GREET Development and Biofuel and Bioproduct Pathway Research and Analysis

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Acronyms

ABF	Agile bio foundry
ACC	American Chemistry Council
AD	Anaerobic digestion
AEO	Annual Energy Outlook
AGE	Air and Greenhouse Gas Emissions
AFTF	Alternative Fuel Task Force
AMF	Advanced Motor Fuels
AMPD	Air Markets Program Data of EPA
ANL	Argonne National Laboratory
AOP	Annual Operation Plan
AR5	Fifth Assessment Report
ARS	Agricultural Research Service of USDA
AWARE-US	Available Water Remaining for the United States
BAT	Biomass Assessment Tool
BAU	Business as usual
BD	Biodegradable
BDO	2,3-butanediol (BDO)
BAT	Biomass Assessment Tool
BECCS	Bioenergy with carbon capture and sequestration
BETO	Bioenergy Technologies Office
BEV	Battery Electric Vehicle
Bio-PE	Bio-polyethylene
CA	California
CAP	Combined algae processing
CARB	California Air Resources Board
CCLUB	Carbon Calculator for Land Use and Land Management Change from Biofuel Production
CCS	Carbon Capture and Sequestration
CFP	Catalytic fast pyrolysis
CI	Carbon intensity
CNG	Compressed natural gas
CO	Carbon monoxide
CORRIM	Consortium for Research on Renewable Industrial Materials
CORSIA	Carbon Offsetting and Reduction Scheme for International Aviation
CRC	Coordinating Research Council
DGS	Distillers' grain with solubles
DMA	Data, Modeling, and Analysis Program of DOE BETO
DME	Dimethyl ether
DOD	U.S. Department of Defense
DOT	Department of Transportation
EC	European Commission
ECCC	Environment and Climate Change Canada
E-fuel	Electro-fuel
eGRID	Emissions & Generation Resource Integrated Database
EIA	Energy Information Administration
EPA	Environmental Protection Agency
ERS	Economic Research Service of USDA
EU	European Union

FAA	Federal Aviation Administration
FBN	Farmers Business Network
FCEV	Fuel Cell Electric Vehicles
FCIC	Feedstock Conversion Interface Consortium
FFV	Flexible Fuel Vehicle
FOA	Funding Opportunity Announcements
FOG	Fats, oils and grease
FRA	Federal Rail Administration of DOT
FT	Fischer-Tropsch
FTD	Fischer-Tropsch Diesel
GGE	Gasoline gallon equivalent
GHG	Greenhouse gas
GREET	GHGs, Regulated Emissions, and Energy use in Technologies
GTAP	Global Trade Analysis Project
GWP	Global warming potential
HDPE	High density Polyethylene
HTL	Hydrothermal liquefaction
IBR	Integrated biorefinery
ICAO	International Civil Aviation Organization of the UN
IPCC	Intergovernmental Panel on Climate Change
IDL	Indirect liquefaction
IEA	International Energy Agency
IMO	International Marine Organization of the UN
INL	Idaho National Laboratory
ISATT	Integrated Systems Analysis Technical Team of the U.S. DRIVE
JRC	Joint Research Center of the EC
KDF	Knowledge Discovery Framework
LCA	Life cycle analysis
LCFS	Low Carbon Fuel Standard
LDPE	Low density Polyethylene
LLNL	Lawrence Livermore National Laboratory
LMC	Land Management Change
LP	Linear Programming modeling for petroleum refineries
LPG	Liquefied natural gas
LUC	Land Use Change
MARAD	The Maritime Administration of DOT
MIT	Massachusetts Institute of Technology
MJ	Megajoule
MOVES	Motor Vehicle Emission Simulator
MPGGE	Miles per gasoline gallon equivalent
MRO	Midwest Reliability Organization
MSW	Municipal Solid Waste
NASS	National Agricultural Statistics Service
NBB	National Biodiesel Board
NC	North Carolina
NERC	North American Electric Reliability Corporation

NHTSA	National Highway Traffic Safety Administration
NG	Natural gas
NOx	Nitrogen oxides
NPCC	Northeast Power Coordinating Council
NREL	National Renewable Energy Laboratory
NZCF	Net-zero carbon fuel
ORNL	Oak Ridge National Laboratory
PE	Polyethylene
PFAD	Palm Fatty Acid Distillate
PI	Principal Investigator
PLA	Polylactic acid
PNNL	Pacific Northwest National Laboratory
PM	Particulate matter
PTW	Pump-to-wheel
QA/QC	Quality assurance/quality control
R&D	Research & development
RD	Renewable diesel
RFA	Renewable Fuels Association
RFS2	Renewable Fuels Standard 2
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
TCP	Technology Collaboration Programs
TEA	Techno-economic analysis
TPA	Terephthalic acid
TT	Tech. Team
UIUC	University of Illinois at Urbana-Champaign
US	United States
USB	United Soybean Board
USDA	U.S. Department of Agriculture
US DRIVE	U.S. Driving Research and Innovation for Vehicle Efficiency and Energy Sustainability
USGS	U.S. Geological Survey
VOC	Volatile organic compound
VTO	Vehicle Technologies Office
WATER	Water Analysis Tool for Energy Resources
WTP	Well-to-pump
WTW	Well-to-wheels

Project Goals, Impact, and Outcome

Goal **Quantify life-cycle energy and environmental impacts of biofuels/bioproducts**

- Energy diversification
- Greenhouse gas emissions
- Criteria air pollutant emissions
- Water consumption

Impact **Present societal value proposition of biofuel/bioproduct technologies**

- Provide LCA results for societal benefits 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

Outcome **Accurate results about energy and environmental implications of biofuel/bioproduct systems to help R&D directions and policy/business 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

Project Overview – What Are We Trying To Do?

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

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 the 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 other stakeholders. • LCA is data intensive. Consistent models and datasets are needed to enable reliable comparisons across technologies.
Why is it important?	• Bioenergy energy and environmental sustainability metrics are key for societal and business commitment. • Argonne's biofuel/bioproduct 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 out-of-date, misleading results. • Complete, consistent LCA system boundary provides holistic, objective biofuel/bioproduct results for decision making.

PI, Co-PIs, and Team Members


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The key to the success of the GREET project is the strength of the team with diversified expertise in chemical engineering, mechanical engineering, and environmental science.

Tasks Structured 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 aviation fuel pathways for ICAO
- Interaction with international, national, and state agencies

2. Feedstock Analysis for LCA of Biofuels and Bioproducts

- Feedstock production, harvest, and logistics
- Regional analysis 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
- Assessment of catalysts and enzymes for biofuel and bioproducts conversion

4. CO_2 Utilization for Production of Fuels and Products

- Project is comprised of interacting and well-coordinated tasks.
- Each task interacts with relevant stakeholders and incorporates data from other BETO projects.
- Task deliverables also support other BETO efforts such as Consortia and benchmark reports.

Task Structure

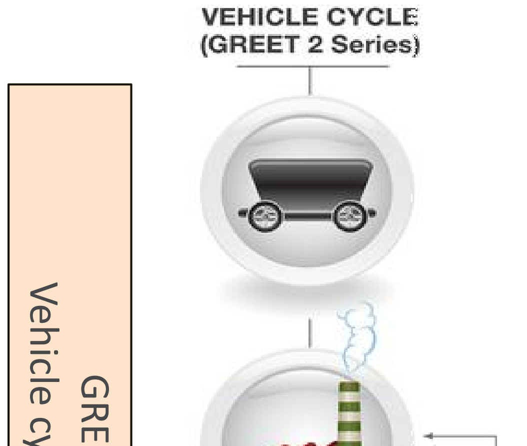
	<u>**Task Leads**, Key Contributors</u>
	Michael Wang (PI), Troy Hawkins
1. GREET Development and Bioeconomy Community Engagement	
– GREET development	**Uisung Lee**, all team members
– Supply chain sustainability analysis (SCSA) for BETO	**Hao Cai**, Longwen Ou
– Development of carbon intensities for aviation fuel pathways for ICAO	**Michael Wang**, Uisung Lee
– Interaction with international, national, and state agencies	**Michael Wang,** others
2. Feedstock Analysis for LCA of Biofuels and Bioproducts	
– Feedstock production, harvest, and logistics	**Hao Cai**, Longwen Ou
– Regional analysis of soil organic carbon and N_2O effects and CCLUB development	**Hoyoung Kwon**, Xinyu Liu
3. Conversion Process Analysis for LCA of Biofuels and Bioproducts	
– Waste-to-energy and waste-to-product technologies	**Uisung Lee**, Eunji Yoo
– Bioplastic technologies	**Thathiana Benavides**, U. Gracida
– Assessment of catalysts and enzymes for biofuel and bioproducts conversion	**Thathiana Benavides**, U. Gracida
4. CO_2 Utilization for Production of Fuels and Products	**Uisung Lee**, Eunji Yoo

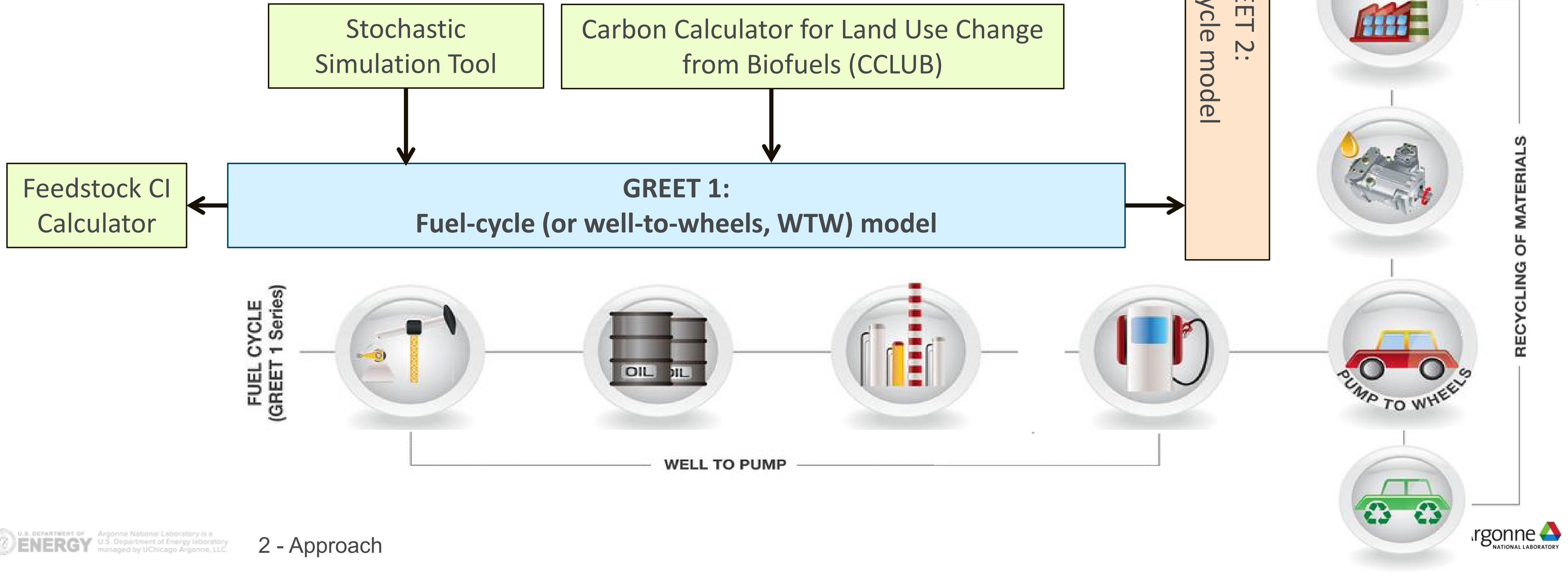
Interactions and Communication Are Key to Project Success

- Regular interactions with BETO staff
  - Maintain focus on programmatic priorities, align with state-of-the-art R&D, and coordinate with related BETO efforts
  - Project tracking through monthly and quarterly written reports to BETO, quarterly briefings with BETO Sponsor
- Internal project communication
  - Internal project plans guide each task, adding details to the project annual plan
  - Biweekly internal team meetings to review technical progress and gain feedback
  - Internal QA/QC procedures implemented for analyses and GREET development
- Interactions with other national laboratories and collaborators
  - National labs: NREL, PNNL, INL, LLNL, ORNL
  - Universities: Purdue, Northwestern, UIUC, Iowa State U, NC State U, SD State U
  - Industries: RFA, Growth Energy, ACC, POET, FBN, NBB, USB
- Outreach to agencies
  - Federal agencies: EPA, USDA, FAA, MARID
  - State agencies: CARB, OR Dept of Environ. Quality
  - International agencies: IEA, IEA Bioenergy TCP, IEA AMF TCP, ICAO, ECCC
  - Others: US DRIVE Tech Teams
- Dissimilation
  - Annual GREET release with updated and expanded bioenergy technology pathways
  - Publications are peer-reviewed and archived on the GREET website
  - Conference/workshop presentations
  - Help organize the biennial CRC LCA Workshop and the Asilomar Transportation Conference

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

- Argonne has been developing the GREET **life-cycle analysis (LCA)** model since 1995 with annual updates and expansions
- BETO has been a GREET sponsor since the beginning
- GREET is available at greet.es.anl.gov





GREET LCA Modeling Includes All Transportation Sectors

- Light-duty vehicles
- Medium-duty vehicles
- Heavy-duty vehicles
- Various powertrains:
  - Internal combustion
  - Battery electric
  - Fuel cells

Rail transportation in GREET includes
- Diesel
- Electricity
- CNG/LNG

A fast-growing sector with GHG reduction pressure. GREET includes
- Passenger and freight transportation
- Various sustainable aviation fuels and petroleum jet fuels

The sector is under pressure to reduce air and GHG emissions. GREET includes
- Ocean and inland water transportation
- Baseline diesel and alternative marine fuels

GREET is now expanded to include buildings.

GREET LCA Modeling Includes Key Metrics Requested by BETO and other DOE Programs

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	• Volatile Organic Compounds • Carbon Monoxide • Nitrogen Oxides • Particulates ($PM_{2.5}$, PM_{10}) • Sulfur Oxides Distinguished between urban and non-urban	Total energy separated to different types • Total Energy • petroleum • natural gas • coal • biomass • nuclear • hydro • wind • solar

Biofuels and CO2 Utilization 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:
- Dedi. energy crops
- Crop residues
- Forest residues
- MSW
- Animal wastes

Algae

Renewable Hydrogen via electrolysis:
- Wind
- Solar
- Nuclear

E-Fuels
- Gasoline
- Diesel
- Jet fuel
- Methanol

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

Besides energy systems, GREET also includes plastics and products.

GREET Development Is Part of BETO Sustainability Modeling

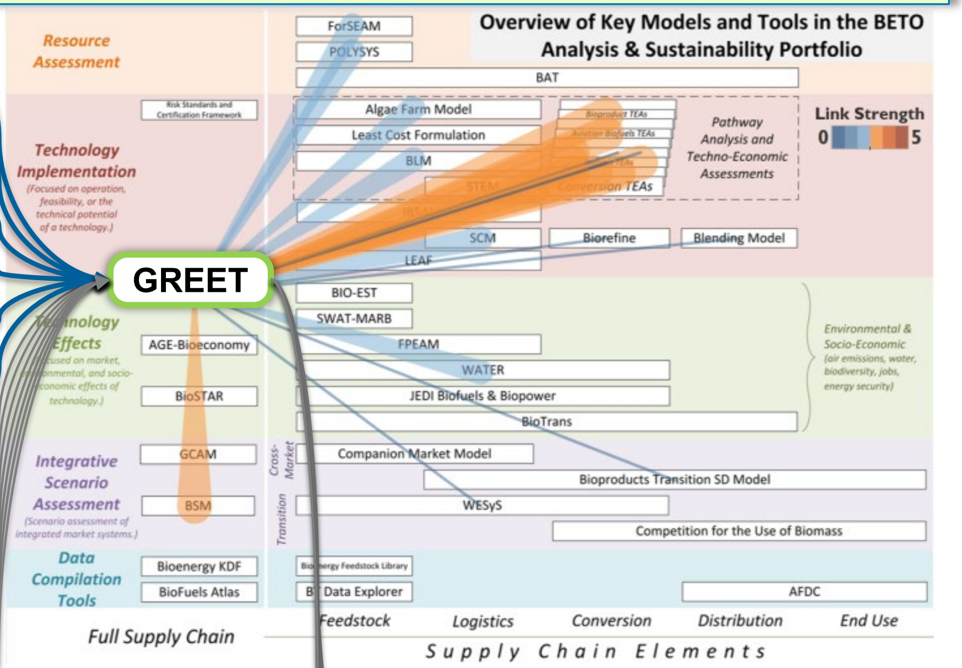
GREET Inputs from BETO-Sponsored Models

- BETO TEA Models
- Algae Farm Model
- Biomass Logistics Model
- WATER
- Biomass Scenario Model
- PNNL BAT

GREET Inputs from Other Models & Databases

- EIA AEO/Statistics
- USDA NASS
- GTAP
- CENTURY
- EPA eGRID
- USGS Water Use
- EPA MOVES

GREET Interactions with Other BETO-Sponsored Models



Examples of GREET Supporting Other Efforts

- DOT MARAD
- ICAO CORSIA
- US DRIVE Tech Teams
- CA-GREET for LCFS
- EPA RFS & Report to Congress

Examples of GREET Interactions

Supply Chain Sustainability Analyses use inputs from INL Biomass Logistics models and NREL/PNNL conversion process models to produce greenhouse gas, water consumption, and energy use results used by BETO to benchmark R&D efforts.

Datasets from GREET are leveraged in studies for the US DRIVE Integrated Systems Analysis Technical Team and the U.S. Environmental Protection Agency's *Biofuels Report to Congress*.

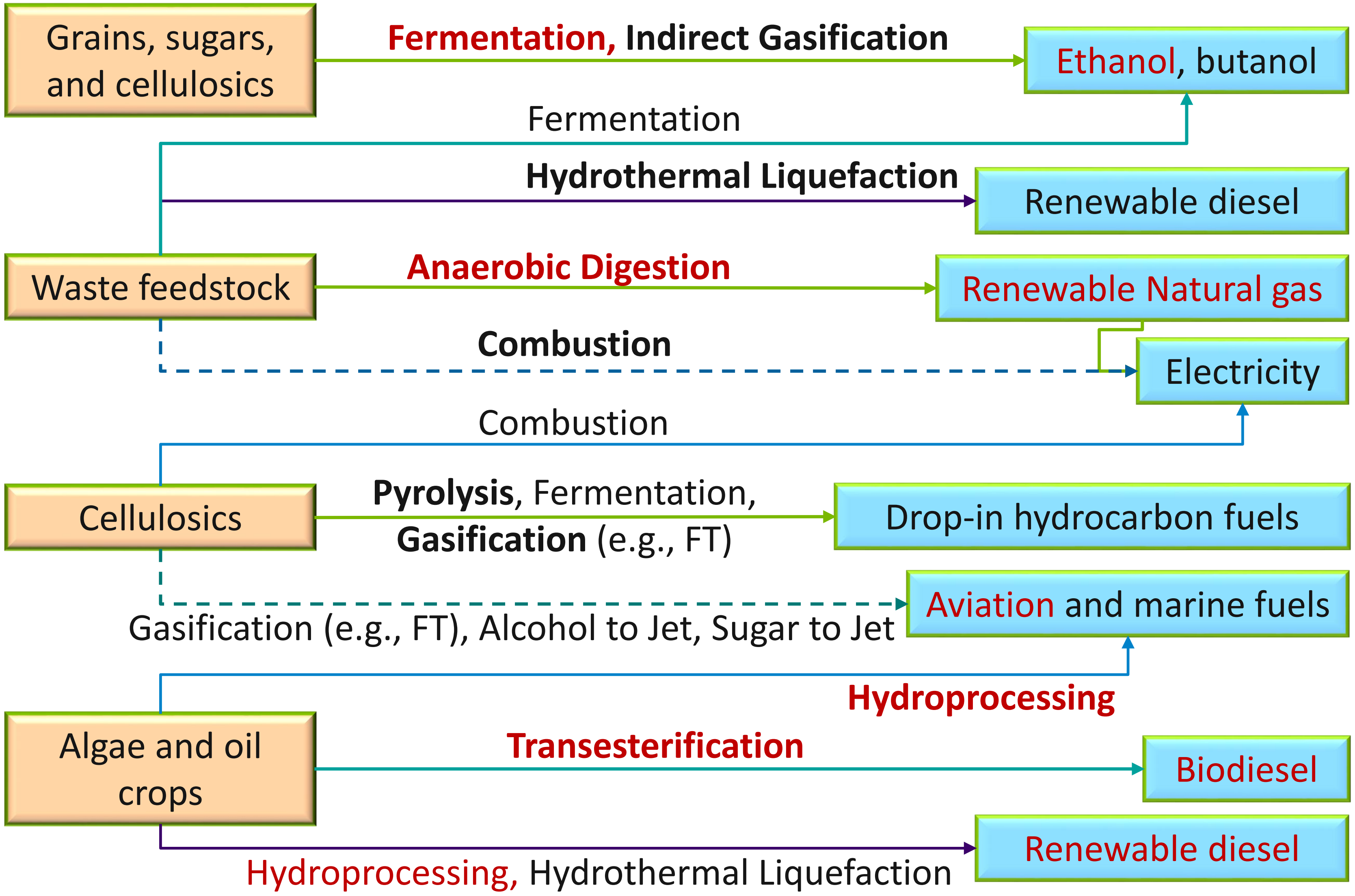
Critical Success Factors Identified for GREET Development and Applications

- 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 concerns
- GREET (and LCA models) should address technology advancements and technical variability and uncertainties
  - LCA simulations should be dynamic to consider technology advancements over time
  - Variability of technology performances 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 Modeling Approach to Address Critical Success Factors

- Build comprehensive LCA modeling capacity
- Build a consistent LCA platform with reliable, widely accepted methods/protocols
- Address emerging LCA issues with science and vigor
- 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
- GREET is based primarily on process-based LCA approach (the so-called attributional LCA); and with some features of consequential LCA (e.g., land use change)

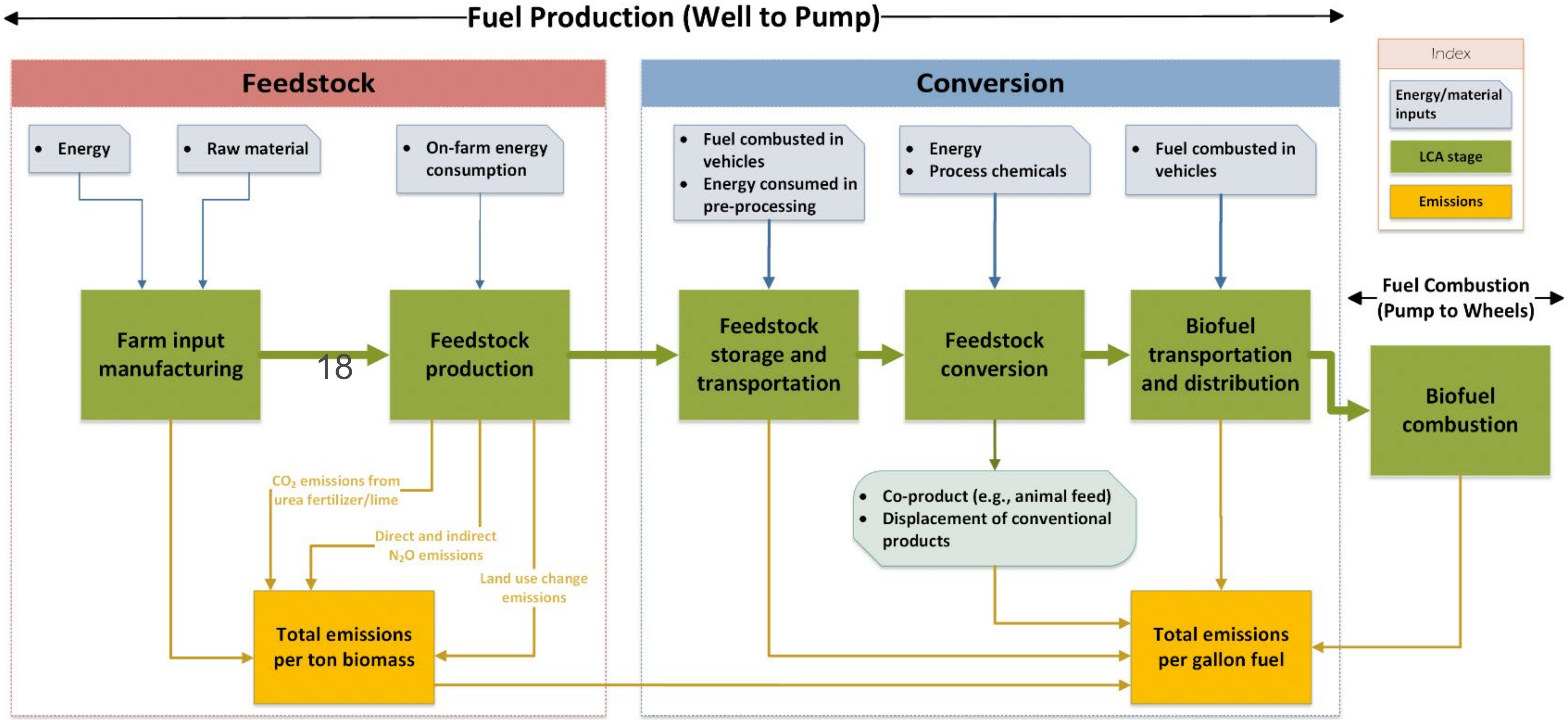
GREET Includes A Variety of Biofuel Technology Pathways of Interest to BETO and Regulations



Consistent comparison across all relevant technologies key to providing actionable insights.

- **The highlighted options have significant volumes in LCFS and RFS**
- **Ethanol accounts for >15 billion gallons nationwide, and >1.1 billion gallons in CA**

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



Including a comprehensive system boundary is key for an accurate LCA result.

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

Baseline technologies and systems

- Energy Information Administration's data and its Annual Energy Outlook projections
- EPA eGrid for electric systems
- U.S. Geological Survey for water data

Field operation data

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

Simulations with models

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

Collaboration with other national laboratories

Industry inputs

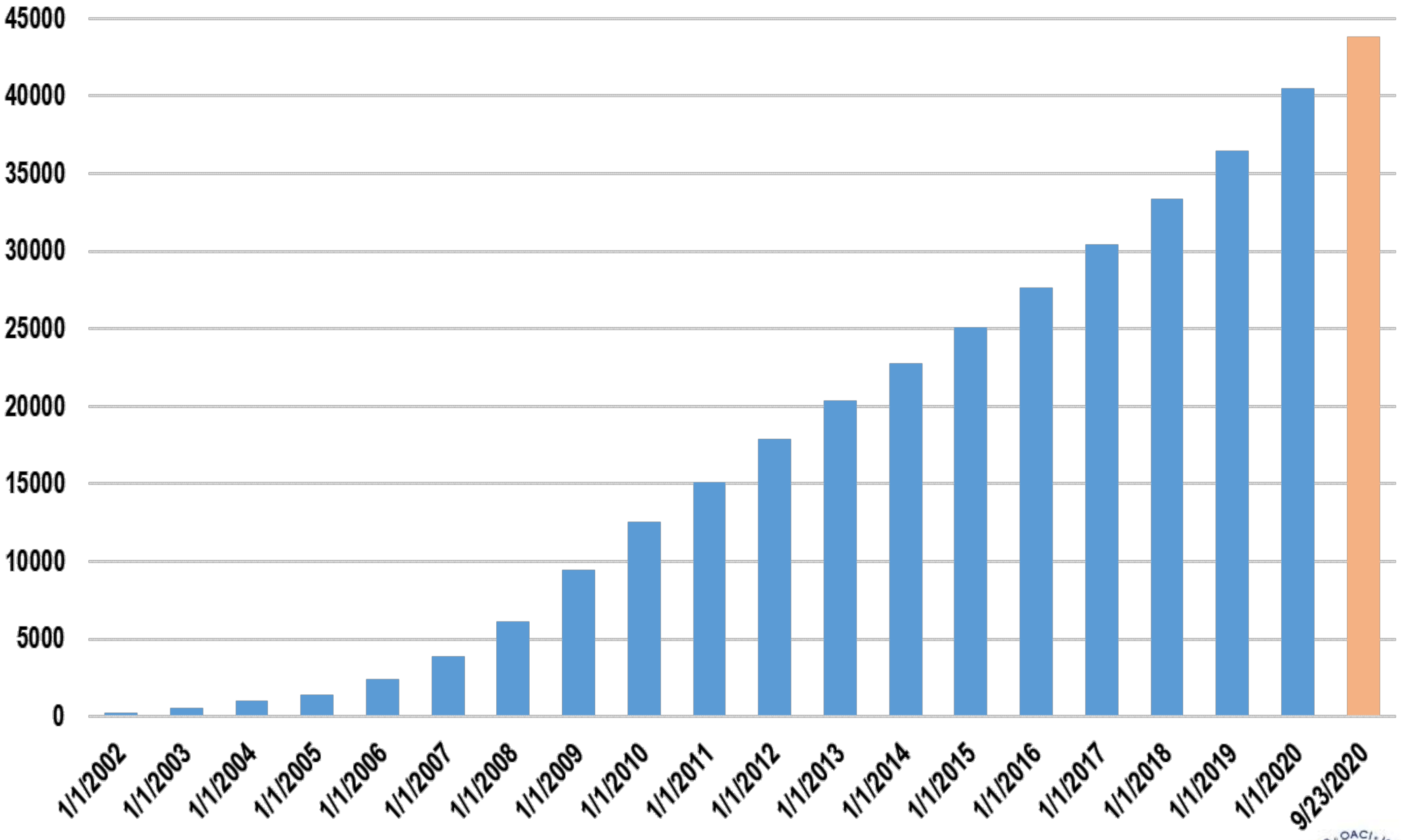
- Fuel producers and technology developers on fuels
- Automakers and system components producers on vehicles

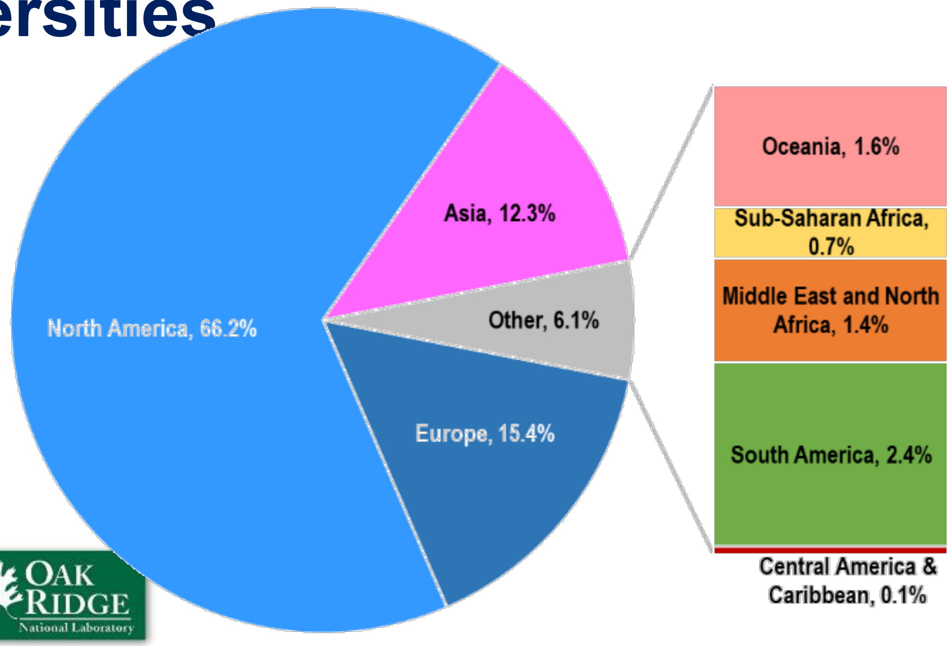
Data availability and reliability are always a challenge for LCA.

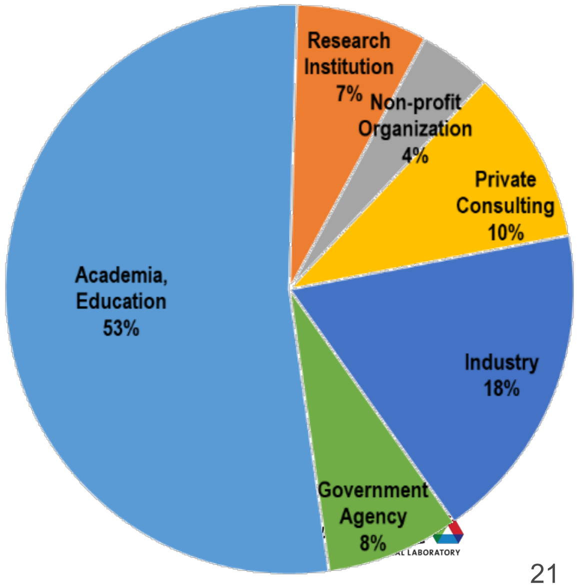
GREET Impact: Address Sustainability of Bioenergy and Bioproducts and Identify Hotspot Sustainability Issues for R&D Opportunities

- 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 companies to identify and pursue biofuel/bioproduct pathways that are environmentally sustainable
- A detailed model with process level fidelity for R&D teams to identify emission and energy consumption hotspots for R&D opportunities

The Large GREET User Base Covers Government Agencies, Corporations, Research Institutions, and Universities







GREET Applications by Federal, State, and International Agencies

- CA-GREET3.0 built based on and uses data from ANL GREET
- Oregon Dept of Environmental Quality Clean Fuel Program
- EPA RFS2 used GREET and other sources for LCA of fuel pathways
- National Highway Traffic Safety Administration (NHTSA) fuel economy regulation
- FAA and ICAO Fuels Working Group using GREET to evaluate aviation fuel pathways
- GREET was used for the US DRIVE Fuels Working Group Well-to-Wheels Report
- LCA of renewable marine fuel options to meet IMO 2020 sulfur regulations for the DOT MARAD
- US Dept of Agriculture: ARS for carbon intensity of farming practices and management; ERS for food environmental footprints; Office of Chief Economist for bioenergy LCA
- Environment and Climate Change Canada: develop Canadian Clean Fuel Standard

GREET Applications by Corporations

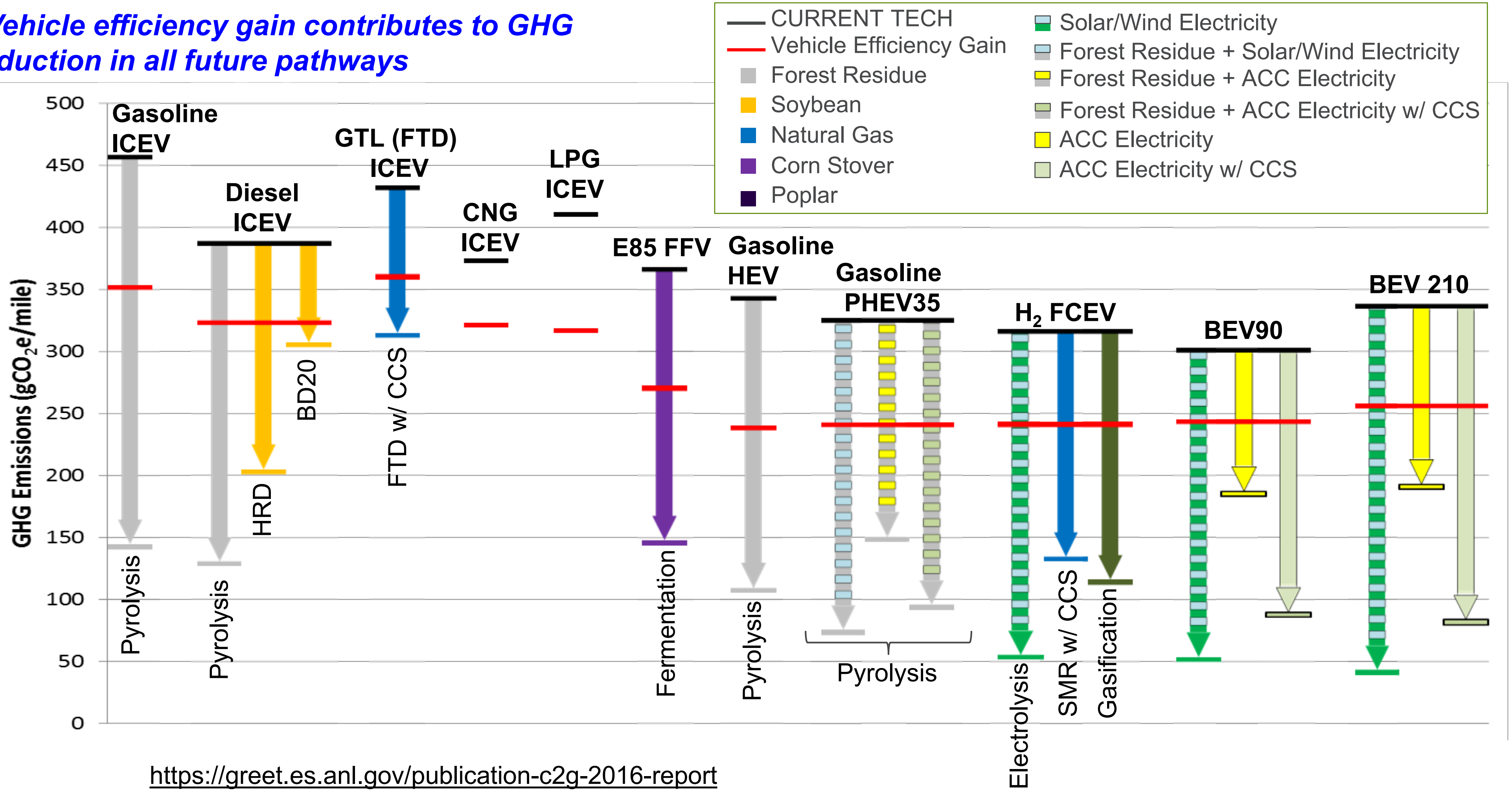
- Net carbon footprints of fuel and chemical products by Shell for annual progress to Shell's commitment of 65% reduction of its carbon footprints by 2050
- Carbon intensities of co-processed biofuels in petroleum refineries
- Impacts of low-carbon feedstocks on carbon intensities of corn ethanol in a POET ethanol plant
- Calculate CIs of biofuel feedstocks
- GHG and other environmental effects of fuels and plastics from pyrolysis of used plastics

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

- Conversion Technologies and Advanced Algae Systems Programs
- Marine multi-lab AOP
- Co-Optima
- Agile BioFoundry (ABF)
- Bioprocessing Separations Consortium
- Feedstock-Conversion Integration Consortium (FCIC)
- 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.
  - Production of Bioproducts from Electrochemically-Generated C1 Intermediates- LanzaTech

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

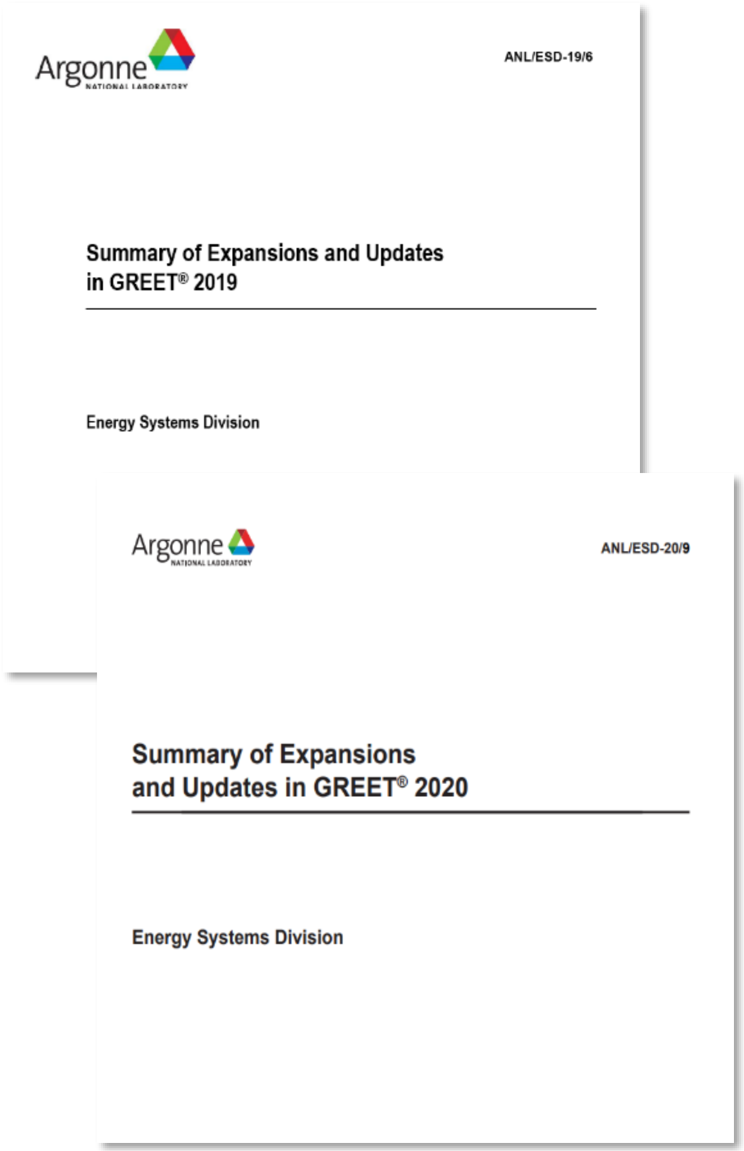
***Note*: Vehicle efficiency gain contributes to GHG reduction in all future pathways**



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

GREET Development: 2019 and 2020 Releases Included Updated and New Biofuel/Bioproduct Pathways and Modules

- New Biofuels/Bioproducts pathways
  - E-fuel production pathways (CO_2 utilization)
  - Bioplastics production pathways
  - Supply Chain Sustainability Analysis (SCSA) pathways
  - Updated SOC modeling using CCLUB
  - Waste-derived fuels and products (renewable natural gas and lactic acid production from four types of waste feedstocks)
  - Newly expanded marine module
- 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 GREET2020
  - Green ammonia
  - PFAD-derived renewable diesel
  - Animal feed LCA module
  - Steam cracking for chemical production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Summary of Expansions and Updates in GREET® 2019

Energy Systems Division

Argonne NATIONAL LABORATORY

ANL/ESD-20/9

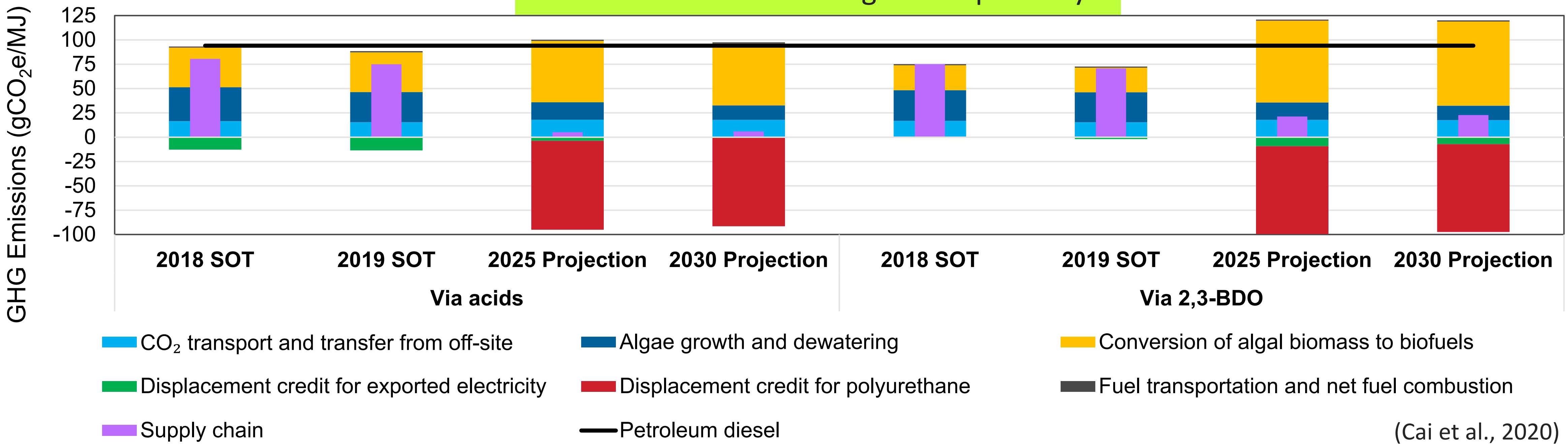
Summary of Expansions and Updates in GREET® 2020

Energy Systems Division

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

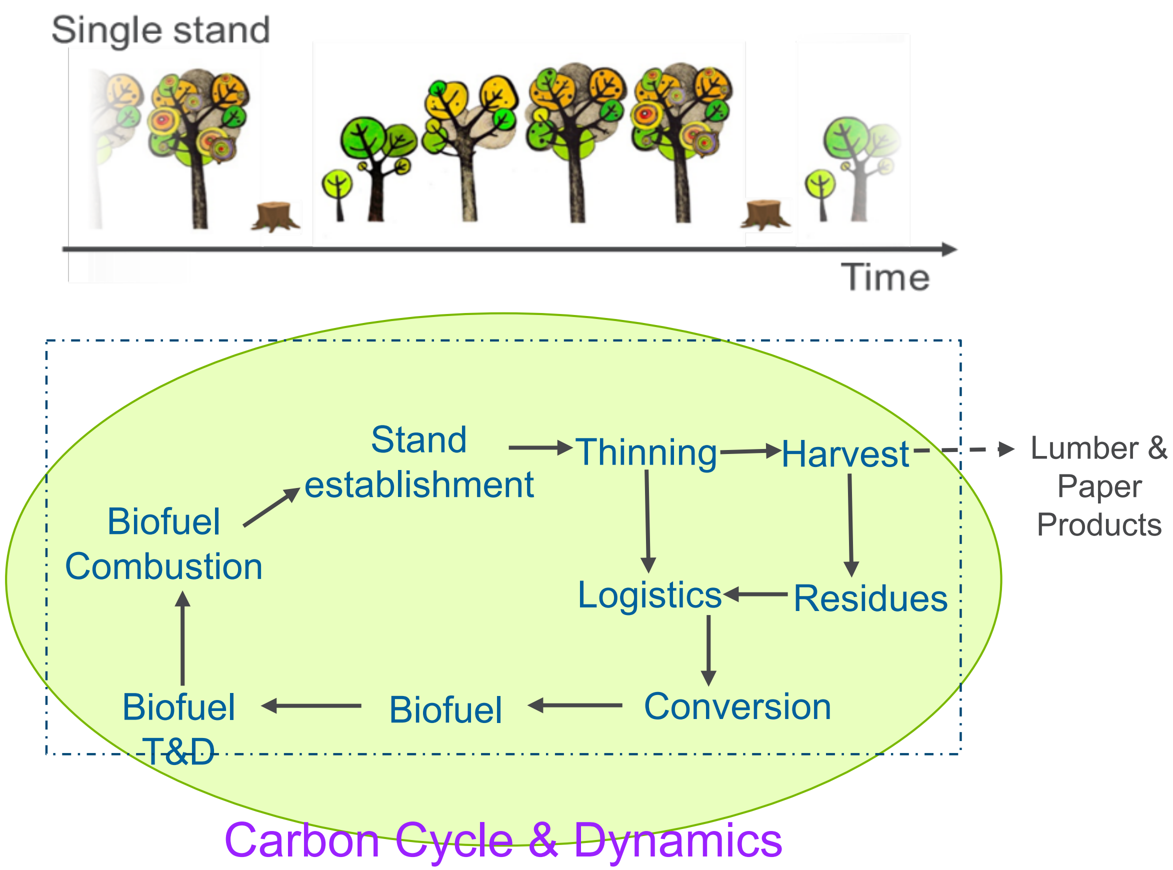
- With BETO coordination, data and information exchange among national labs (ANL, INL, NREL, and PNNL)
- **Three dry feedstock pathways** to produce renewable gasoline and renewable diesel: woody feedstock via IDL, woody feedstock via ex-situ CFP, and herbaceous feedstock via biochemical conversion
- **Three wet feedstock pathways** to produce renewable diesel: algae via HTL, algae via CAP, and wastewater plant wet sludge via HTL
- **Continuous sustainability improvements in 2019 SOT cases** were 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 biofuel SCSA results

SCSA GHG Results for Algae CAP pathway

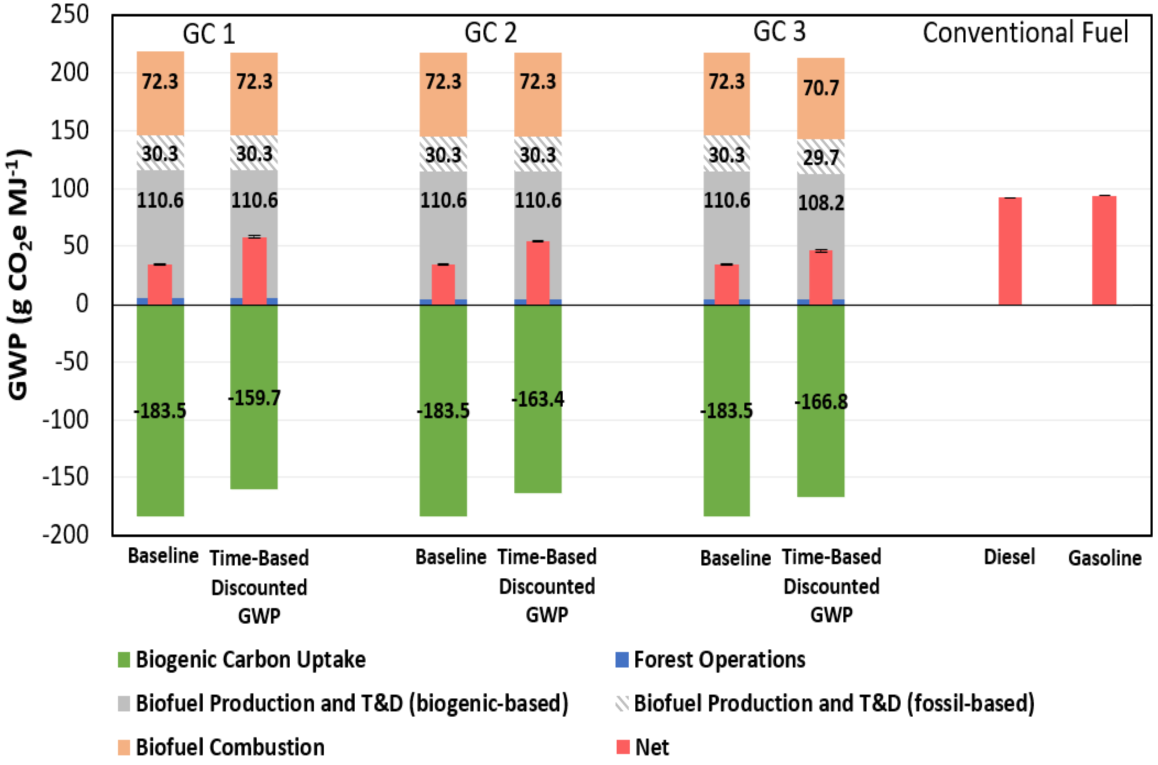


(Cai et al., 2020)

Feedstock Analysis Addresses Temporal Carbon Effects of Woody Biomass on Biofuel Carbon Intensities



Carbon Uptaking and Release of Woody Biofuels Happen at Different Times



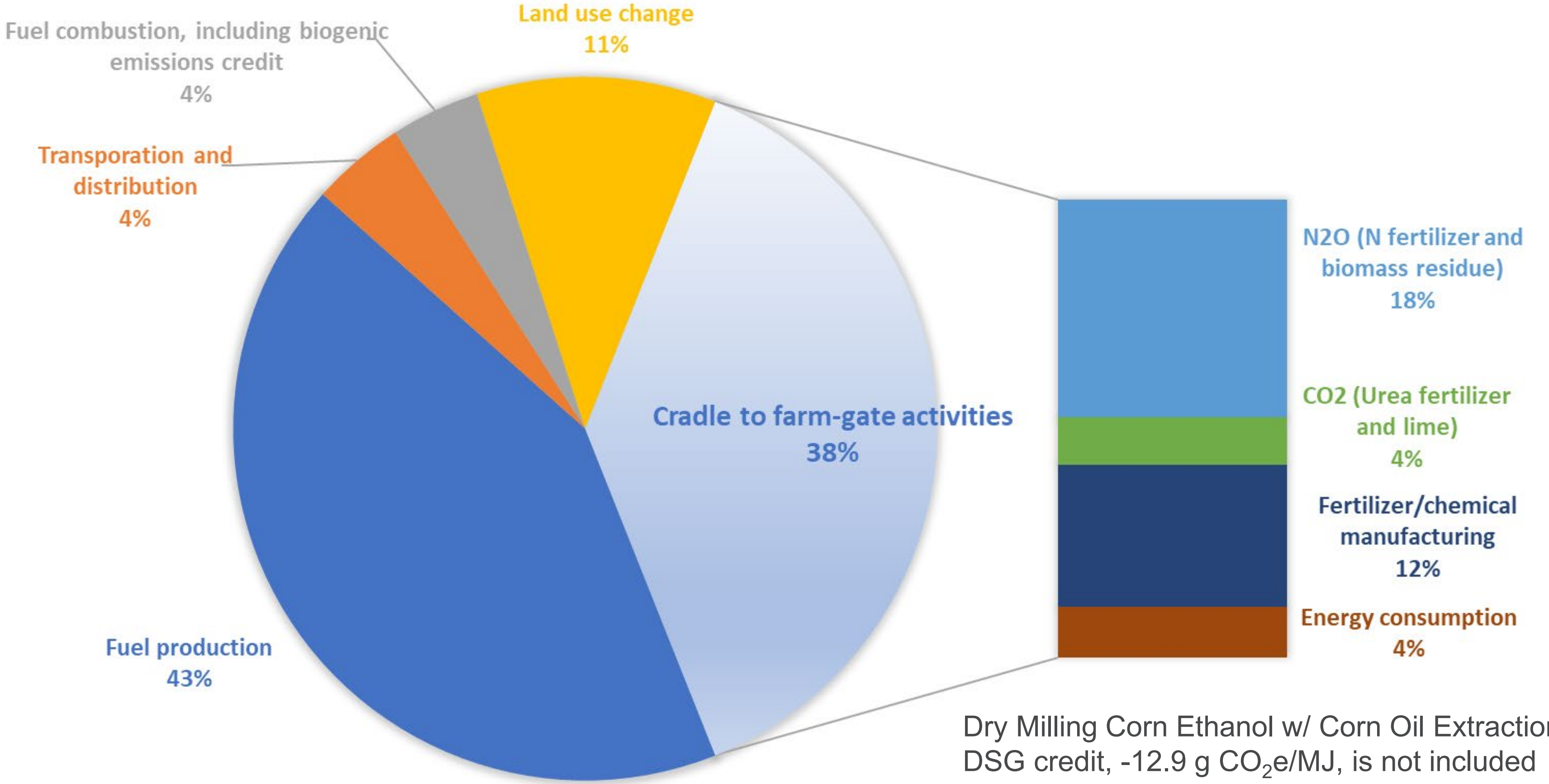
Fuel carbon intensities under three growth cycles vary between with and without considering temporal carbon effects

- The three cycles reflect forest productivity, thinning practice, and fertilizer applications.

Considering temporal carbon effects may result in somewhat smaller GHG emission reductions by pine residue-derived biofuels compared to a straight carbon neutrality assumption.

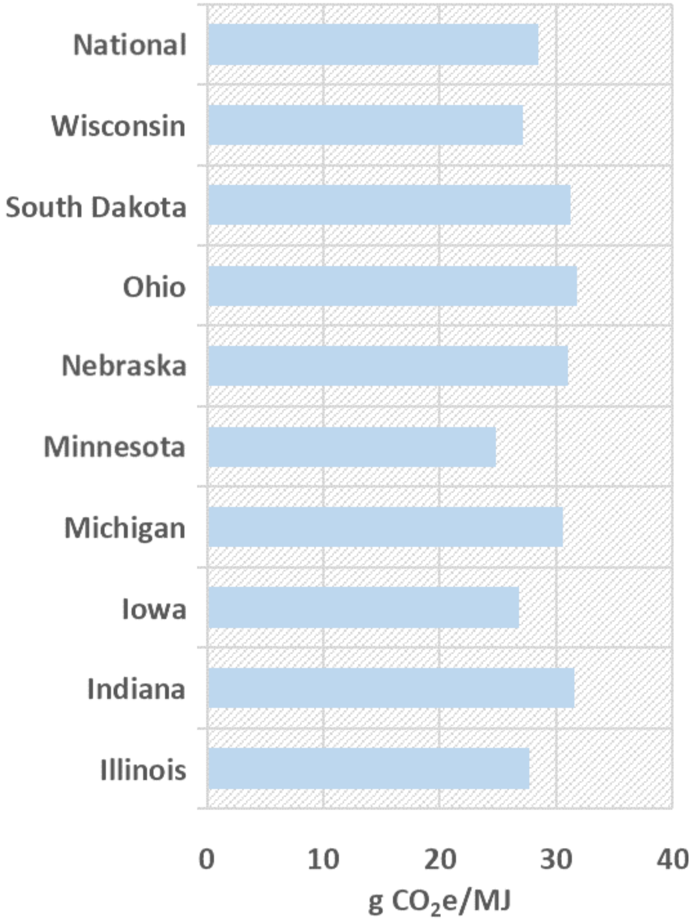
(Lan et al., 2021)

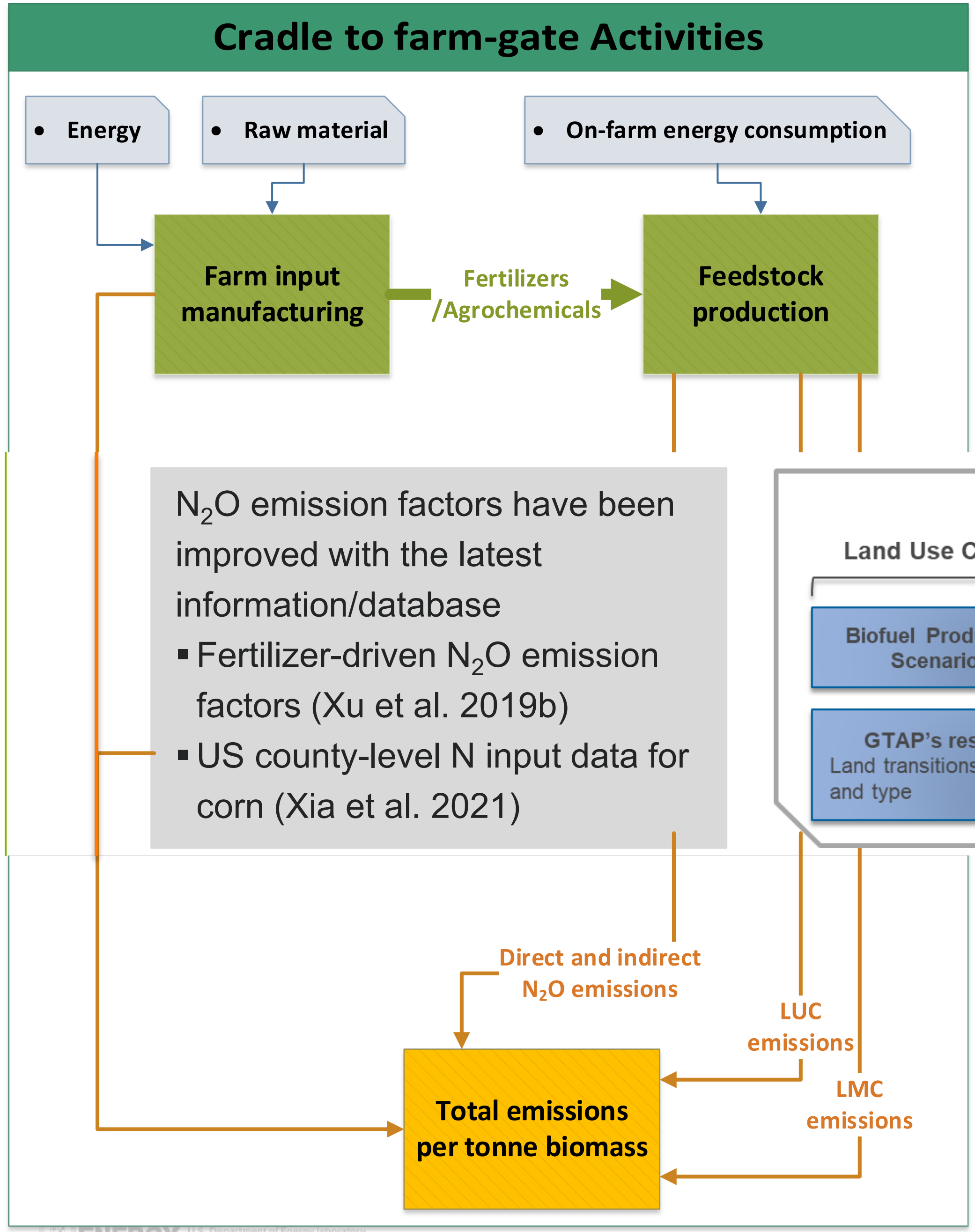
Feedstock Growth Is a Significant Contributor to Corn Ethanol LCA GHGs: 38% of 56 gCO_2e/MJ (after DGS credit)



Dry Milling Corn Ethanol w/ Corn Oil Extraction.
DSG credit, -12.9 g CO_2e/MJ, is not included

Significant variation exists in feedstock CI among regions



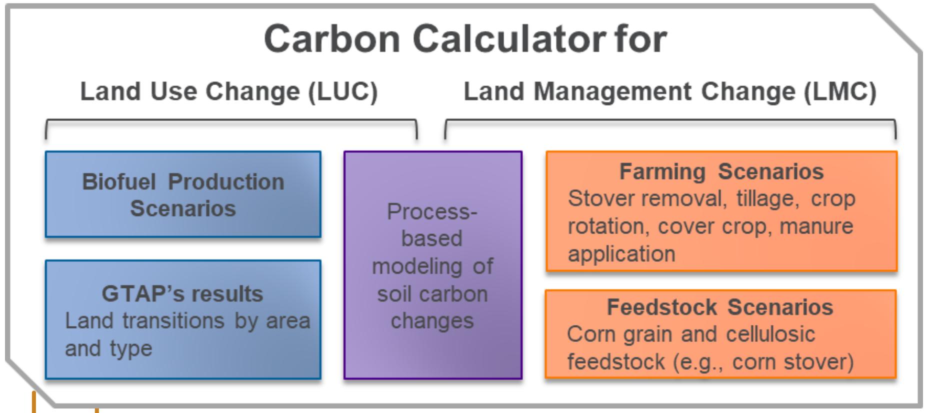


CCLUB's Soil Carbon Modeling Provides Understanding of Feedstock Production for biofuel LCA

CCLUB has been updated with new data and actual observations to address issues and constructive critiques in estimating LUC and associated GHG emissions (Taheripour et al. 2021)

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)



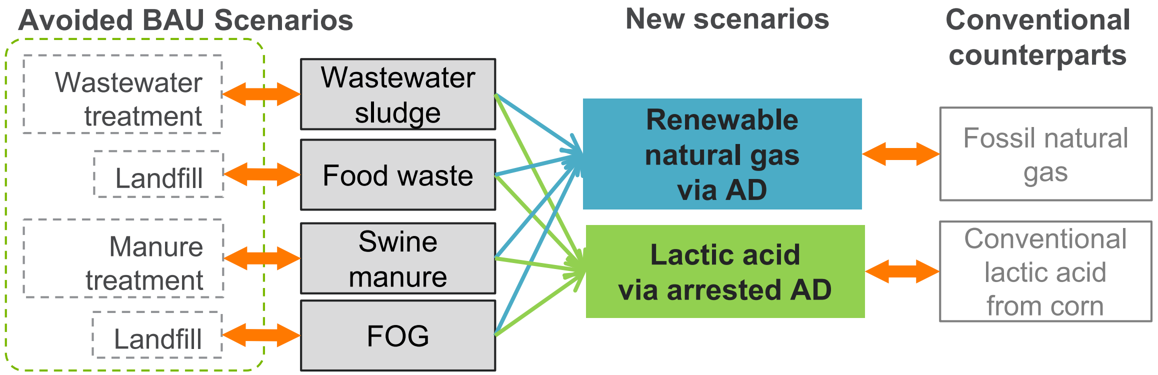
It accounts for the LMC effects on soil carbon changes during feedstock production, whose consideration in biofuel LCA can help deep carbon reductions by biofuels (Liu et al. 2020)

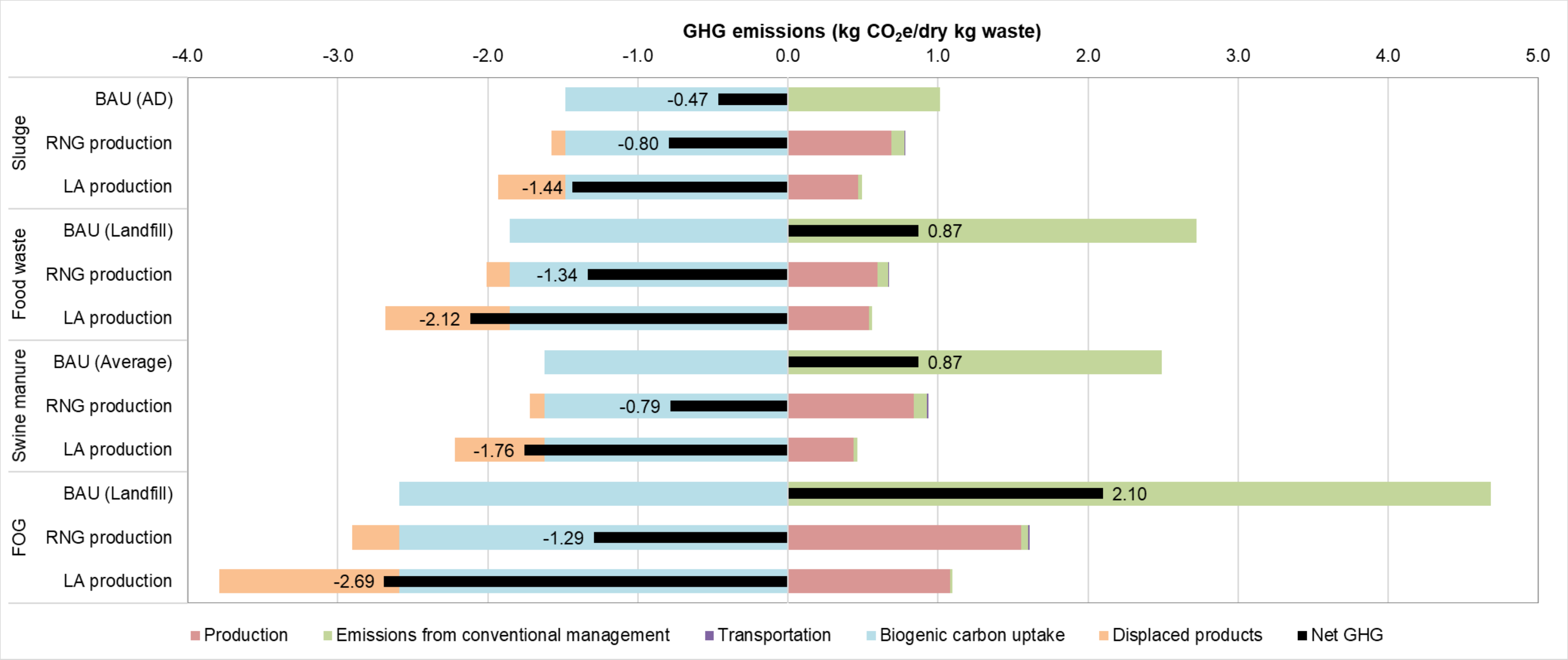
Process-based modeling and meta-analysis of field data have been adopted to refine soil carbon emission factors

- 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 (Xu et al. 2019a); forest residue harvest (James et al. 2021))

New Waste-to-Energy and Waste-to-Product Pathways Include Renewable Natural Gas and Lactic Acid from Four Wet Waste Feedstock Types

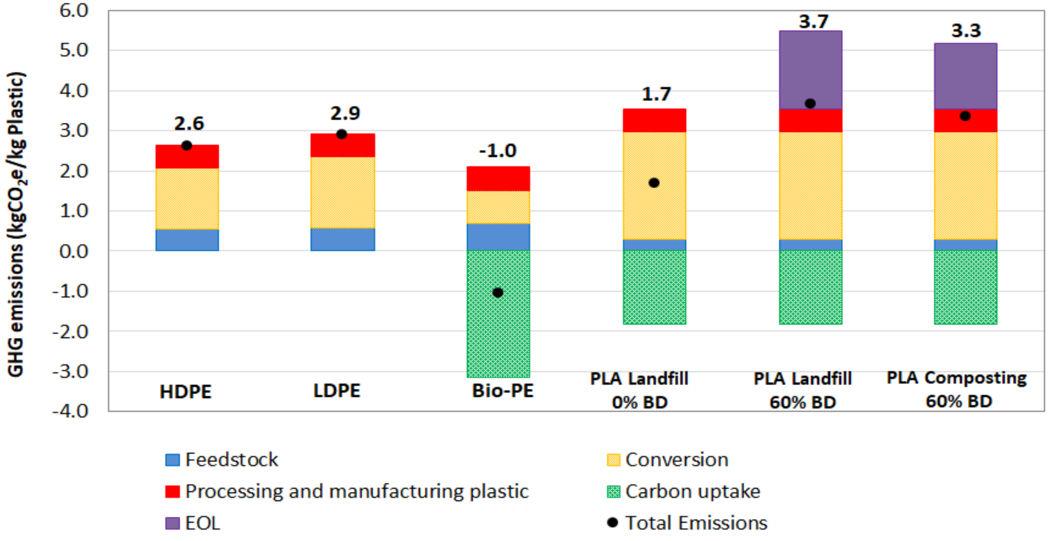
- Quantified GHG emission reductions and potential economic benefits, in collaboration with NREL
- LCA results show waste-derived fuels and chemicals can provide significant GHG emission reductions

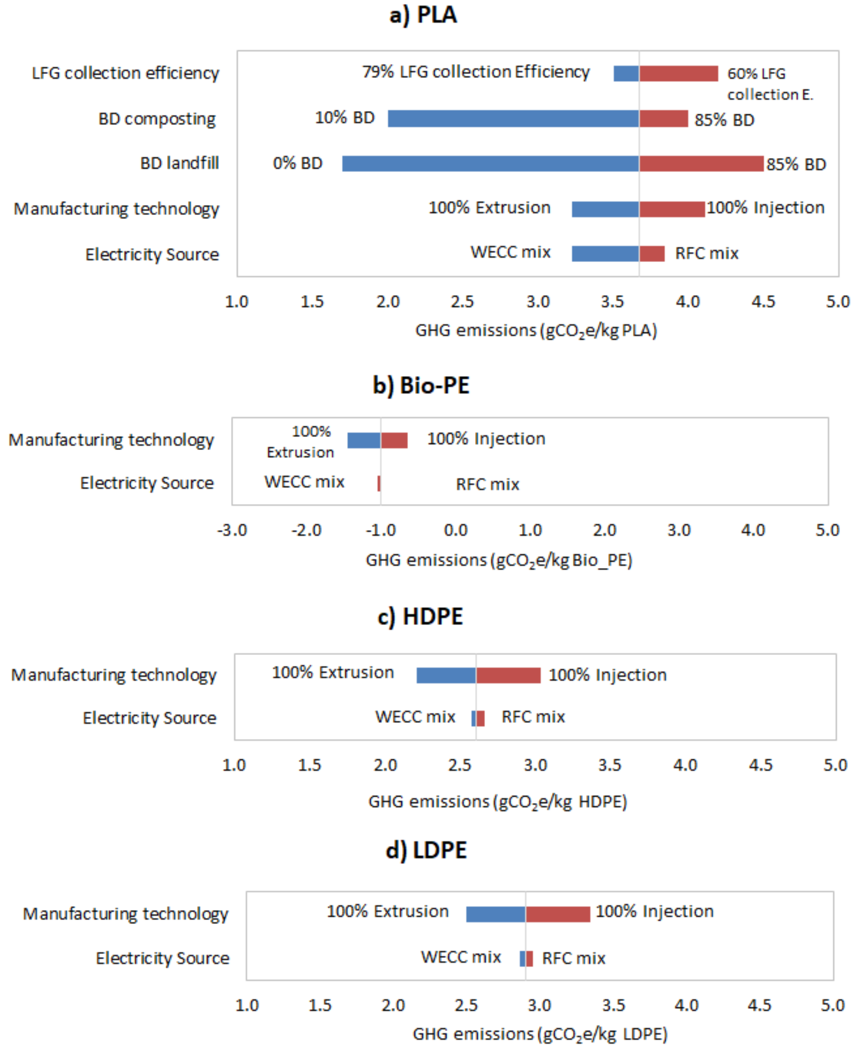




(Lee et al., 2021, forthcoming in J. Cleaner production)

Understanding End-of-Life (EOL) Environmental Effects of Plastics: Biodegradability Could Increase GHG Emissions from Plastics

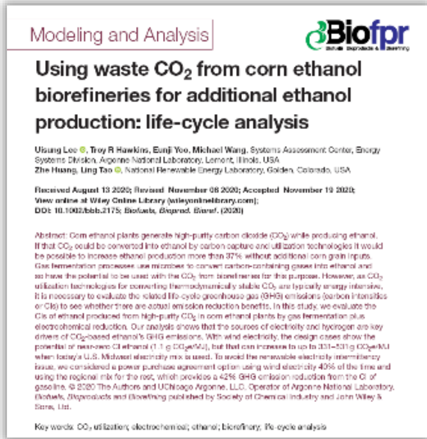




Benavides PT et al., (2020)

- Bio-PE offers lower GHG emissions than fossil-based counterparts due to less energy intensive process and carbon uptake credits
- Biodegradability can greatly influence GHG emissions of bioplastics designed to degrade (e.g., PLA)
  - ✓ Landfill and composting conditions of PLA determine biodegradability rates
  - ✓ Use of renewable electricity can improve GHG performance of PLA production
- Less energy-intensive processes can benefit GHG performance of plastic pathways

Developed a New GREET Module for CO_2 Utilization for Fuel Production (E-fuels) and Conducted LCA for a Few Pathways


Modeling and Analysis

Biofpr

Using waste CO_2 from corn ethanol biorefineries for additional ethanol production: life-cycle analysis

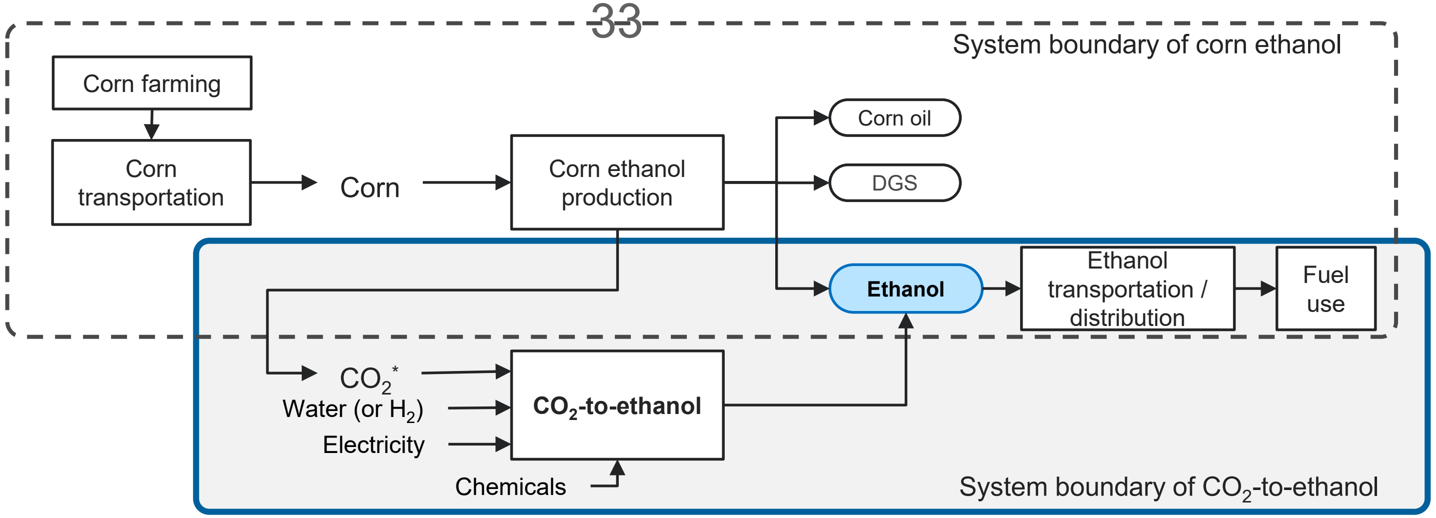
Uisung Lee, Troy R Hawkins, Eunji Yoo, Michael Wang, Systems Assessment Center, Energy Systems Division, Argonne National Laboratory, Lemont, Illinois, USA
Zhe Huang, Ling Tao, National Renewable Energy Laboratory, Golden, Colorado, USA

Received August 13 2020; Revised November 08 2020; Accepted November 19 2020;
View online at Wiley Online Library (wileyonlinelibrary.com);
DOI: 10.1002/bbb.2175; *Biofuels, Bioprod. Bioref.* (2020)

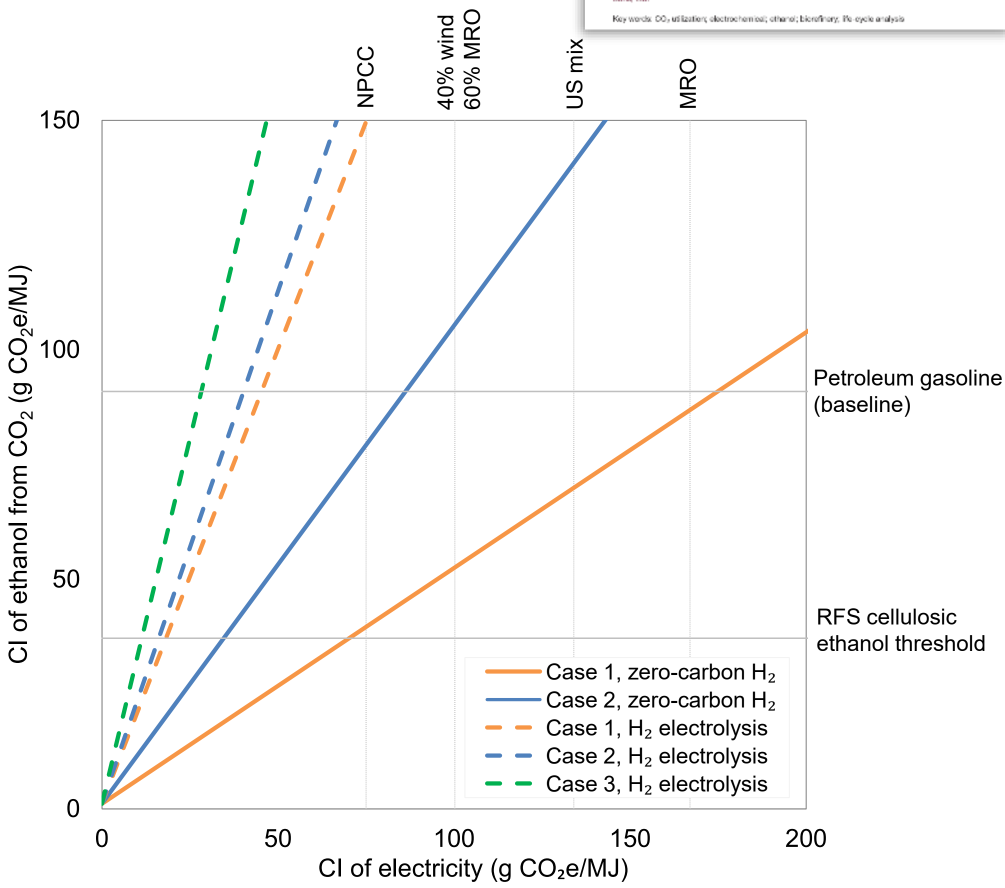
Abstract: Corn ethanol plants generate high-purity carbon dioxide (CO_2) while producing ethanol. If that CO_2 could be converted into ethanol by carbon capture and utilization technologies it would be possible to increase ethanol production more than 37% without additional corn grain inputs. Gas fermentation processes use microbes to convert carbon-containing gases into ethanol and so have the potential to be used with the CO_2 from biorefineries for this purpose. However, as CO_2 utilization technologies for converting thermodynamically stable CO_2 are typically energy intensive, it is necessary to evaluate the related life-cycle greenhouse gas (GHG) emissions (carbon intensities or CIs) to see whether there are actual emission reduction benefits. In this study, we evaluate the CIs of ethanol produced from high-purity CO_2 in corn ethanol plants by gas fermentation plus electrochemical reduction. Our analysis shows that the sources of electricity and hydrogen are key drivers of CO_2-based ethanol's GHG emissions. With wind electricity, the design cases show the potential of near-zero CI ethanol (1.1 g CO_2e/MJ), but that can increase to up to 331–531 g CO_2e/MJ when today's U.S. Midwest electricity mix is used. To avoid the renewable electricity intermittency issue, we considered a power purchase agreement option using wind electricity 40% of the time and using the regional mix for the rest, which provides a 42% GHG emission reduction from the CI of gasoline.

Key words: CO_2 utilization; electrochemical; ethanol; biorefinery; life-cycle analysis

- LCA of high-purity fermentation CO_2 in corn ethanol plants for additional ethanol production with renewable electricity (to renewable hydrogen)
- CO_2 utilization ethanol pathway shows opportunities and challenges
- Use of renewable electricity and hydrogen is key for low CI e-fuel ethanol



* No upstream burdens are assigned to the waste CO_2 used to produce E-fuel ethanol.



(Lee et al. 2020)

Future Work: Improve LCA Methods; Analyze New Technologies/Pathways; Identify Deep Decarbonization Opportunities

- **Develop/improve LCA methods**
  - Bioenergy LCA system boundary is dynamic: feedstock offers great opportunity for deep GHG reductions by biofuels
  - 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, e.g., criteria air pollutants, soil organic carbon, water stress; these are especially important for feedstock certification and bioenergy deep decarbonization
  - Circular economy modeling framework for bioenergy and bioproducts (e.g., plastic)

- **New technologies/pathways**
  - CO_2 utilization for e-fuel production: maximize carbon conversion efficiencies with renewable electricity
  - Expand GREET aviation module to examine LCA of new sustainable aviation fuel pathways for domestic and international agencies
  - Expand and improve GREET marine module for biofuel opportunities to decarbonize the marine sector
  - Co-processing to produce biofuels in petroleum refineries

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

Summary

- GREET project management benefits from
  - Close interactions with BETO sponsors
  - Extensive collaboration with national lab partners
  - Active interaction with industry stakeholders

- GREET project takes a holistic approach to provide consistent, reliable, and transparent LCA 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)
  - Improve GREET LCA by considering emerging analytic issues and new bioenergy technologies

- Argonne continues to produce impactful outcomes
  - Updated LCA results for existing bioenergy technologies to reflect technology improvements
  - New LCA results for emerging technologies for their potential contribution to deep decarbonization
  - GREET and its results are impactful
    - Societal value proposition of a bioeconomy
    - Identify R&D opportunities to improve bioenergy sustainability performance
    - Help performance-based policies and regulations to incentivize bioenergy technologies (CA LCFS, OR Clean Fuel Program, Canadian Clean Fuel Standard, and ICAO CORSIA)

Quad Chart Overview

Timeline

- Project start date: 10/01/2017
- Project end date: 9/30/2020 (Renewed until 9/30/2023)

	FY20	Active Project
DOE Funding	(10/01/2019 – 9/30/2020): $1.25M	(10/01/2020 – 9/30/2023): $3.18M

Project Partners

- No partners

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 GREET2020 with updates including new SCSA pathway results, new bioenergy and bioproduct production technologies, and connections to the updated CCLUB model.

Funding Mechanism

Analysis and Sustainability Program (now Data, Modeling, and Analysis) since 2017.

Questions?

greet.es.anl.gov

Michael Wang (mwang@anl.gov)

Publications: Selected Peer Reviewed Journal Articles

- Lee U, Hawkins T, Yoo E, Wang M, Huang Z, Tao L. **2021.** “Using waste CO2 from corn ethanol biorefineries for additional ethanol production: life-cycle analysis” *Biofuels, bioproducts & Biorefining*.
- Lan K, Ou L, Park S, Kelley S, Nepal P, Kwon H, Cai H, Yao Y. **2021.** “Dynamic Life Cycle Carbon Analysis for Fast Pyrolysis Biofuel Produced from Pine Residues: Examine Carbon-Neutral Assumption for Woody Biomass”. Under Review by Biotechnology for Biofuels.
- Xia, Y., Kwon, H., Wander, M. **2021**. *Developing county-level data of nitrogen fertilizer and manure inputs for corn production in the United States.* Journal of Cleaner Production *(In revision)*
- James, J., Page-Dumroese D., Busse, M., Palik, B., Zhang, J., Eaton, B., Slesak, R., Tirocke, J., Kwon, H. **2021**. *Effects of forest harvesting and biomass removal on soil carbon and nitrogen: two complementary meta-analyses.* Forest Ecology and Management *(Accepted)*
- Taheripour, F., Mueller, S., Kwon, H. **2021**. *Response to “How robust are reductions in modeled estimates from GTAP-BIO of the indirect land use change induced by conventional biofuels?”* Journal of Cleaner Production *(In revision)*
- Benavides P, Lee U, Zare-Mehrjerdi O. **2020**. “Life Cycle Greenhouse Gas Emissions and Energy Use of Polylactic Acid, Bio-Derived Polyethylene, and Fossil-Derived Polyethylene” *Journal of Cleaner production*. 277: 124010.
- Xu H, Lee U, Coleman A, Wigmosta M, Sun N, Hawkins T, Wang M. **2020**. “Balancing Water Sustainability and Productivity Objectives in Microalgae Cultivation: Siting Open Ponds by Considering Seasonal Water-Stress Impact Using AWARE-US” *Environmental Science & Technology*. 54 (4): 2091-102.
- Lee U, Chou J, Xu H, Carlson D, Venkatesh A, Shuster E, Skone T, Wang M. **2020**. “Regional and Seasonal Water Stress Analysis of United States Thermoelectricity” *Journal of Cleaner production*. 270: 122234.
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- Field J, Richard T, Smithwick E, Cai H, Laser M, LeBauer D, Long S, Paustian K, Qin Z, Sheehan J, Smith P, Wang M, Lynd L. **2020**. “Robust paths to net greenhouse gas mitigation and negative emissions via advanced biofuels” *Proceedings of the National Academy of Sciences*. 117 (36): 21968-77.
- Liu, X., Kwon, H., Northrup D., Wang, M. **2020**. *Shifting Agricultural Practices to Produce Sustainable, Low Carbon Intensity Feedstocks for Biofuel Production*. Environ. Res. Lett. 15 084014.
- Xu H, Sieverding H, Kwon H, Clay D, Stewart D, Johnson J, Qin Z, Karlen D, Wang M. **2019**. “A global meta-analysis of soil organic carbon response to corn stover removal” *Global Change Biology-Bioenergy.* 11 (10): 1215-33.
- Nguyen, T.H., Field, J., Kwon, H., Hawkins, T.R., Paustian, K., Wang, M. *A multi-product landscape–LCA approach to evaluate local agricultural intensification opportunities.* Applied Energy (In review)

Publications: Selected Technical Reports and Book Chapters

- Cai H., Wang M. **2021**. Book chapter: “Case Study – Bioenergy Lifecycle Analysis and Implications on Bioenergy-driven Circular Economy” In *Life Cycle Assessment: A Metric for the Circular Economy*. Royal Society of Chemistry.
- Wang M, Elgowainy A, Lee U, Bafana A, Benavides P, Burnham A, Cai H, Dai Q, Gracida-Alvarez U, Hawkins T, Jaquez P, Kelly J, Kwon H, Lu Z, Liu X, Ou L, Sun P, Winjobi O, Xu H, Yoo E, Zaimes G, Zang G. **2020**. “Summary of Expansions and Updates in GREET® 2020” Argonne National Lab.(ANL), Lemont, IL (United States). ANL/ESD-20/9.
- Ou L, Cai H. **2020**. “Update of Emission Factors of Greenhouse Gases and Criteria Air Pollutants, and Generation Efficiencies of the U.S. Electricity Generation Sector” Argonne National Lab.(ANL), Lemont, IL (United States). ANL/ESD-20/41.
- Cai H, Ou L, Wang M, Tan E, Davis R, Dutta A, Tao L, Hartley D, Roni M, Thompson D, Snowden-Swan L, Zhu Y. **2020**. Supply chain sustainability analysis of renewable hydrocarbon fuels via indirect liquefaction, ex situ catalytic fast pyrolysis, hydrothermal liquefaction, and biochemical conversion: update of the 2019 state-of-technology cases Argonne National Lab.(ANL), Lemont, IL (United States). ANL/ESD-20/2.
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- X. Liu, H. Kwon, and M. Wang, **2020** “Feedstock Carbon Intensity Calculator (FD-CIC): Users’ Manual and Technical Documentation” https://greet.es.anl.gov/tool_fd_cic
- Lee U, Benavides P, Wang M. **2020**. Book chapter: “Life cycle analysis of waste-to-energy pathways” In *Waste-to-Energy Multi-Criteria Decision Analysis for Sustainability Assessment and Ranking*. Academic Press. 213-33.
- Xu, H., Cai, H., Kwon, H. **2019**. “*Update of Direct N2O Emission Factors from Nitrogen Fertilizers in Cornfields in GREET® 2019*”. (https://greet.es.anl.gov/publication-n2o_update_2019).
- Benavides PT, Zare`-Mehrjerdi O, Lee U. **2019**. "Life Cycle Inventory for Polylactic Acid Production". Lemont, IL (United States). . https://greet.es.anl.gov/publication-pla_lca
- M. Wang, A. Elgowainy, U. Lee,P. Benavides, A. Burnham, H. Cai, Q. Dai, T. Hawkins, J. Kelly, H. Kwon, X. Liu, Z. Lu, L. Ou, P. Sun, O. Winjobi, H. Xu. **2019**. Summary of Expansions and Updates on GREET 2019" Argonne National Lab.(ANL), Lemont, IL (United States). ANL/ESD-19/6

Selected Presentations and Awards

Selected Presentations

- Benavides P et al., **2020**. “Life-cycle analysis of plastic pathways with the GREET model” The American Center for Life Cycle Assessment (ACLCA) 2020 Virtual Conference. Sep. 22 – 24. 2020.
- Xu H. **2019**. “Impact of corn stover removal on soil organic carbon dynamics: a global meta-analysis” International Soils Meeting, San Diego, CA, Jan. 6–9, 2019.
- Cai H. **2019**. “Life cycle analysis of emerging biomass-derived fuels: Key issues and impacts of fossil fuel systems” 23rd Annual Green Chemistry & Engineering Conference and 9th International Conference on Green and Sustainable Chemistry, Reston, VA, Jun. 10-13. 2019.
- **2019**. “Seasonal water-stress impact analysis for algae biofuel scenarios” 2019 Algae Biomass Summit, Orlando, FL., Sept 16-19. 2019.
- **2019**. “Life-cycle analysis work on woody-based biofuel production” LCA XIX, Tucson, AZ, Sep. 24-26. 2019.
- **2019**. "GREET Introduction Workshop" The 6th Coordinating Research Council Workshop on Life Cycle Analysis of Transporation Fuels, Lemont, IL Oct. 15

Awards

- Argonne Impact Award **2019** for GREET Model Team for the significant updates to GREET 2019 and its on schedule release

Responses to Selected 2019 Reviewer Comments

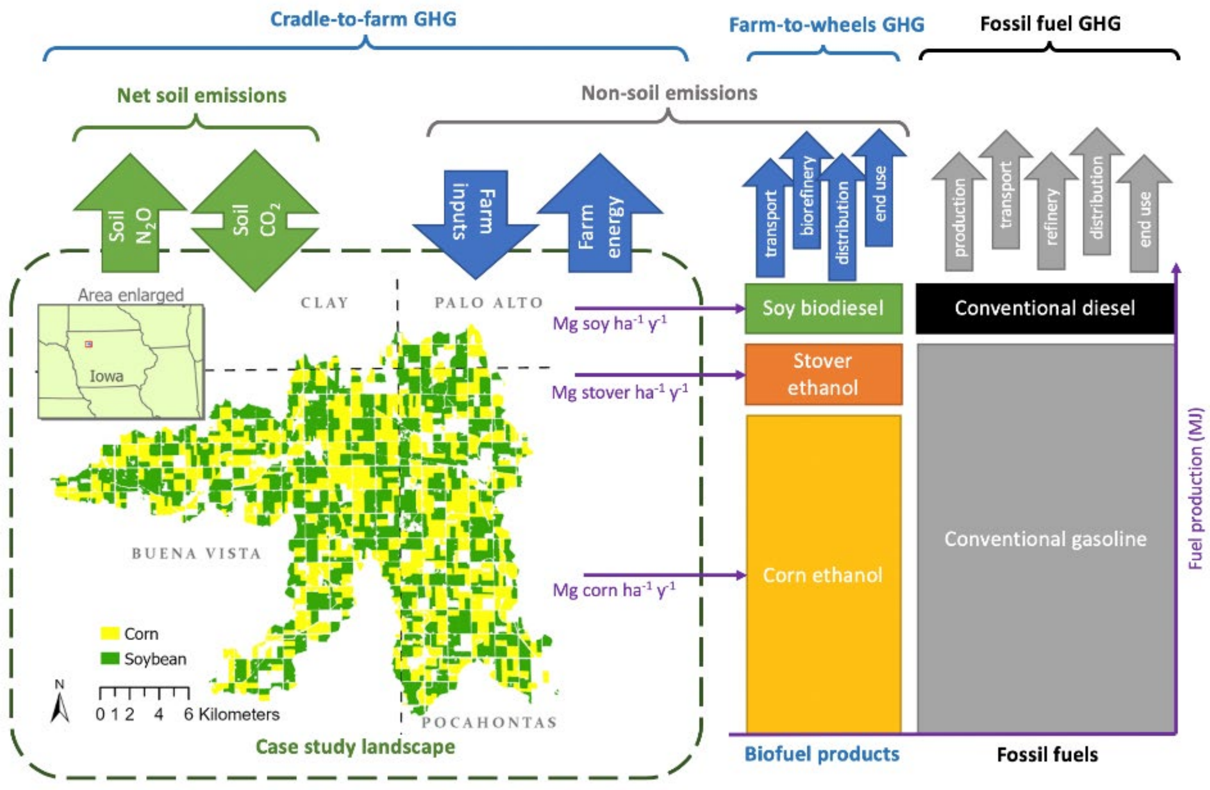
Reviewer Comment	Response to Comments
GREET is a widely used and trusted model, and the recent advances have made it even more comprehensive. To continue to bolster the already high credibility of the model, the GREET team should continue to work with other teams on parallel life cycle analyses or external 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.	We recognize that LCA is inherently an integrative and interdisciplinary approach. Our team is working closely with counter parts from other labs to coordinate efforts and incorporate outputs and datasets to streamline efforts across the projects. There appears to be some confusion regarding GREET LCA, WATER assessment of water availability, and the AWARE-US water stress assessment method. All of these efforts are part of the Argonne Biofuel Analysis Team. GREET LCA tracks water consumption across the supply chains of fuels, vehicles, and products. WATER estimates the amount of water available in a region for new feedstock growth. AWARE-US estimates the relative water stress from using additional water in a region considering hydrologic factors as well as existing anthropogenic demand. These three efforts are based on common inputs and shared common outputs to address different aspects of water sustainability of biofuels. Moving forward, we will continue to work closely with the other BETO projects as well as external collaborators to continue to improve and integrate these analyses.
Is the GREET work proactive and identifying areas of needed research/analysis or reactive in responding to demands placed upon the model by Federal stakeholders?	Thanks for this comment, this is an important topic in the context of GREET development and application for analysis. This project's work is responsive first and foremost to the needs expressed by BETO. Our team works closely with BETO program sponsors to proactively identify areas where research is needed to address emerging issues. This happens in the context of allocating available resources to the most pressing needs. Among federal agencies, we have worked closely with the EPA RFS team, USDA, CARB, and several agencies in DOT (FAA, NHTSA, MARAD, FRA) to address their needs. We will continue to reach out to Federal agencies. We're also actively pursuing opportunities where interagency collaborative research is needed to achieve our goal to quantify the life-cycle energy and environmental impacts of bioenergy and bioproducts in order to provide accurate information to inform R&D and business decisions. Our group has been successful in supplementing BETO funding with outside funding to address specific stakeholder interests, to expand GREET's capabilities, and to use GREET to provide quantitative results to answer new questions related to our goal.

Responses to Selected 2019 Reviewer Comments (continued)

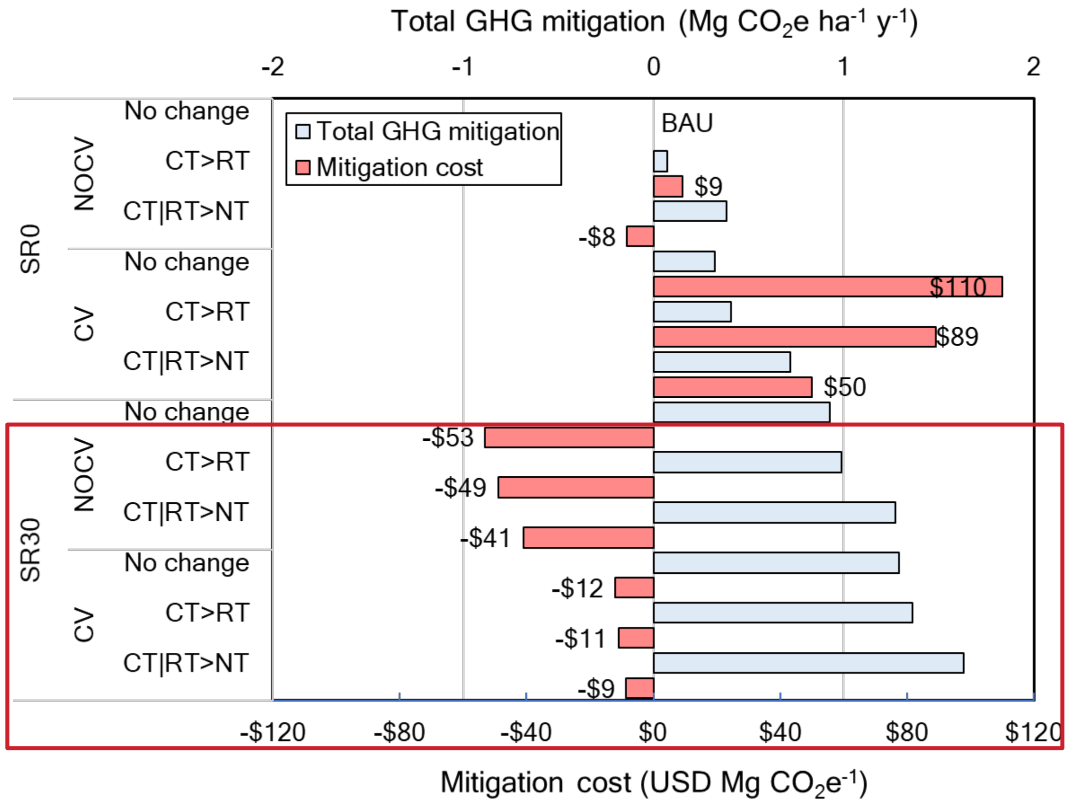
Reviewer Comment	Response to Comment
What is missing from the GREET Framework? Is it possible to refine the bio-products component? Would bio-products work be a pri42ority area?	Bio-products are important for the bioeconomy and due to recent increased interest, we have been adding various conversion processes and bio-products into GREET. We will continue to do so. The GREET modeling framework is currently configured mainly for energy products (fuels, electricity, hyrogen, etc.), which reflects historical interest in bioenergy and regulations such as LCFS and RFS. As integrated biorefineries are being proposed to co-produce a significant amount of bio-products, we have been reconsidering the energy-focused functional unit as it has the potential to generate some arbitrary results, as demonstrated in a recent joint journal article by ANL and NREL looking at cases which produce significantly more co-products than biofuel product. Also, as sustainablie farming practices become an important driver for sustainble bioenergy, landscape-based analysis, instead of end product-based analysis, may become necessary to address the effect of sustainable farming practices holistically. We are currently exploring these aspects.
A specific set of milestones/schedule were not provided, making it difficult to assess how near term these updates are and what the level of effort is on incorporating them. Recommendations: I strongly urge the team to continue to perform parallel analyses with groups such as JRC to better understand distinctions among models/modelers with regard to assumptions, and also as a way to verify and validate the assumptions within GREET. GREET is such a valued, trusted, and widely accepted model, there is risk that any error could be perpetuated indefinitely, so it is of great value to delve deeply into the calculations with outside researchers on a regular basis. A more formal external V&V effort would also have value simply to maintain the trust in GREET that has been so effectively developed over the years.	We are regularly comparing the GREET modules to newly published results from other groups. The GREET model is updated annually to incorporate updates where appropriate. We are also regularly fielding questions from GREET users and stakeholders and value these opportunities for the natural vetting of GREET values. We have on-going efforts with JRC to compare modeling approaches and results between ANL and JRC. We understand the differences between GREET and JRC WTW study, and when appropriate we harmonize key parameters between the two. We would welcome an opportunity to perform a validation and verification effort with GREET and to identify areas for potential improvement.

Additional Technical Slides

A Landscape-LCA Approach Can Evaluate Local Agricultural Intensification Opportunities



Landscape-LCA conceptual diagram (Nguyen et al. in review)



Total GHG mitigation potential and associated mitigation costs for the different landscape management scenarios, relative to BAU

Analyzing marginal changes in corn grain, corn stover, and soybean production from a landscape in the context of biofuel production (corn ethanol, soy biodiesel, and cellulosic ethanol from stover) and associated net displacement of conventional fossil-derived fuel use

Conducted LCA for USDRIVE Net Zero Carbon Fuel Tech Team

LLNL with **ANL** assistance

Corn ethanol with carbon capture and sequestration

ANL/PNNL

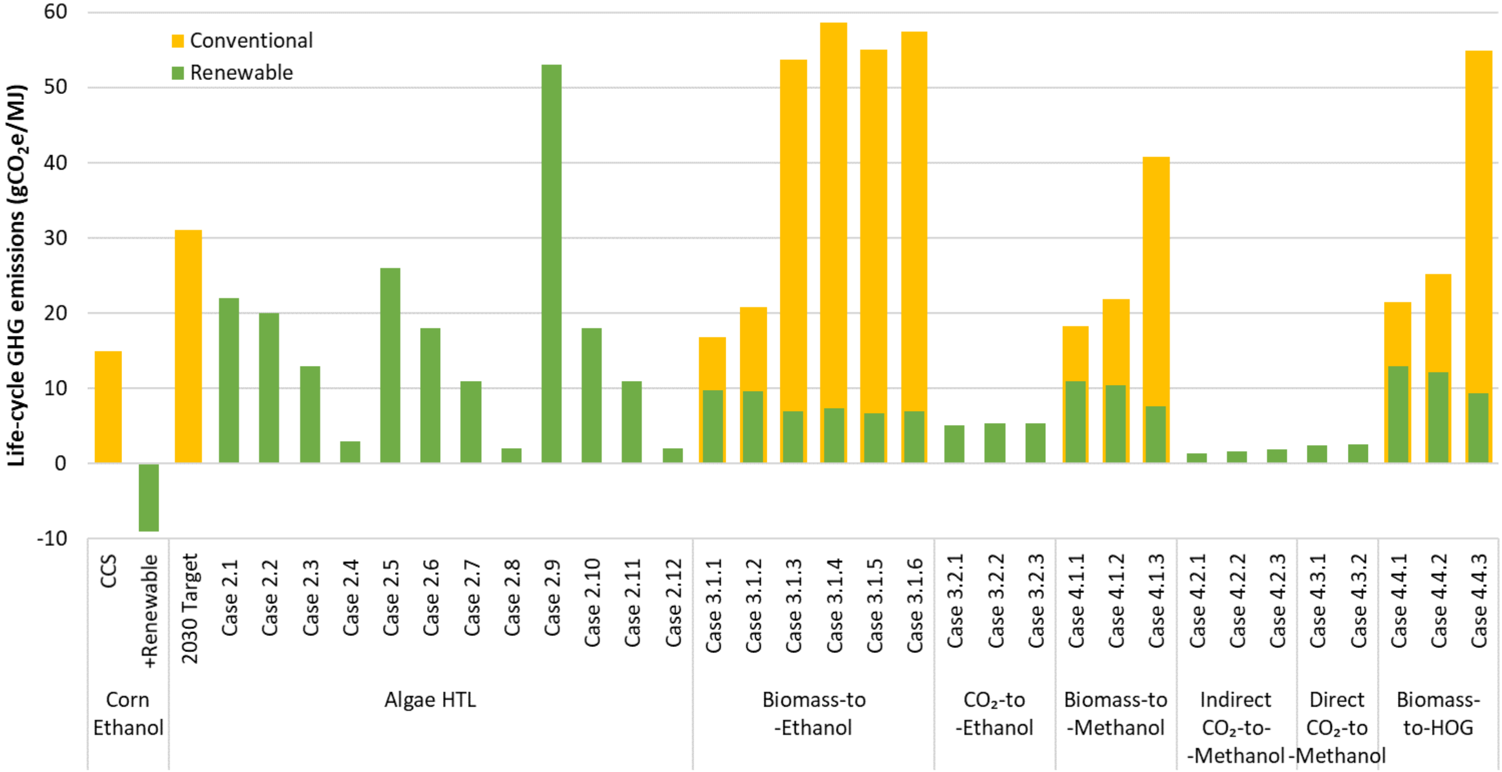
Algae to hydrocarbon fuels

ANL/NREL

Biomass to ethanol plus CO_2 to ethanol via syngas fermentation

ANL/NREL

Biomass to methanol plus CO_2 to methanol via syngas fermentation



- Multi-lab effort (ANL, NREL, PNNL, LLBL) supports USDRIVE NZCF TT with LCA and TEA (latter by the other labs)
- Analyzed four groups of NZCF production pathways (combinations of feedstocks, conversion, and products)
- Demonstrated potentials to achieve net-zero carbon fuels using renewable sources
- A technical report by the tech-team is under review

	Conventional scenario	Renewable scenario
Electricity	U.S. grid mix 483 g CO_2e/kWh (2018) 414 g CO_2e/kWh (2030)	Renewable electricity 0 g CO_2e/kWh
H_2	NG SMR (off-site, 50 miles) 80 g CO_2e/MJ	On-site electrolysis with renewable electricity 0 g CO_2e/MJ
NG	Fossil NG 69 g CO_2e/MJ	Renewable NG from landfill gas 9.8 g CO_2e/MJ