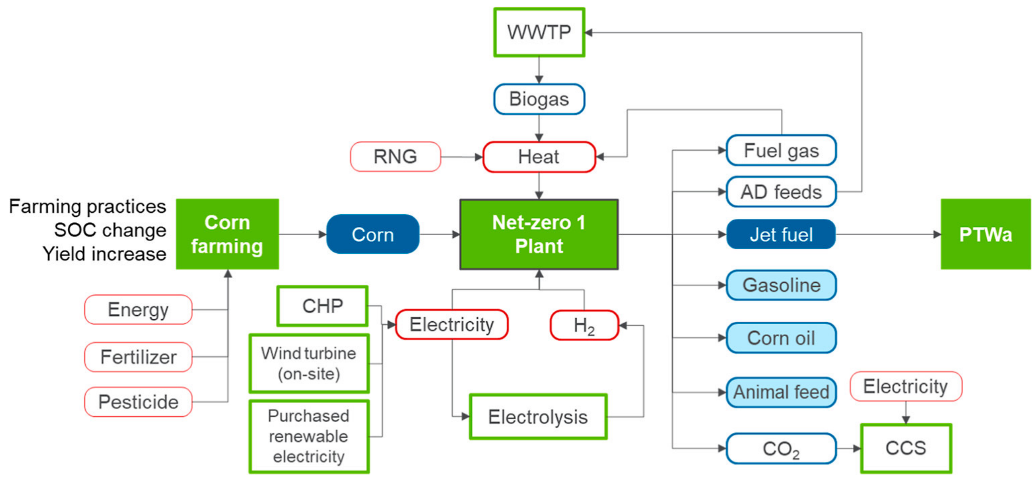
ANL/ESIA-22/1

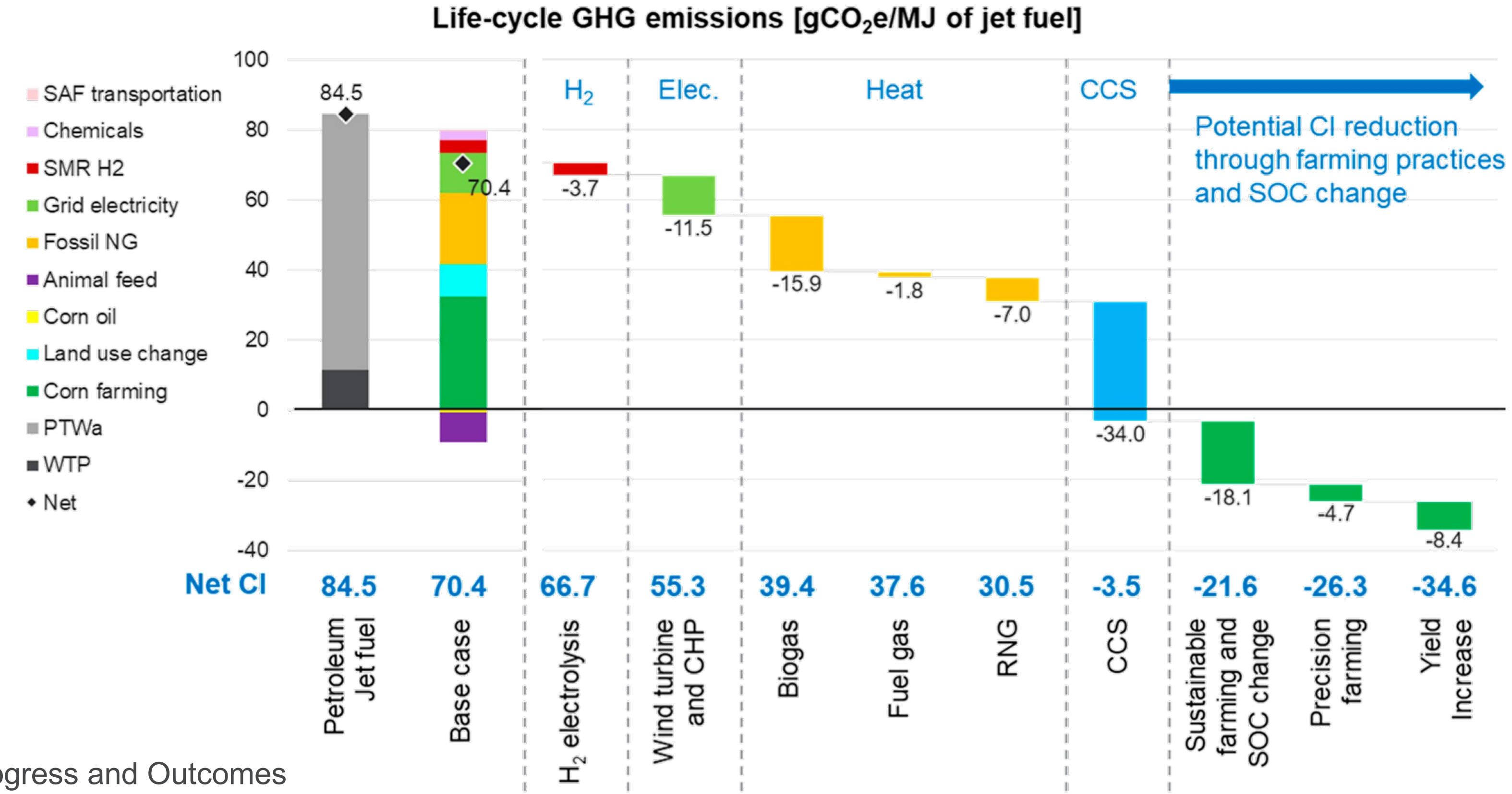
Summary of Expansions and Updates in GREET® 2022

Energy Systems and Infrastructure Analysis Division
Argonne National Laboratory

Deep Decarbonization of a Bio-Refinery: Net-Zero Carbon SAF Production

- Using renewable hydrogen, renewable electricity, heat integration, and carbon capture and sequestration (CCS) makes corn-derived SAF to be net-zero carbon fuel.
- Sustainable farming practices show further emission reduction potential.
- Feasible net-zero carbon SAF production.

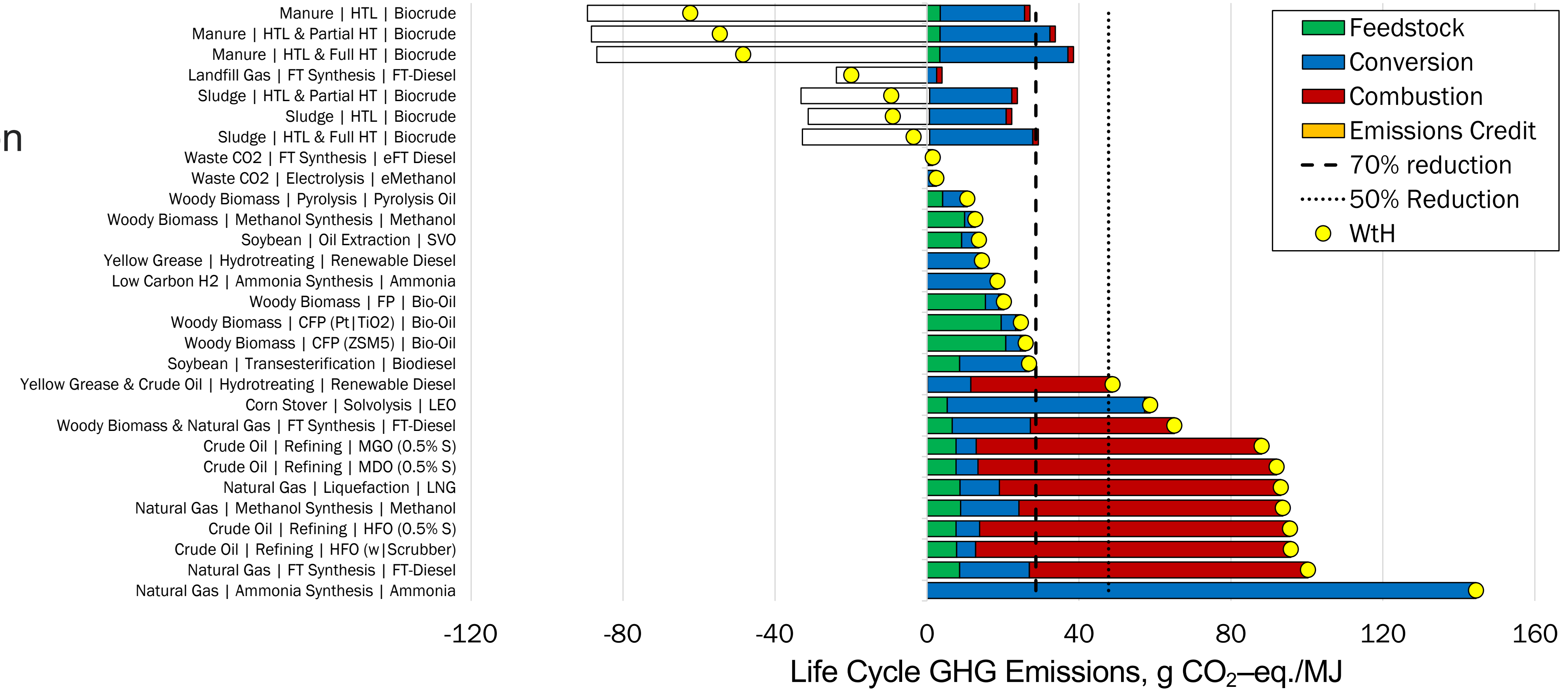




Expanded Marine Fuel Pathways and Released a New Marine Module

Supporting decarbonization of maritime shipping.

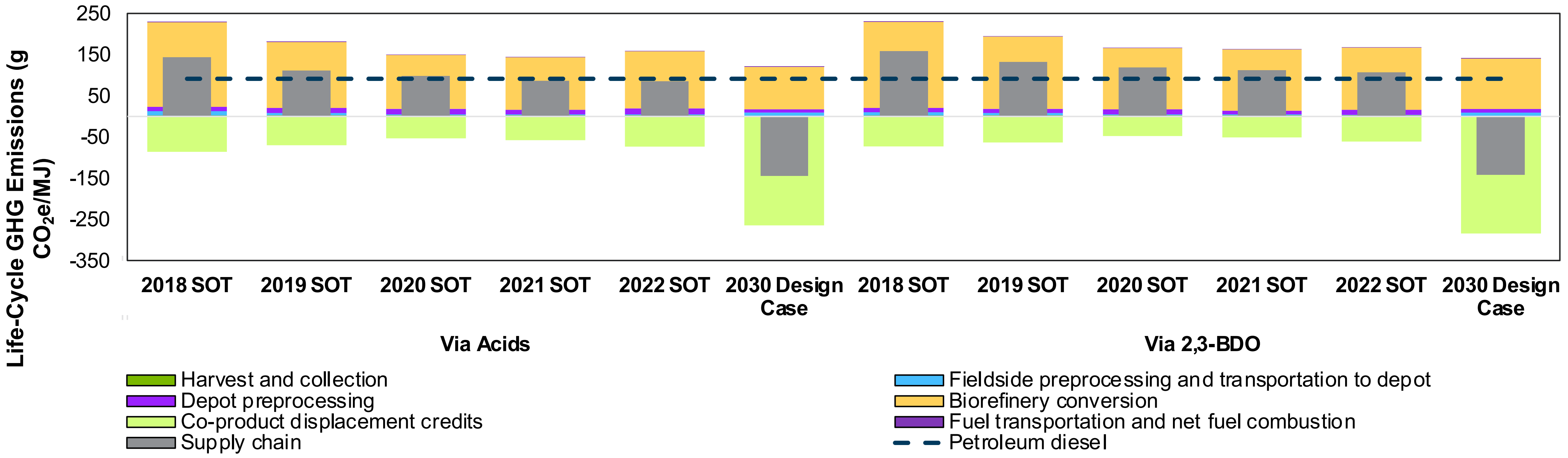
- New stand-alone Marine Module facilitates stakeholder customization of results.
- Real-time connection to GREET enabling flexible parameter manipulation.
- Added new marine fuel pathways leveraging multi-lab marine biofuels project.



- Engaging with the Maersk, McKinney, Moeller Center for Low Carbon Shipping to incorporate GREET LCA in decision-support tools.

SCSA Continues to Track Progress and Identify Opportunities for Sustainability Improvement with Significant BETO R&D Efforts

- Coordinated TEA/LCA efforts among national labs (ANL, INL, NREL, and PNNL)
- **Three dry feedstock pathways** to produce renewable gasoline and renewable diesel: woody feedstock via IDL, woody feedstock via ex-situ CFP, and herbaceous feedstock via biochemical conversion
- **Three wet feedstock pathways** to produce renewable diesel: algae via HTL, algae via CAP, and wastewater plant wet sludge via HTL
- **Continuous improvement in recent SOT cases** driven by improvements in conversion yields and energy efficiency in feedstock logistics
- Co-products in the biochemical conversion and algae CAP pathways have significant impacts on SCSA results

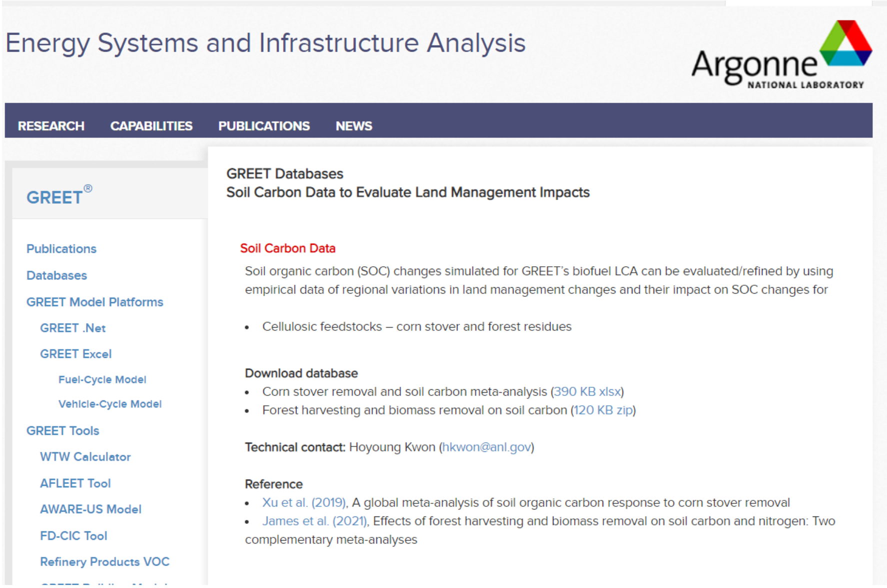


Biochemical conversion pathway

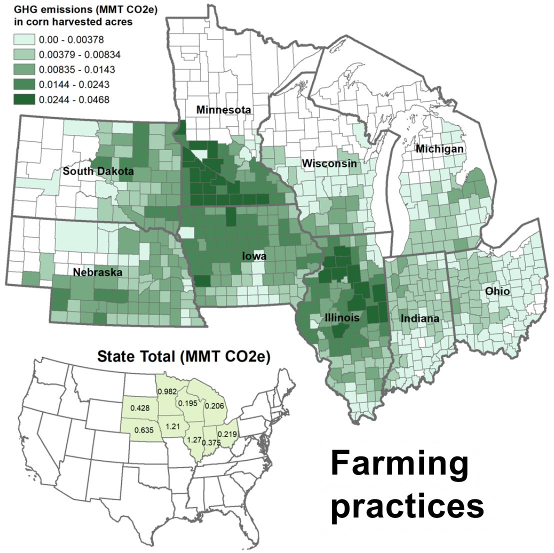
(Cai et al., 2022)

SOC Impacts on Feedstock Carbon Intensity Are Addressed with Meta-Analyses/Process-Based Modeling

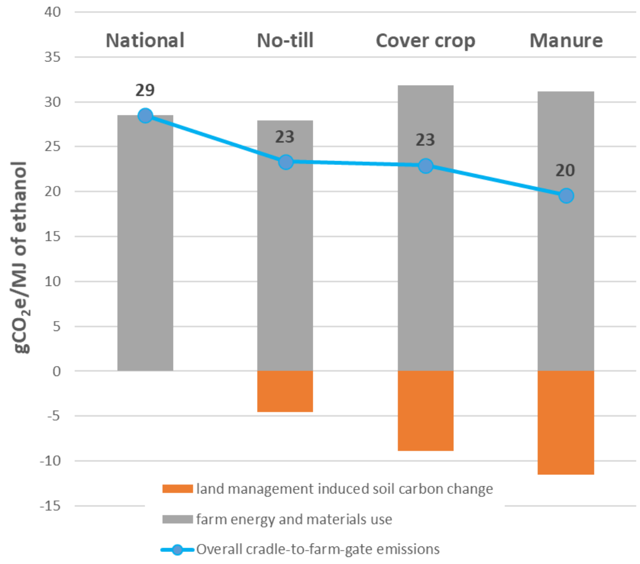
- Meta-analysis synthesizes information from measured data and recent peer-reviewed literature



- Process-based modeling provides spatially explicit SOC estimates associated with land use change and diverse farming practices at the US county-level



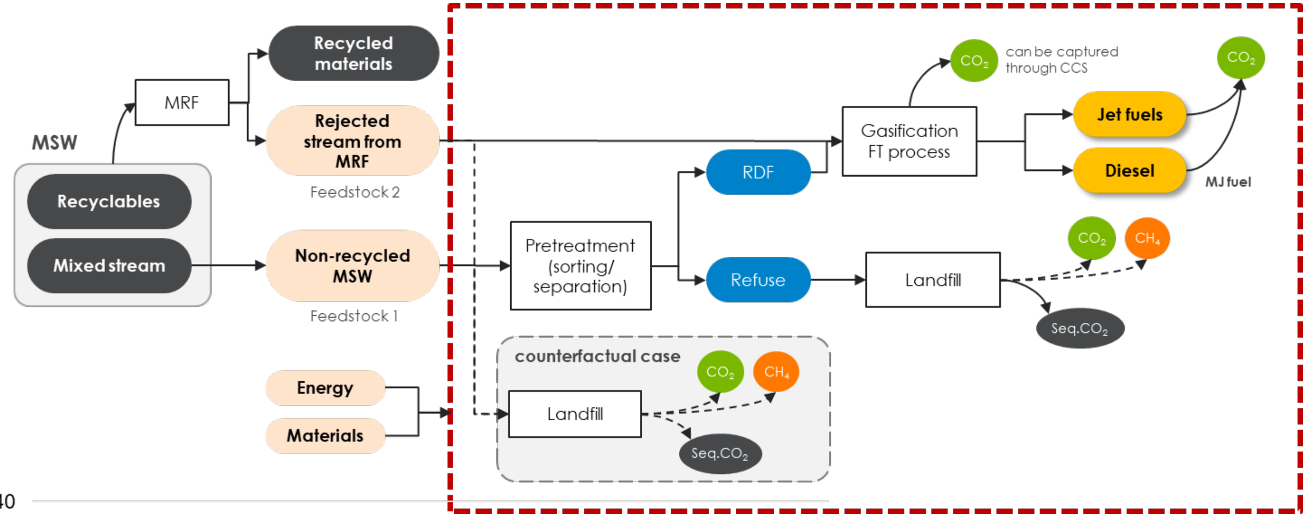
SOC impacts on feedstock carbon intensity

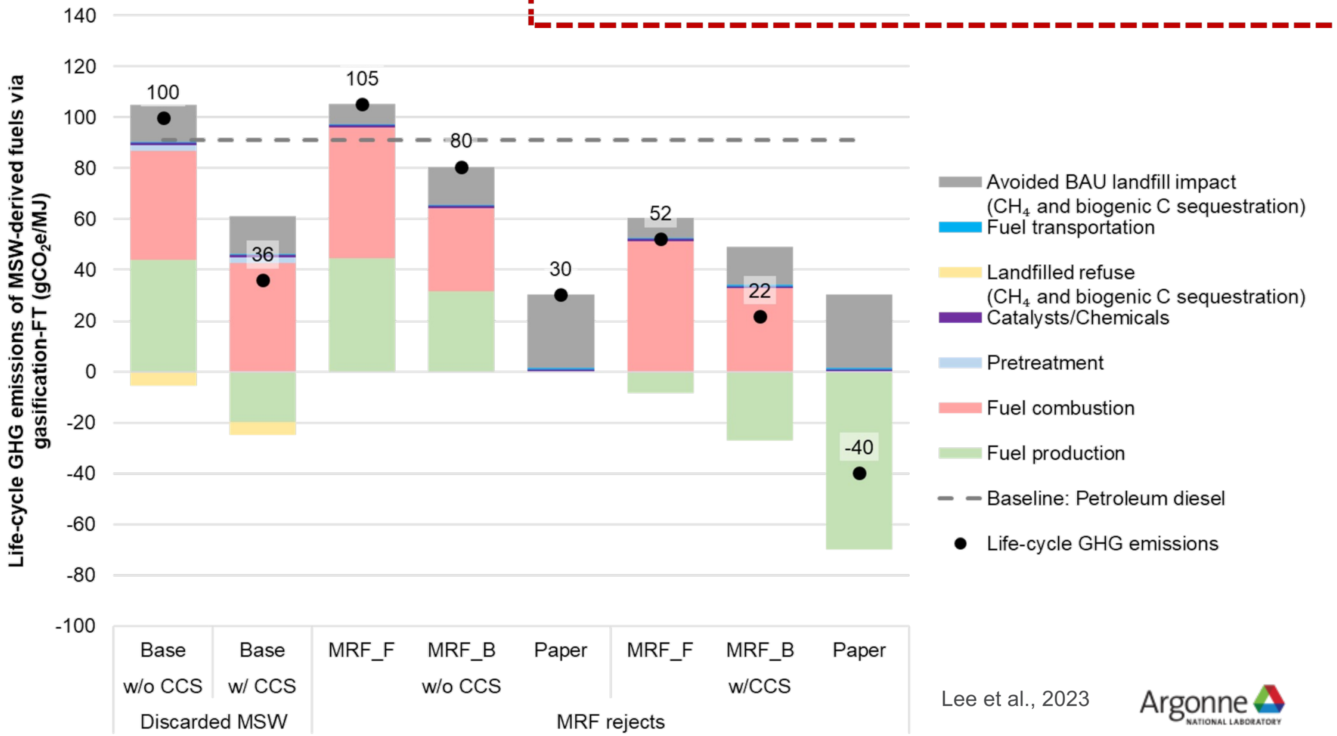


- Facilitate discussions among government agencies and the private sector for opening low-carbon intensity feedstock certification

New Waste-to-Energy Pathway Include Gasification and Fischer-Tropsch Conversion of Municipal Solid Waste for Fuels

- Quantified life-cycle GHG emissions of producing SAF using municipal solid waste (MSW) via gasification followed by Fischer-Tropsch conversion.
- Evaluated the impact of counterfactual scenarios (i.e., conventional waste management practices) and MSW composition (fossil vs. biogenic).
- LCA results show that fossil carbon and avoided BAU significantly affect SAF CI.
- Carbon capture and sequestration (CCS) can be used to reduce the CI.

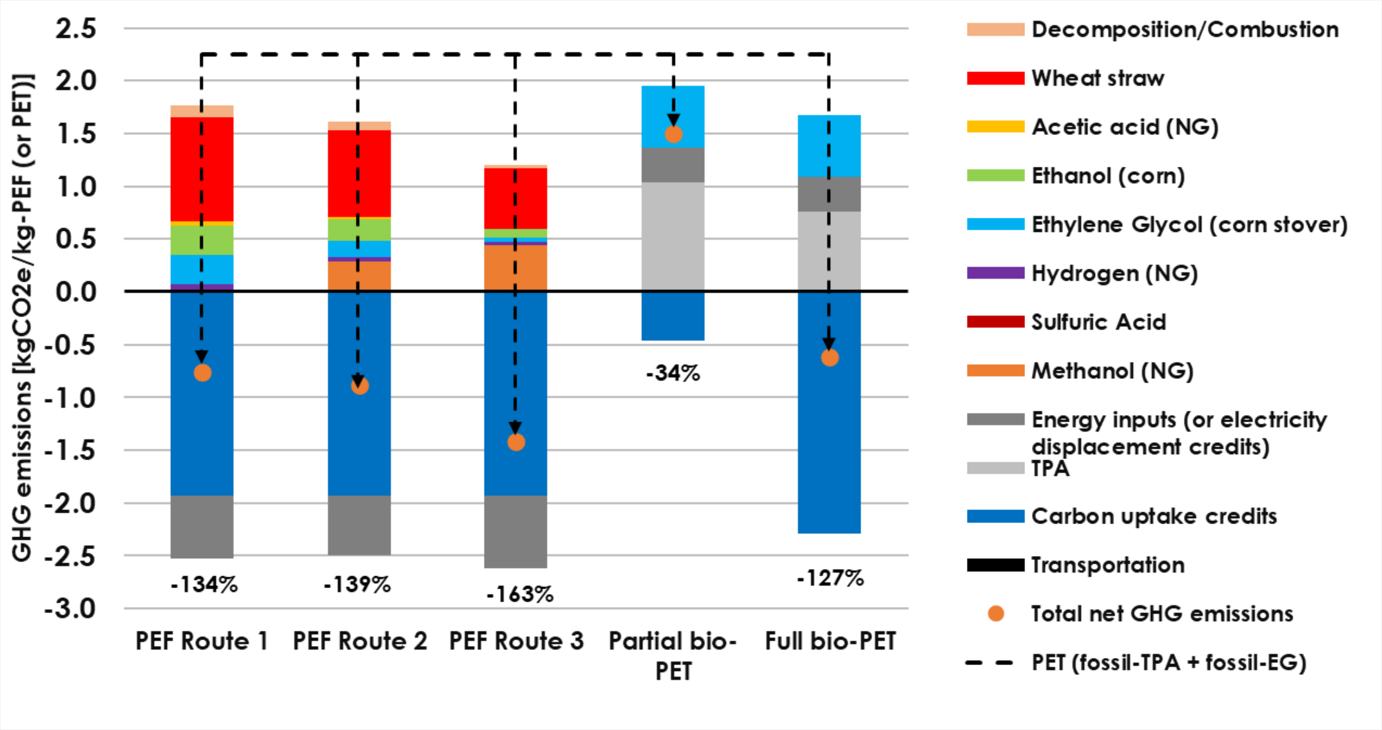




Lee et al., 2023

Bio-Derived Plastic with Performance Advantaged Properties: Polyethylene Furanoate (PEF)

- Conducted LCA PEF, a potential alternative for polyethylene terephthalate (PET).
- Estimated the potential improvement in sustainability metrics when PEF replaces PET (fossil and bioderived).
- Significant GHG emission and fossil energy reductions for PEF routes relative to fossil-PET, but with tradeoff in water consumption for some routes (1 and 2)
- Largest contributor for GHG emissions was the feedstock production for the baseline cases



From fossil-based PET	Route 1	Route 2	Route 3
Δ GHGs	-134%	-139%	-163%
Δ Fossil energy	-79%	-57%	-53%
Δ Water consumption	+168%	+79%	-77%

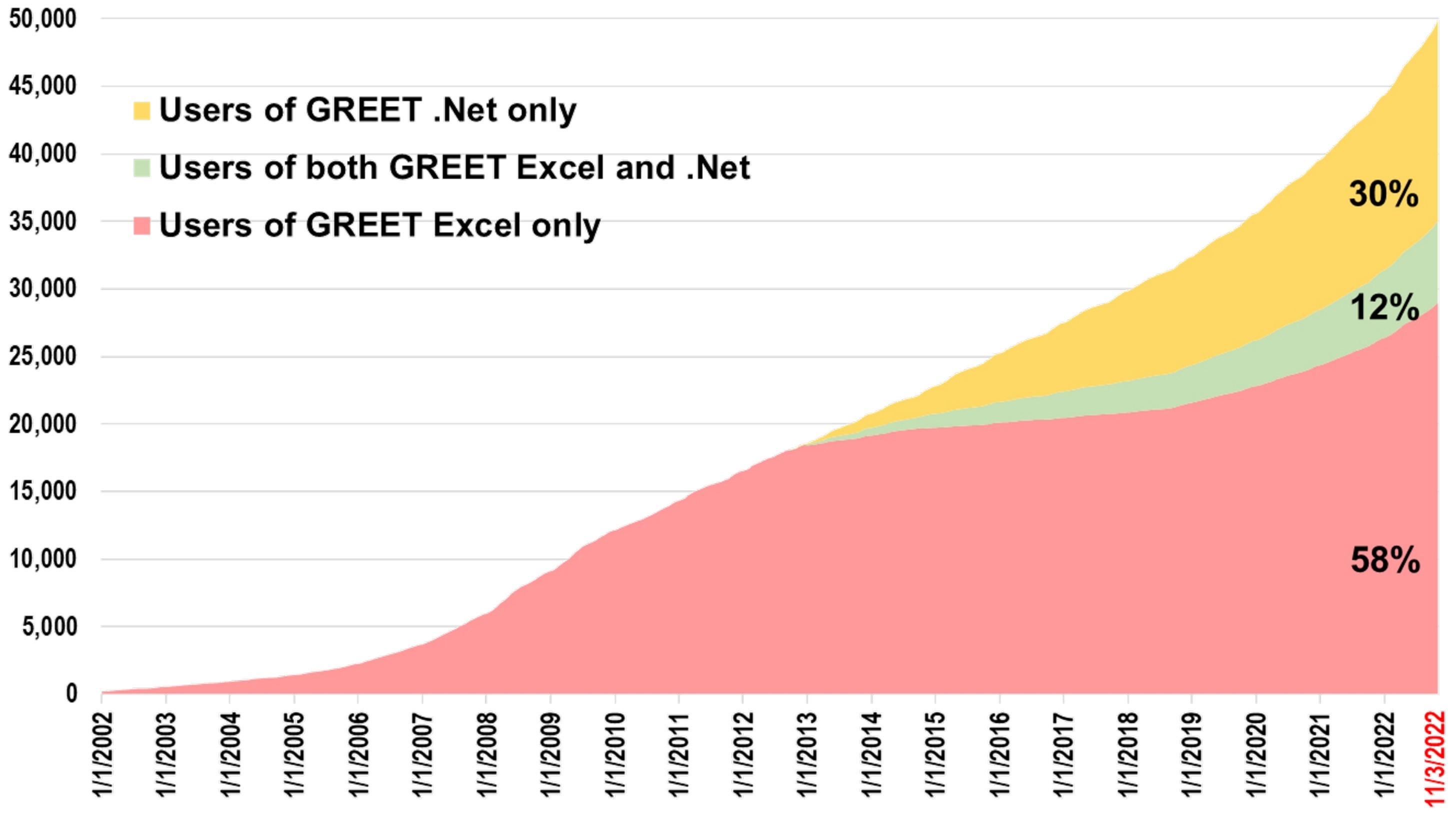
https://pubs.acs.org/doi/full/10.1021/acssuschemeng.1c08429

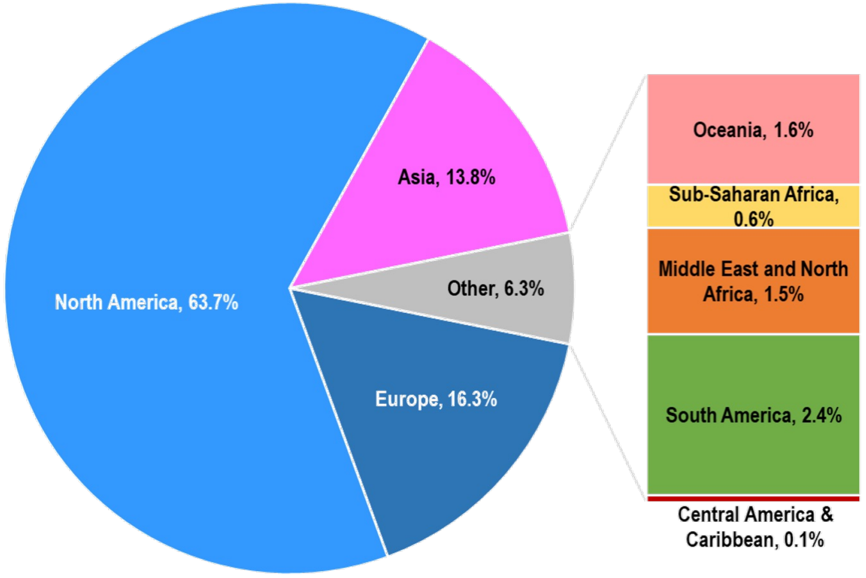
SECTION 3: IMPACT

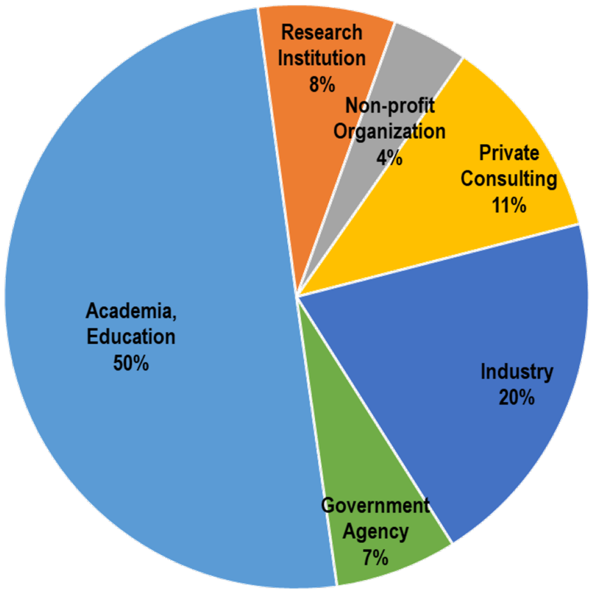
GREET Impact: Address Sustainability of Bioenergy and Bioproducts and Identify Hotspot Sustainability Issues for R&D Opportunities

- A holistic modeling platform to develop CIs of biofuels for regulations and policies to encourage low-carbon fuel development and deployment
- A reliable model to produce LCA results for biofuels and bioproducts for societal value proposition of the bioeconomy
- A comprehensive tool for corporations to identify and pursue biofuel/bioproduct pathways for truly environmental sustainability
- A detailed model with process level fidelity for R&D teams to identify emission and energy consumption hotspots for R&D opportunities

There are ~50,000 Registered GREET Users Globally







GREET Informs Policies and Regulations

- **California-GREET** is an adaptation of Argonne's GREET model
- **Oregon Clean Fuels Program** also uses an adaptation of Argonne's GREET model
- **U.S. EPA** uses GREET with other sources for **Renewable Fuels Standard** pathway evaluations
- **National Highway Traffic Safety Administration** for fuel economy regulation
- **Federal Aviation Administration** and **International Civil Aviation Organization** using GREET to evaluate aviation fuel pathways
- **USDRIVE** Well-to-Wheels Report
- **U.S. Maritime Administration -** renewable marine energy options for IMO GHG intensity and sulfur limits
- **U.S. Dept. of Agriculture bioenergy LCA** and carbon intensity of farming practices
- **Canadian Clean Fuel Standard** for Environment and Climate Change Canada fuel pathways
- LCA results for use in different provisions of the 2021 **Bipartisan Infrastructure Bill** and the 2022 **Inflation Reduction Act**

GREET Is Used by Industries

- Shell: net carbon footprints of fuel and chemical products by Shell for annual progress to Shell's commitment of 65% reduction of its carbon footprints by 2050
- Exxon: carbon intensities of co-processed biofuels in petroleum refineries; GHG emission of ethylene from biomass resources via co-processing operations
- POET: impacts of low-carbon feedstocks on carbon intensities of corn ethanol in a POET ethanol plant
- Gevo: net zero carbon SAF of Gevo new plants
- American Chemistry Council: GHG and other environmental effects of fuels and plastics from pyrolysis of used plastics

GREET Is Used by BETO Consortia and FOA Projects to Evaluate Sustainability Impacts of R&D Progress

- The Advanced Algae Program
- Marine multi-lab AOP
- Co-Optima
- Agile BioFoundry (ABF)
- Bioprocessing Separations Consortium
- Feedstock-Conversion Integration Consortium (FCIC)
- EERE DECARB
- EERE WTW Records by three EERE transportation programs (BETO, VTO, and HFTO)
- USDRIVE ISATT and Net Zero Carbon Fuel Tech Teams
- BETO FOA projects
  - ResIn – Northwestern Univ.
  - Catalytic Reactors for Single-Use Polyolefin Upcycling to High Quality Lubricants- Iowa State Univ.
  - Biomass Component Variability and Feedstock Conversion Interface – Purdue Univ.
  - Decarbonizing the Skies – Sustainable Aviation Fuel from Alder Biocrude Oil – Alder Fuels
  - Reduced Carbon Intensity Ethanol via Biogas from Stillage & Other Feedstocks – Lincolnway Energy

Future Work: Improve LCA Methods, Analyze New Technologies/Pathway, and Identify Deep Decarbonization Opportunities

- **Develop/improve LCA methods**
  - Bioenergy LCA system boundary is dynamic: consequential vs. attributional
  - Co-product methods: define criteria for product classification to allow for appropriate allocation, i.e., main products, co-products, and by-products
  - Address regional differences, ex. criteria air pollutants, soil organic carbon, water stress, resource availability; these are especially important for feedstock certification and bioenergy deep decarbonization
  - Counterfactual scenarios for waste and residue feedstocks can affect LCA results significantly

- **New technologies/pathways**
  - Develop GREET aviation module to examine LCA of expanded sustainable aviation fuel pathways for domestic and international agencies
  - Improve GREET marine module for biofuel opportunities to decarbonize the marine sector
  - Feedstock opportunities (such as soil organic carbon) for deep decarbonization of SAFs and biofuels

- **Bioenergy opportunities for deep decarbonization**
  - Bioenergy with carbon capture and sequestration (BECCS) for a variety of feedstocks and conversion technologies
  - Soil carbon storage from bioenergy feedstocks
  - Biofuels and bioproducts from waste streams

Summary

- **GREET project takes a holistic LCA approach to provide consistent, reliable, and transparent results for BETO and bioenergy community**
  - Holistic approach of considering the entire supply chain of bioenergy systems
  - Process-based, attributional approach with supplement of consequential analysis (e.g., LUC effects, counterfactual scenarios)
  - Improve GREET LCA by considering emerging analytic issues and new bioenergy technologies
- **Argonne continues to produce outcomes with GREET**
  - Updated LCA results for existing bioenergy technologies to reflect technology improvements
  - Identify the path to net-zero/negative GHGs for bioenergy technologies such as SAF
  - New LCA results for emerging technologies for their potential contribution to deep decarbonization of U.S. economy
- **GREET results have had impacts**
  - Societal value proposition of a bioeconomy
  - Advance GHG performance-based bioenergy policies and regulations to incentivize bioenergy technologies (LCFS, RFS, IRA, etc.)
  - Identify R&D opportunities to improve bioenergy sustainability performance

Quad Chart Overview

Timeline

- Project start date: 10/01/2020
- Project end date: 9/30/2023

	FY23	Active Project
DOE Funding	(10/01/2022 – 9/30/2023): $0.93M	(10/01/2020 – 9/30/2023): $2.78M

Project Partners

- NLs: NREL, PNNL, INL, ORNL
- Universities: Purdue, UIC, ND State
- Industry: Gevo, Poet, ACC, Exxon, Corn Refiners A.
- Agencies: FAA, USDA, CARB, EPA

Barriers addressed

- At-B: analytical tools and capabilities for system-level analysis
- At-A: analysis to inform strategic direction
- At-E: quantification of economic, environmental, & other benefits & costs

Project Goal

Identify and quantify life-cycle energy and environmental impacts of biofuels and bioproducts with analytical tools.

End of Project Milestone

Public release of GREET2023 with updates including new SCSA pathway results, new bioenergy and bioproduct production technologies, new SAF production pathways, new waste-to-energy technologies, and connections to the updated CCLUB model.

Funding Mechanism

Lab Call of BETO DMA (Data, Modeling, and Analysis).

Questions?

Michael Wang (mwang@anl.gov)

Publications: Selected Peer Reviewed Journal Articles

- T Kim, A Bhatt, L Tao, PT Benavides. 2022. Life cycle analysis of polylactic acids from different wet waste feedstocks. Journal of Cleaner Production 380, 135110. https://doi.org/10.1016/j.jclepro.2022.135110
- M Saidani, A Kreuder, G Babilonia, PT Benavides, N Blume, S Jackson, C Koffler, M Kumar, C Minke, J Richkus, C Smith, M Wallace. 2022. Clarify the nexus between life cycle assessment and circularity indicators: A SETAC/ACLCA interest group. The International Journal of Life Cycle Assessment. 27, 916–925
- T Kim, J Bamford, UR Gracida-Alvarez, PT Benavides. 2022 Life Cycle Greenhouse Gas Emissions and Water and Fossil-Fuel Consumptions for Polyethylene Furanoate and Its Coproducts from Wheat Straw. ACS Sustainable Chemistry & Engineering 10 (8), 2830-2843
- AL Lehr, KL Heider, EA Aboagye, JD Chea, JP Stengel, PT Benavides . Yenki Kirti. 2022. Design of solvent-assisted plastics recycling: Integrated economics and environmental impacts analysis. Frontiers in Sustainability–Sustainable Chemical Process Design
- U Lee, H Cai, L Ou, PT Benavides, Y Wang, M Wang. 2023. Life cycle analysis of gasification and Fischer-Tropsch conversion of municipal solid waste for transportation fuel production. Journal of Cleaner Production, 382, 135114.
- H Xu, L Ou, Y Li, TR Hawkins, M Wang. 2022. Life cycle greenhouse gas emissions of biodiesel and renewable diesel production in the United States. Environmental Science & Technology. 56(12), 7512-7521.
- AW Bartling, PT Benavides, SD Phillips, TR Hawkins, A Singh, M Wiatrowski, E Tan, et al. 2022. Environmental, economic, and scalability considerations of selected bio-derived blendstocks for mixing-controlled compression ignition engines. ACS Sustainable Chemistry & Engineering 10(20), 6699-6712.
- H Cai, M Prussi, L Ou, M Wang, M Yugo, L Lonza, N Scarlat, 2022. Decarbonization potential of on-road fuels and powertrains in the European Union and the United States: a well-to-wheels assessment. Sustainable Energy & Fuels, 6(19), 4398-4417.
- L Ou, S Li, L Tao, S Phillips, TR Hawkins, A Singh, L Snowden-Swan, H Cai. 2021. Techno-economic analysis and life-cycle analysis of renewable diesel fuels produced with waste feedstocks. ACS Sustainable Chemistry & Engineering, 10(1), 382-393.
- L Ou, S Banerjee, H Xu, AM Coleman, H Cai, U Lee, MS Wigmosta, TR Hawkins, 2021. Utilizing high-purity carbon dioxide sources for algae cultivation and biofuel production in the United States: Opportunities and challenges. Journal of Cleaner Production, 321, 128779.
- K Lan, L Ou, S Park, SS Kelley, BC English, TE Yu, J Larson, Y Yao. 2021. Techno-Economic Analysis of decentralized preprocessing systems for fast pyrolysis biorefineries with blended feedstocks in the southeastern United States. Renewable and Sustainable Energy Reviews 143, 110881.
- Y Gan, Z Lu, X He, C Hao, Y Wang, H Cai, M Wang, A Elgowainy, S Przesmitzki, J Bouchard. 2021. Provincial greenhouse gas emissions of gasoline and plug-in electric vehicles in China: comparison from the consumption-based electricity perspective. Environmental Science & Technology, 55(10), 6944-6956.
- E Yoo, U Lee, G Zang, P Sun, A Elgowainy M Wang. 2022. Incremental approach for the life-cycle greenhouse gas analysis of carbon capture and utilization. Journal of CO2 Utilization, 65, 102212.
- E Yoo, U Lee, M Wang. 2022. Life-Cycle Greenhouse Gas Emissions of Sustainable Aviation Fuel through a Net-Zero Carbon Biofuel Plant Design. ACS Sustainable Chemistry & Engineering, 10(27), 8725-8732.
- H Xu, U Lee, M Wang. 2022. Life-cycle greenhouse gas emissions reduction potential for corn ethanol refining in the USA. Biofuels, Bioproducts and Biorefining, 16(3), 671-681.
- H Xu, G Latta, U Lee, J Lewandrowski, M Wang. 2021. Regionalized life cycle greenhouse gas emissions of forest biomass use for electricity generation in the United States. Environmental Science & Technology, 55(21), 14806-14816.
- U Lee, A Bhatt, TR Hawkins, L Tao, PT Benavides, M Wang. 2021. Life cycle analysis of renewable natural gas and lactic acid production from waste feedstocks. Journal of Cleaner Production, 311, 127653.
- EC Tan, TR Hawkins, U Lee, L Tao, PA Meyer, M Wang, T Thompson. 2021. Biofuel options for marine applications: technoeconomic and life-cycle analyses. Environmental Science & Technology, 55(11), 7561-7570.
- G Zang, P Sun, E Yoo, A Elgowainy, A Bafana, U Lee, M Wang, S Supekar. 2021. Synthetic methanol/Fischer–Tropsch fuel production capacity, cost, and carbon intensity utilizing CO2 from industrial and power plants in the United States. Environmental Science & Technology, 55(11), 7595-7604.
- K Lee, X Liu, P Vyawahare, P Sun, A Elgowainy, M Wang, 2022. Techno-economic performances and life cycle greenhouse gas emissions of various ammonia production pathways including conventional, carbon-capturing, nuclear-powered, and renewable production. Green Chemistry, 24(12), 4830-4844.
- H Kwon, X Liu, H Xu, M Wang. 2021. Greenhouse gas mitigation strategies and opportunities for agriculture. Agronomy Journal, 113(6), 4639-4647.
- X Liu, H Kwon, M Wang. 2021. Varied farm-level carbon intensities of corn feedstock help reduce corn ethanol greenhouse gas emissions. Environmental Research Letters, 16(6), 064055.
- M Prussi, U Lee, M Wang, R Malina, H Valin, F Taheripour, ... & J Hileman. 2021. CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels. Renewable and Sustainable Energy Reviews, 150, 111398.

Publications: Selected Technical Reports and Book Chapters

- PT Benavides, K Kingsbury. 2021. Life Cycle Inventories for Palladium on Niobium Phosphate (Pd/NbOPO4) and Zirconium Oxide (ZrO2) Catalysts Argonne National Lab.(ANL), Argonne, IL (United States)
- L Ou, M Sheely, H Cai. 2022. GREET-Based Interactive Life-Cycle Assessment of Biofuel Pathways-User Manual. ANL-22/50. Argonne National Lab.(ANL), Argonne, IL (United States).
- M Ha, G Gutenberger, L Ou, H Cai, TR Hawkins. 2022. Opportunities for Recovering Resources from Municipal Wastewater. ANL/ESD-21/11. Argonne National Lab.(ANL), Argonne, IL (United States).
- H Cai, L Ou, M Wang, R Davis, A Dutta, K Harris, MR Wiatrowski, E Tan, et al. 2022. Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2021 State-of-Technology Cases. ANL/ESD-22/5 Rev. 1. Argonne National Lab.(ANL), Argonne, IL (United States).
- H Cai, L Ou, M Wang, R Davis, A Dutta, K Harris, MR Wiatrowski, E Tan, et al. 2021. Supply Chain Sustainability Analysis of Renewable Hydrocarbon Fuels via Indirect Liquefaction, Ex Situ Catalytic Fast Pyrolysis, Hydrothermal Liquefaction, Combined Algal Processing, and Biochemical Conversion: Update of the 2020 State-of-Technology Cases. ANL/ESD-21/1 Rev. 1. Argonne National Lab.(ANL), Argonne, IL (United States).
- A Elgowainy, P Vyawahare, C Ng, A Bafana, A Burnham, P Sun, H Cai, U Lee, K Reddi, M Wang. 2022. Hydrogen Life Cycle Analysis in Support of Clean Hydrogen Production. ANL/ESIA-22/2. Argonne National Lab.(ANL), Argonne, IL (United States).
- PT Benavides, UR Gracida-Alvarez, U Lee, M Wang. 2022. Life-cycle Analysis of Conversion of Post-Use Plastic via Pyrolysis with the GREET Model. ANL-22/37. Argonne National Lab.(ANL), Argonne, IL (United States).
- X Liu, H Kwon, M Wang. 2022. Feedstock Carbon Intensity Calculator (FD-CIC) - Users' Manual and Technical Documentation. ANL/ESD-21/12 Rev. 1. Argonne National Lab.(ANL), Argonne, IL (United States).
- H Kwon, X Liu, JB Dunn, S Mueller, MM Wander, M Wang. 2021. Carbon calculator for land use and land management change from biofuels production (CCLUB). ANL/ESD/12-5 Rev. 7. Argonne National Lab.(ANL), Argonne, IL (United States).

Selected Presentations and Awards

Selected Presentations

- Kim, T. Bamford J. Gracida U., PT Benavides. 2021. "Life Cycle GHG Emissions, Water and Fossil-Fuel Consumption for Polyethylene Furanoate (PEF) and Its Co-Products from Lignocellulosic Biomass Via Furanics Conversion" American Institute of Chemical Engineers (AIChE) 2021 Annual Meeting, 2021
- Cai H., PT Benavides. 2022. "GREET LCA of Building Materials, Chemicals, Bioproducts, Plastics, and Catalysts" GREET workshop Argonne National laboratory, Lemont. IL. Nov 7-8. 2022.
- Cai H. Reducing Methane Emissions Via Waste-To-Energy Technologies. Promising Approaches for Reducing Methane Emissions in the United States. Apr. 20, 2022.
- Cai H., Kwon H., Lee U., Zhou J. Argonne's Energy Justice Webinar on GREET Bioenergy Life-Cycle Analysis. Sep. 19, 2022
- Hawkins T. and Cai H. Biofuels Life Cycle Analysis. GREET Training Workshop. Nov. 7, 2022
- Xu H., Ou L., Troy, H., Wang, M. 2021. "Life Cycle Analysis of Biodiesel and Renewable Diesel Production in the United States –2021 update" National Biodiesel Board (NBB) Sustainability Workshop. Kansas City, MO. Nov 9-10. 2021
- Yoo E., Lee U., Wang M., Tao L., Harris K. 2022. "Toward net-zero carbon fuels through carbon capture, utilization, and sequestration: a life-cycle analysis" 19th International Conference on Carbon Dioxide Utilization. Princeton, NJ. June 26-30, 2022.
- Lee U. and Wang M., 2022. "Life-cycle Analysis of Electro-fuels Using GREET" International Energy Agency E-fuel Workshop (Virtual). September 22, 2022.
- Lee U., Wang M., Gururajan V., Som S., Moon C. 2022. "Efforts to support the carbon negative shot" Carbon negative shot MRV Listening Session hosted by DOE. Washington DC, September 7, 2022.
- Wang M., Lee U., Zhou J. 2022. "Potential Approach to Environmental Justice of CCUS" CO2 utilization TEA/LCA Workshop. Ann Arbor, MI. May 19-20, 2022.
- Lee U., Kwon H., Wu M., Wang M. 2022. "Life-cycle Analysis of U.S. Corn Ethanol Production Pathways Using GREET" US-Japan Ethanol Workshop (Virtual). Oct 4-5, 2022.
- Lee U., Kwon H., Wu M., Wang M. 2022. "Retrospective Analysis of U.S. Corn Ethanol Industry for 2005-2019: Implications for Greenhouse Gas Emission Reductions" The Role of Biofuels in the Climate Crisis and Carbon Neutral Era. International Symposium (Virtual). July 11, 2022.
- Lee U. and Wang M. 2022. "Decarbonization of the Aviation Sector Using Sustainable Aviation Fuels and Its Regional Implications" Argonne's Energy Justice Webinar on GREET Bioenergy Life-Cycle Analysis (Virtual). Sep 19, 2022.
- Lee U. and Wang M., 2022. "Life-cycle Analysis (LCA) of Sustainable Aviation Fuels (SAFs) Using GREET" Connecticut Department of Energy and Environmental Protection's 2022 Comprehensive Energy Strategy (Virtual). Sep 1, 2022.
- Tao L., Harris K., Lee U., Yoo E. 2022. "Techno-Economic Evaluation of Strategies to Approach Net-Zero Carbon Sustainable Aviation Fuel via Woody Biomass Gasification and Fischer-Tropsch Synthesis" tcbiomass 2022. Denver CO. April 19-21, 2022.
- Meyer A., Snowden-Swan L., Yoo E., Lee U. 2022. "Decarbonization of Hydrothermal Liquefaction of Wet Waste to Transportation Fuels and Its Techno-economic and Life Cycle and Analysis" tcbiomass 2022. Denver CO. April 19-21, 2022.

Awards

- M. Wang: Climate Leadership Award, Clean Fuels Alliance America, Jan, 2023
- M. Wang: DOE Secretary Achievement Award for the Federal SAF Grand Challenge Multi-Agency Team, Jan. 2023
- M. Wang: Reuters' "Hot List" of the most influential climate scientists in the world (https://www.reuters.com/investigates/special-report/climate-change-scientists-list/), April 2021

Responses to Selected 2021 Peer Review Comments

2021 Peer Review Comment	*Response*
GREET is a widely used and trusted model, and the recent advances have made it even more comprehensive. To continue to bolster the already high credibility of the model, the GREET team should continue to work with other teams on parallel life cycle analyses or external review to continue to enhance verification and validation of the model, and should work with other teams across the national labs when incorporating additional sustainability aspects. I have some concern about the scope of GREET and whether AWARE-US is at the same level of quality and validation as GREET's core strengths. I would like to see the GREET team leverage the depth of expertise in other teams modeling water availability and water footprinting (e.g., the WATER modeling group) and maintain the overall quality and trust in GREET by putting equal care into the water scarcity analysis/tool as is used for the core GHG LCA modeling and data quality . GREET could represent an opportunity to integrate a number of additional tools, resources, and analytical approaches in the long-term, and it is important that it be as strong in these additional areas (e.g., water scarcity) as it is on the GHG LCA side. Leveraging strengths from other teams will ensure that the quality remains even across different modules if GREET is expanded further to incorporate other sustainability considerations besides GHG emissions.	In response to the reviewer's question regarding whether ANL has evaluated if it makes sense to transition GREET from Excel to another platform: Yes, we have given this considerable thought and took steps in this direction with the creation of GREET.net. We also began to develop different modules (such as the SAF and marine modules) with interactive user interfaces linked to GREET Excel version. Nonetheless, we anticipate maintaining GREET Excel based on user feedback. GREET has been expanded significantly since its first version in Excel in 1995. Although Excel is transparent in presenting data and results, calculation logic and configuration of simulation pathways/options in Excel are difficult to follow and execute. In the early 2000s, we began to make efforts to add extensive user interfaces inside GREET Excel to help users make simulation choices and follow through data, calculation logic, and results. In the mid-2000s, we further began to develop GREET in the .net programming platform. The .net platform for GREET is designed with dynamic picking and dropping functions that users can readily configure simulation options and get results; however, the extensive databases built in GREET are not as transparent in the .net platform as in the Excel platform. We initially envisioned that we would eventually stop the Excel platform for GREET to move it completely to the .net platform. But many GREET users (some of whom are intensive GREET users) continued to use the Excel platform and asked us to continue to maintain the Excel platform; thus, we have maintained the two modeling platforms for GREET for more than 15 years. Nonetheless, many new GREET users in fact use the .net platform. Although it is time consuming to maintain the two parallel GREET modeling platforms, we have found that the development and maintenance of the two platforms give us a unique opportunity to cross-check GREET expansion for quality assurance/control; thus, we will maintain both platforms for the foreseeable future. Both are open-source platforms where users can expand LCA simulation options and conduct LCA simulations, which are free of charge to download from the GREET website (https://greet.es.anl.gov/). We are currently exploring two modeling platform options for GREET: Python programming and OpenLCA for the next generation of GREET development.

Responses to Selected 2021 Peer Review Comments (Continued)

2021 Peer Review Comment	*Response*
The GREET team has done a phenomenal job developing a model that is as comprehensive as it is well regarded and widely used. This project delivers on its stated goal of quantifying the outcomes from different bioenergy and bioeconomy products while also doing an excellent job of making the modeling framework and results accessible to a wide audience, which is very clear from the list of partners and model download data shared by the presenters. The usage metrics provided in the presentation illustrate this project's growing success and influence within the community. Further, the ongoing work to update the model to match progress with its covered technologies and to expand its scope of coverage is critical to its continued relevance. A few notes of caution, however. It is critical that the modelers take the opportunity to validate the model assumptions and results against real-world data as part of a systematic approach. It may be necessary to regularly conduct sensitivity analyses and investigate how assumptions in GREET may be influencing the results or causing them to diverge from real-world findings (for example, for soil carbon changes in CCLUB). Further, the expansion to cover more nonfuel biomaterials is potentially risky, particularly in cases where the scope and assumptions for product use and lifetime differ from fuels because it may introduce additional complexity and layers to what is already a very complex model.	The reviewer's point about validating GREET model assumptions and results against real-world data is one we take very seriously, which is the subject of constant discussion and updates within our group. There are key experts in our group responsible for each of the pathways in GREET, and we monitor the literature and statistics for new data to inform the pathways. These data are considered for updates to key parameters during each GREET release and are documented in GREET release publications. New pathways and significant changes to pathway modeling are published in our peer-reviewed articles. Nonetheless, this is a struggle, in general, for the field of LCA. The nature of LCA that covers the entire supply chain of a fuel/product makes the validation of LCA results with measured data impractical because there are no reported/measured results for the entire supply chain of a fuel/product; however, data for key stages of a supply chain are indeed available and can be validated, and we regularly use these to validate key input parameters in GREET. For example, for the corn ethanol supply chain, fertilizer use in corn farming and energy use in ethanol plants are two key input parameters and are reported in government statistics and in private benchmarking database. We validate key GREET input parameters with such data from agencies and industry sources. We use government statistics, such as U.S. Energy Information Administration's data on the energy use of various sectors and the Environmental Protection Agency's (EPA's) emissions data from its annual emissions inventory report in the annual release of the new GREET version. Further, we periodically validate specific fuel pathways with up-to-date input data. For example, we used the USDA farming data and an ethanol plant benchmarking database in 2020 to update corn farming inputs, corn yield, ethanol plant energy use, and ethanol product yield between 2005 and 2019 for corn ethanol pathway simulations. We documented the GREET 2021 update in a widely cited journal article. We also conducted a similar effort to update and validate biodiesel and renewable diesel pathways in GREET 2022 and documented the update in a journal article. LCA of plastics and materials has been in GREET 2 (which LCA of fuels has been in GREET 1) since later 1990s. Adding additional plastics and materials has indeed made GREET more complex, while LCA of plastics and materials is benefited from extensive GREET databases. We are contemplating to develop plastic LCA module linked to GREET to reduce the complexity of GREET.

Responses to Selected 2021 Peer Review Comments (Continued)

2021 Peer Review Comment	*Response*
The integration of the wide range of other BETO models and inputs is impressive. The impact of the project is clearly high—from extensive stakeholder engagement (43,000 users, wow!), to the expansion of the modeling capabilities, to the increasing growth in users. The approach related to the bioproducts portion of the work was not well described. It would be nice to see more on how the bioproducts pathways were developed. As you build out more bioproducts, be sure that you are collaborating with the USDA. Same for buildings: Work with NREL and Lawrence Berkeley National Laboratory (LBNL) and the U.S. Green Business Council. As you develop "extensive databases" (per your presentation), investigate ways to make those databases available in other LCA software environments or databases, like the Federal LCA Commons.	Expansion of GREET from fuels LCA to products LCA has been an effort for more than 8 years at ANL. This was driven by BETO's R&D efforts in the chemicals and plastic area. LCAs of fuels are somewhat straightforward with their combustion to end their lives. Chemicals, especially plastics, may not be destroyed at the end of their use. The fate of these products is important in their LCA, especially when we examine life cycle GHG emissions. In these cases, we track down fates of products after their uses, such as their degradation and decomposing, so that environmental releases such as methane emissions are captured in product's LCA. For all the pathways implemented in the GREET model (biofuels or bioproducts), we have peer-reviewed documentation available on the GREET website (https://greet.anl.gov/publications). The intent with these documents is not only to have the pathway descriptions and explanation of the methodology and data source but also to present sensitivity analyses results, which help understand the variability in the results led by key parameters. The need for constant monitoring of LCA models requires the continued support of GREET, which plays a critical role in harmonizing and providing consistent and accurate data, allowing comparisons across the technologies in which DOE invests. We appreciate the reviewers' interest in our work on bioproducts, plastics, and chemicals. Our LCA of products, including chemicals and plastic, benefits from our ongoing collaboration with other national labs, including NREL, PNNL, and LBNL. We also collaborate with industry stakeholders, such as member companies of the American Chemistry Council, through projects. We have been engaged with USDA related to the analysis of biofuels and will continue to seek opportunities to deepen our collaboration related to bioproducts. Technology development efforts and data accumulated by the national labs and industry stakeholders have helped our LCA efforts tremendously. Within GREET, we have expanded our LCA to fossil-based and bio-based chemicals leveraging the new biorefinery models. In addition, we have been developing an analysis framework for the circular economy of plastics. Several publications are available on our GREET website, which reflect the efforts in the LCA of chemicals and plastics. The results of our LCA have helped identify the key drivers that influence GHG emissions and other sustainability metrics and pursue opportunities to mitigate the adverse environmental impacts. For example, we have shown that sodium hydroxide, used during pretreatment of corn stover, is a major GHG driver in biochemical conversion technologies; therefore, collaborators at other national labs have been expanding their research to find less GHG-intensive chemical agents for the pretreatment of feedstock. We expanded GREET to the buildings sector with support of DOE Building Technology Office. This expansion benefits from our LCA efforts for key materials such as steel, aluminum, and cement that we have built in GREET for vehicle cycle analyses. We have been interacting with other national labs, including ORNL, PNNL, and LBNL; as well as government agencies, such as the National Institute of Standards and Technology; industry, such as vacuum insulation panel manufacturers; architecture firms, such as Skidmore, Owings & Merrill; and trade associations, such as North American Insulation Manufacturers Association, to benefit our LCA efforts on building envelope and insulation materials, building construction, and building operations.

ADDITIONAL SLIDES

Project Context

How is it done today and what are the improvements to address limitations?

- Today, Argonne's peer-reviewed LCA studies and the GREET model are regularly used to benchmark bioenergy R&D progress.
- Continued technological developments require new analysis to understand their life-cycle energy and environmental implications.
- Improvements in analysis methods are needed to address new questions raised by the bioeconomy community and others.
- LCA is data intensive. Consistent models and datasets are needed to enable comparisons across technologies.

Why is it important?

- Bioenergy energy and environmental sustainability metrics are key for societal and business commitment.
- Argonne's bioenergy LCA enables rigorous, objective, and comprehensive comparison across energy and environmental metrics based on datasets made publicly-available in annual GREET releases.

What are the risks?

- Comprehensive and detailed analysis based on the best available data is required to avoid misleading results.
- Complete, consistent LCA system boundary provides holistic, objective bioenergy/bioproduct results for policies and deployment.

GREET LCA Modeling Includes Key Metrics Requested by BETO

Greenhouse Gases	Water Consumption	Criteria Air Pollutants	Energy Use
Carbon dioxide Methane Nitrous Oxide Black carbon Albedo Characterized by global warming potential (CO_2-eq.) based on IPCC AR5.	Withdrawals less local releases AWARE US model estimates regional and seasonal water stress (With EJ implications)	Volatile Organic Compounds (VOCs) Carbon Monoxide (CO) Nitrogen Oxides (NO_x) Particulates ($PM_{2.5}$, PM_{10}) Sulfur Oxides (SO_x) Distinguished as Urban and Non-Urban (with EJ implications)	Total energy incl. fossil and renewable • petroleum • natural gas • coal • biomass • nuclear • hydro • wind • solar

For the Transportation Sector, GREET Covers all Transportation Subsectors

- Passenger and freight transportation
- Various SAFs and petroleum jet

- Ocean and inland water transportation
- Baseline diesel and alternative marine fuels

Share of US transportation GHG emissions; remaining 12% for US is from pipelines and offroad.

GREET Also Includes LCA of Materials, Chemicals, Bioproducts and Plastics

- Platform chemicals from refinery operations
- Bio-based chemicals

- Materials for vehicles
- Building and construction materials

- Major building blocks to promote and expand the U.S bioeconomy
- Integration of biorefinery process with biofuels

- Major fossil-based plastics
- Bioplastics,
- Plastic re-/upcycling, and plastic-to-fuels

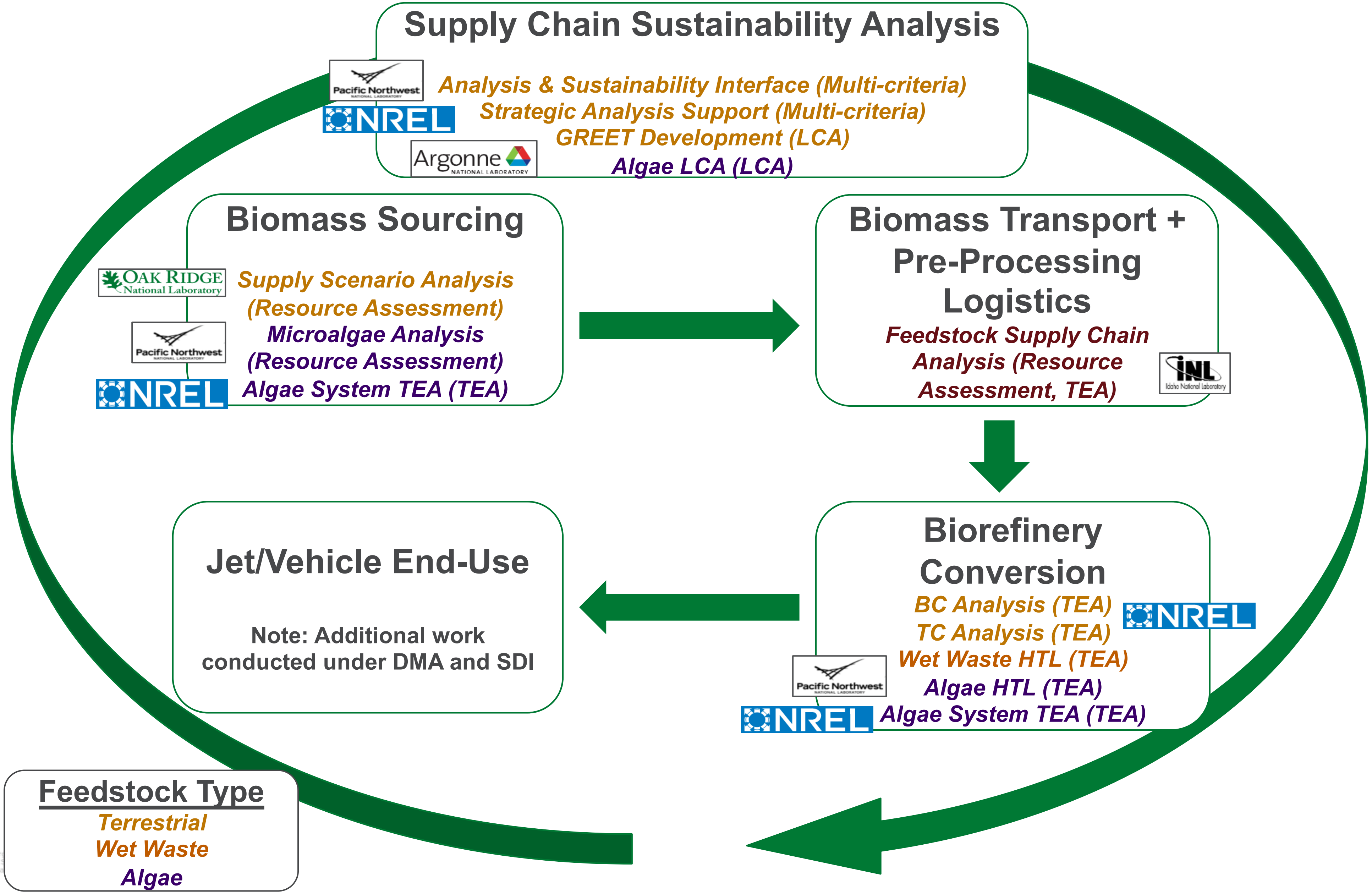
Supplementary Information on Approach

- Project Management
  - Regular project check-in meetings among team members to discuss project progress and address technical issues
  - Monthly and quarterly reporting and briefings to BETO project managers to inform project progress and seek feedback
  - Regular outreach to project partners to seek inputs to inform on-going modeling and analysis effort
- Risk Mitigation
  - Data gaps, uncertainties, and limitations are addressed through engineering modeling, literature review, and stakeholder engagement
  - Regular communications and discussions via conference calls with stakeholders and partners to mitigate risks of delays in data collection and other critical inputs and feedback.
- Go/No-Go
  - Selection of bioenergy pathways for LCA may be subject to data availability and BETO/community priority; changes are made in pathway selection by considering these factors
- Diversity, Equity and Inclusion
  - A diversified project team comprising of members and internship students of varied races, ethnic, and educational backgrounds
  - The GREET LCA and model development effort addresses EEEJ impacts of bioenergy technology development via quantifying environmental issues such as water consumption and regional water stress, criteria air pollutant emissions, and waste management that can be used by EEEJ research efforts
  - Dissemination of research outcomes and modeling tools to the public via webinars and in-person training workshops

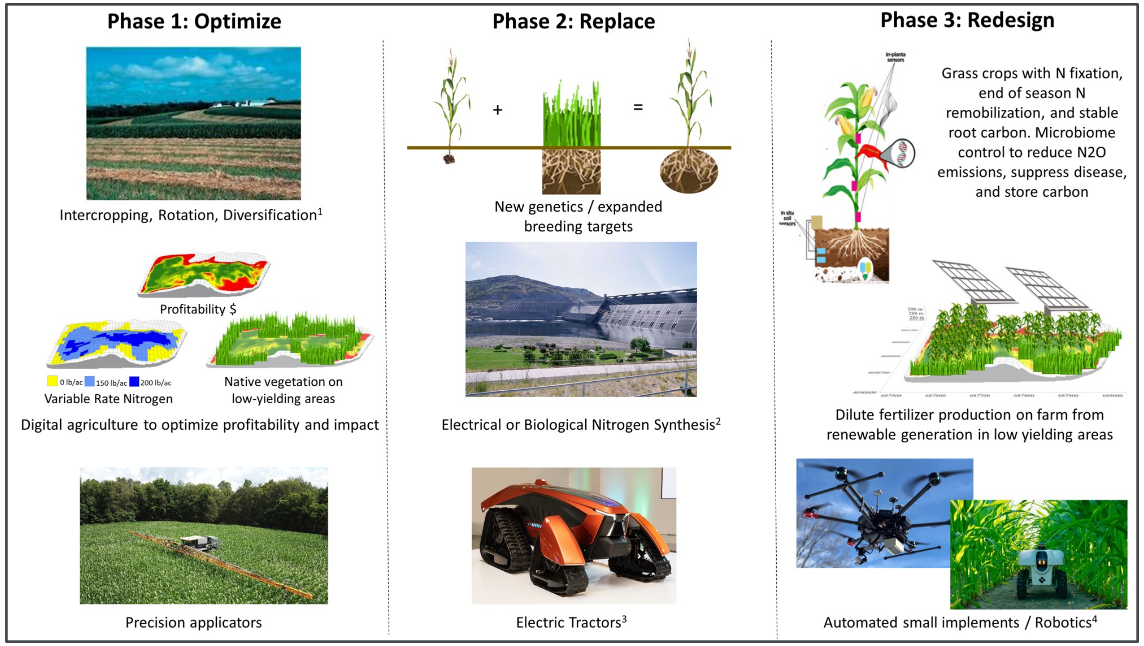
GREET Modeling Framework to Address Critical Success Factors

- Build LCA modeling capacity
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues such as iLUC, counterfactual scenarios, co-product methods, end-of-life implications (e.g., biodegradability)
- Access to primary data sources and conduct detailed analysis
- Document sources of data, modeling and analysis approach, and results/conclusions
- Maintain openness and transparency of LCAs by making GREET and its documentation publicly available
- Primarily process-based LCA approach (the so-called attributional LCA); some features of consequential LCA are incorporated

Supply Chain Sustainability Analysis (SCSA) Interacts with and Supports Broad BETO R&D and Analysis Projects

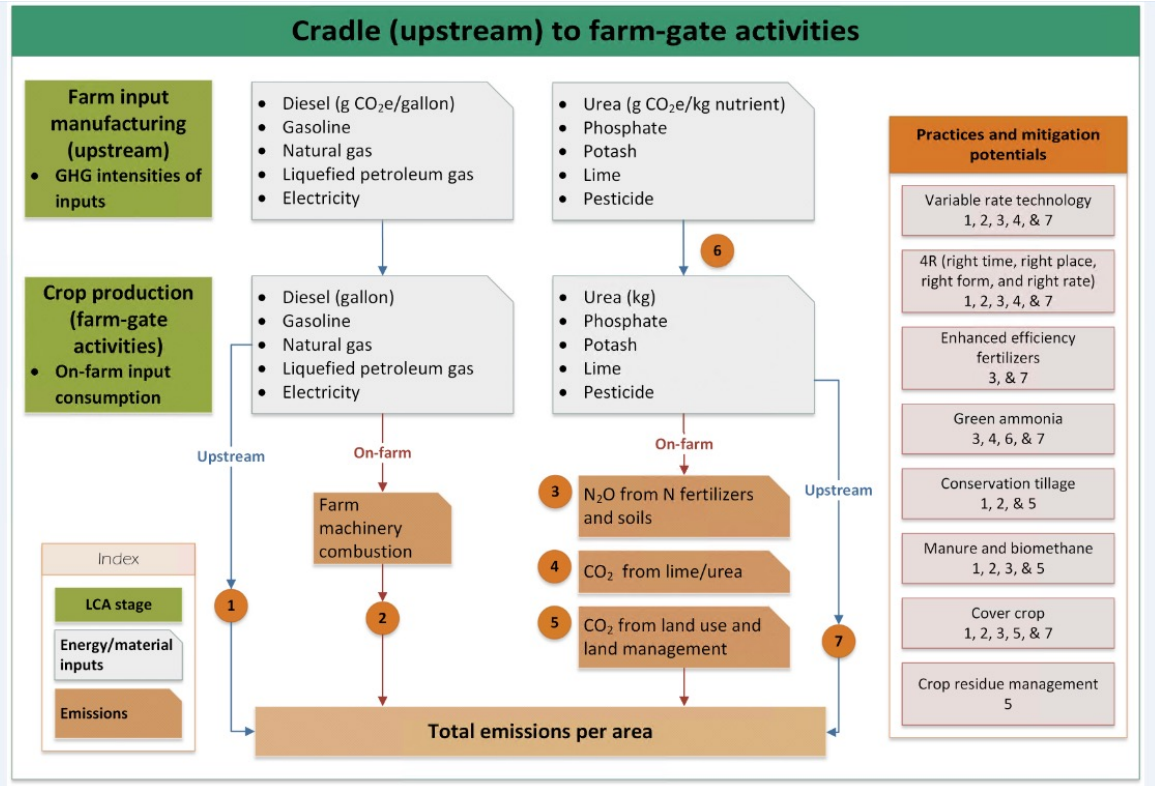


Feedstock Analysis Considers Near-Term GHG Reduction Opportunities by Changing Farming Practices/Technologies

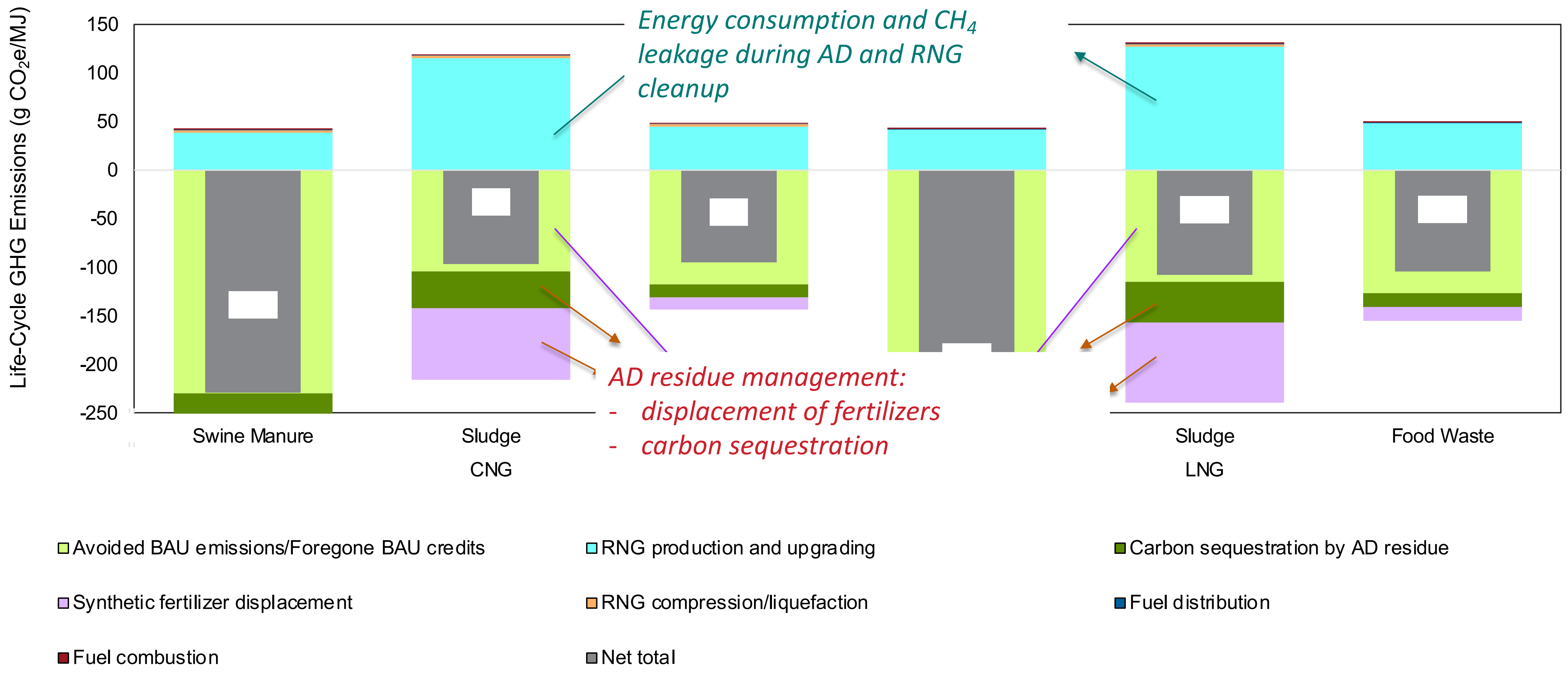


- Elaborated novel technologies to facilitate deep decarbonization of row crop production (*Northrup et al. 2021*)

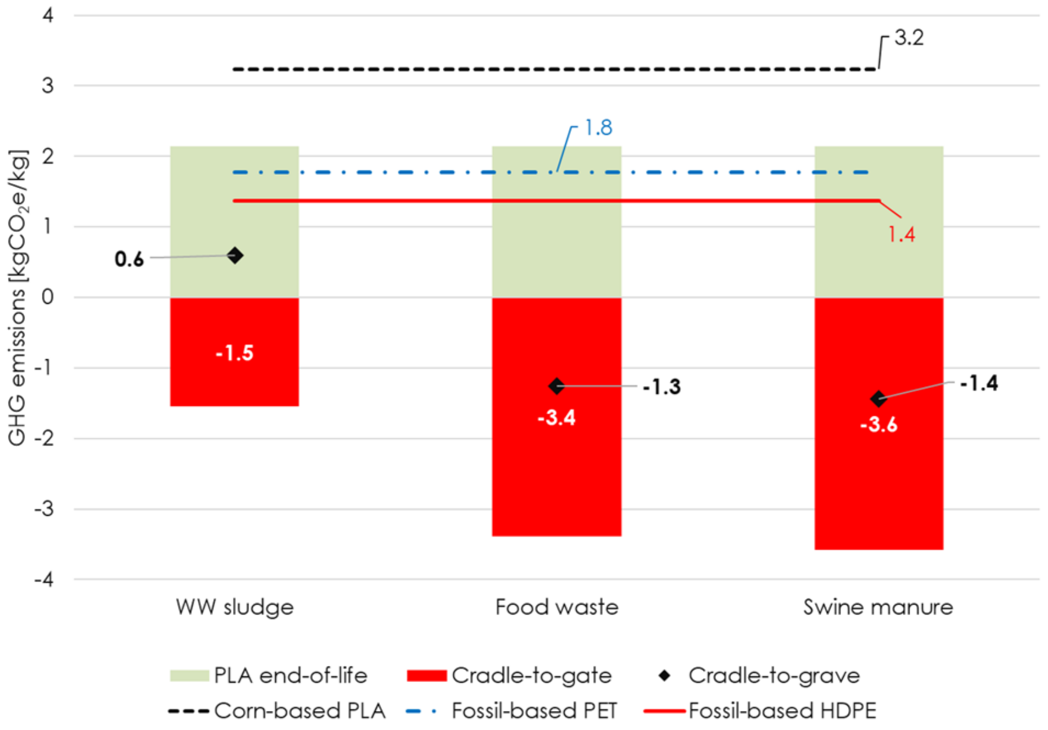
- Identify GHG mitigation strategies for US farming from the perspective of biofuel LCA (*Kwon et al. 2021*)

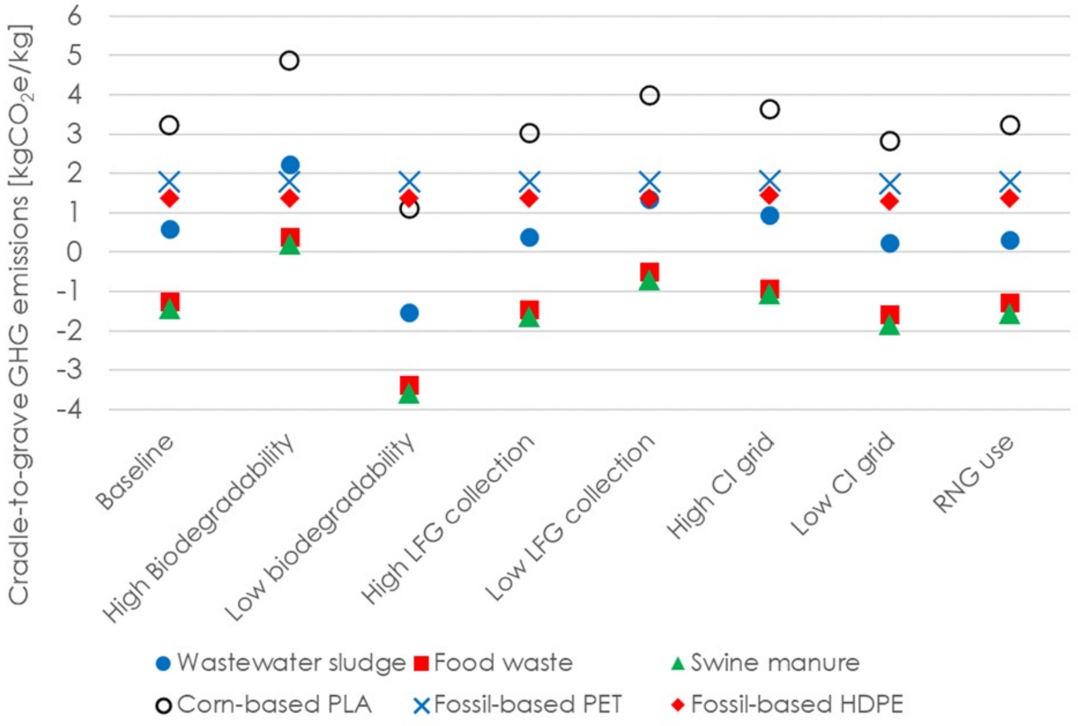


Counterfactual Waste Management Practices Can Greatly Affect LCA Results of WTE Technologies



Bio-Derived Plastic Pathways from Wet Waste Feedstocks: Polylactic Acid





- All three feedstocks outperform fossil-PET and corn-PLA in terms of GHG emissions
- Food waste- and swine manure-based pathways are “carbon-negative” because of BAU credits
- Largest GHG contributor was the electricity consumption for polymerization

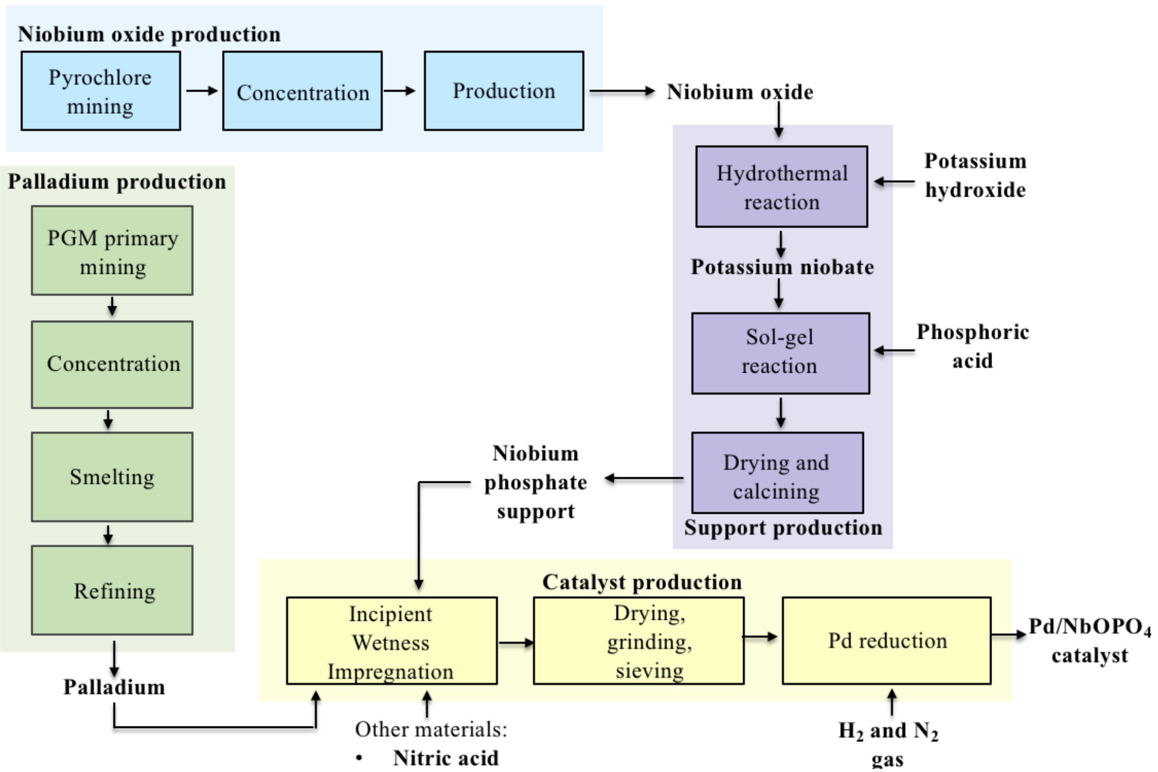
https://doi.org/10.1016/j.jclepro.2022.135110

Supply Chains Developed for New Catalyst for Biofuel Production

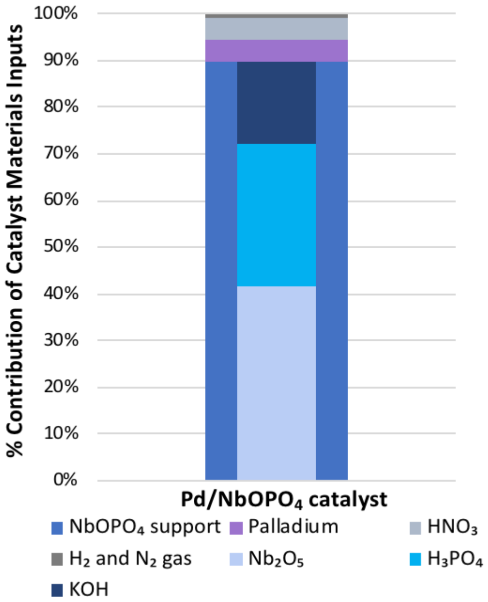
New catalysts

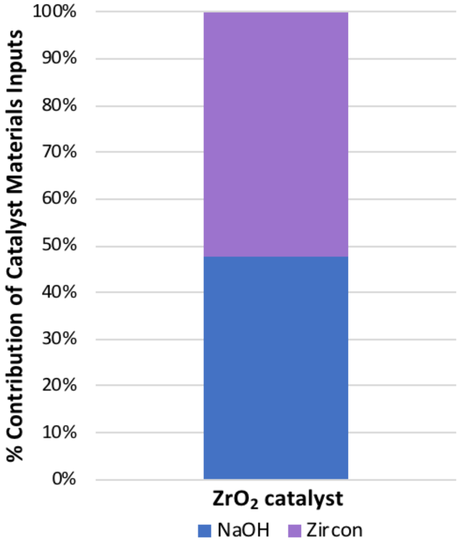
- single-phase catalyst composed of palladium metal on a niobium phosphate support: $Pd/NbOPO_4$
- Zirconium oxide: ZrO2

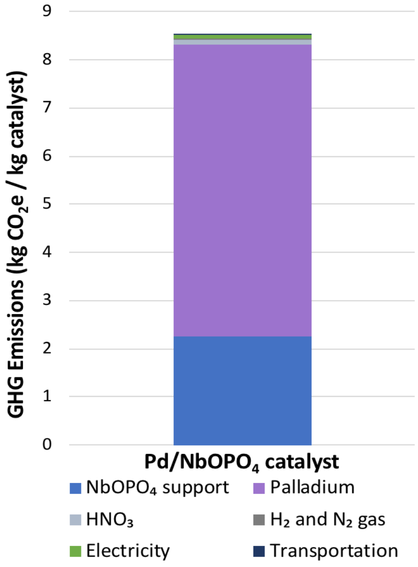
Analysis helps understand impact of major materials and processes involved in production of catalysts

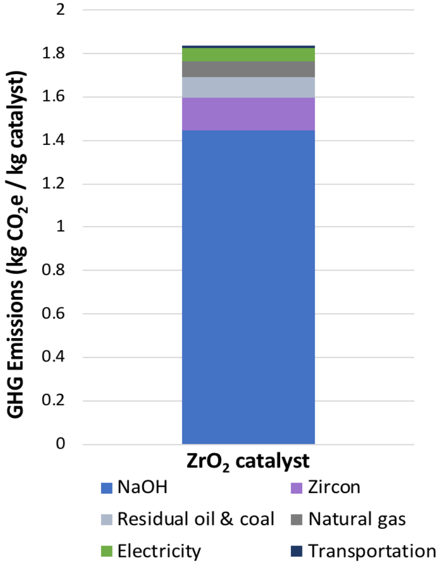


Supply chain featuring the primary materials inputs and outputs for production of Pd/NbOPO4 catalyst (Kingsbury & Benavides 2021)



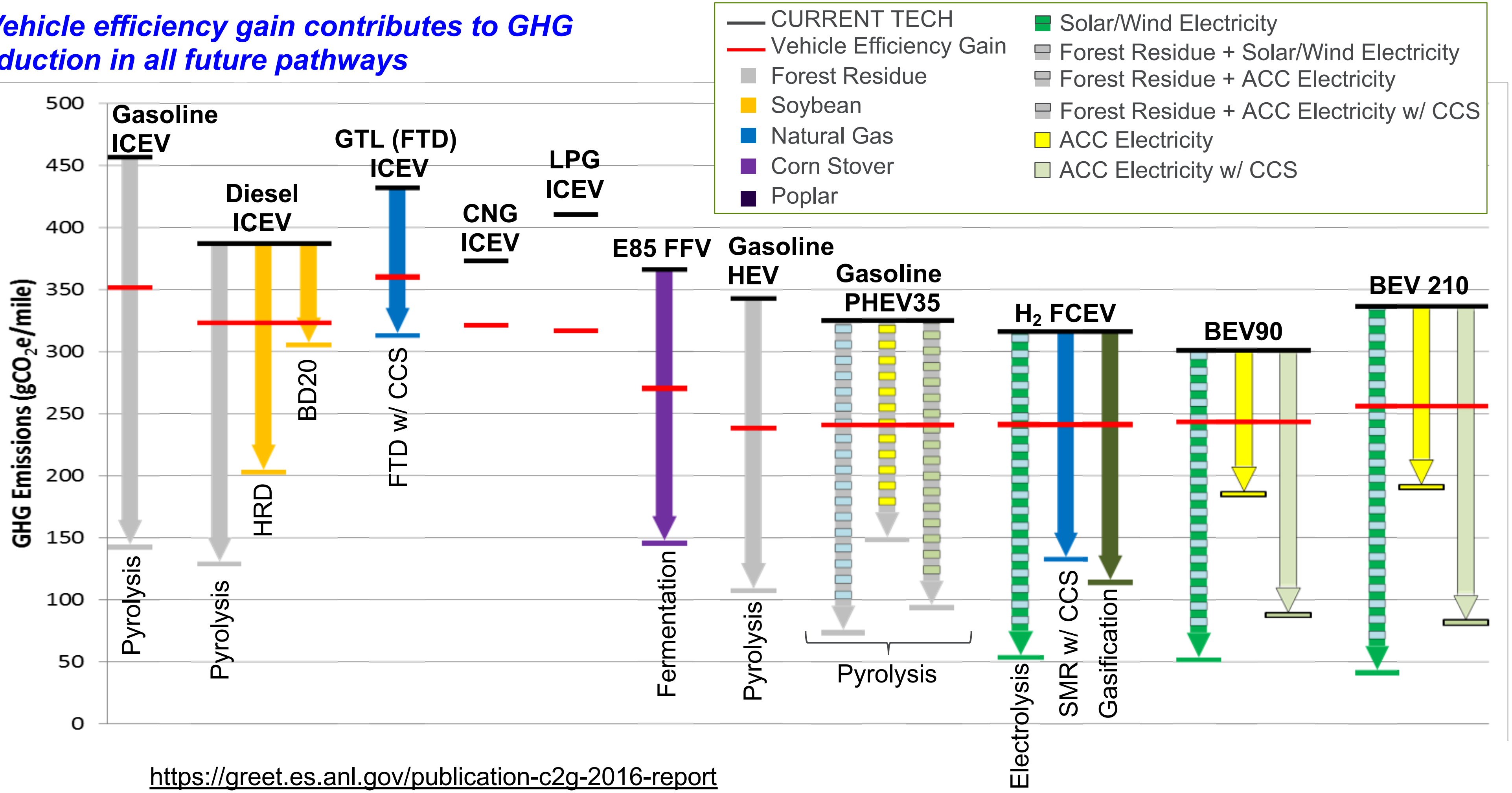






USDRIVE ISATT Tech Team Results from GREET: Biofuels Can Play Important Role in Transportation Decarbonization

***Note*: Vehicle efficiency gain contributes to GHG reduction in all future pathways**



https://greet.es.anl.gov/publication-c2g-2016-report
https://pubs.acs.org/doi/abs/10.1021%2Fes302420z