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Life-Cycle Greenhouse Gas Results of Fuels from Waste Streams and Biomass with the R&D GREET Model

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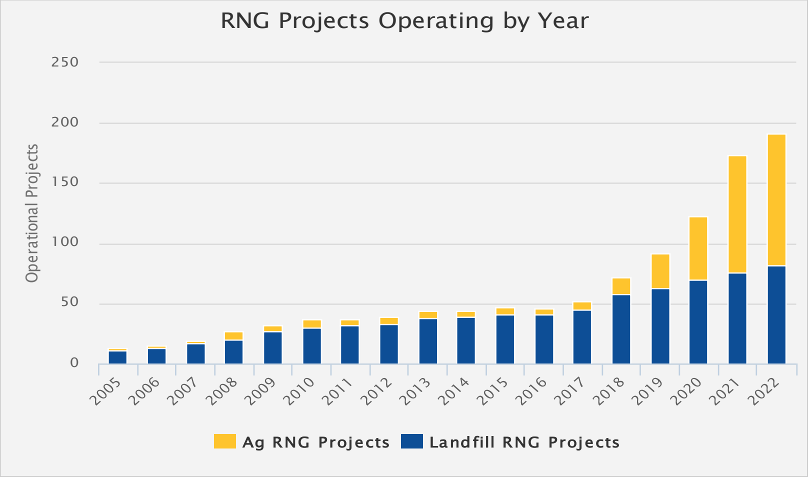
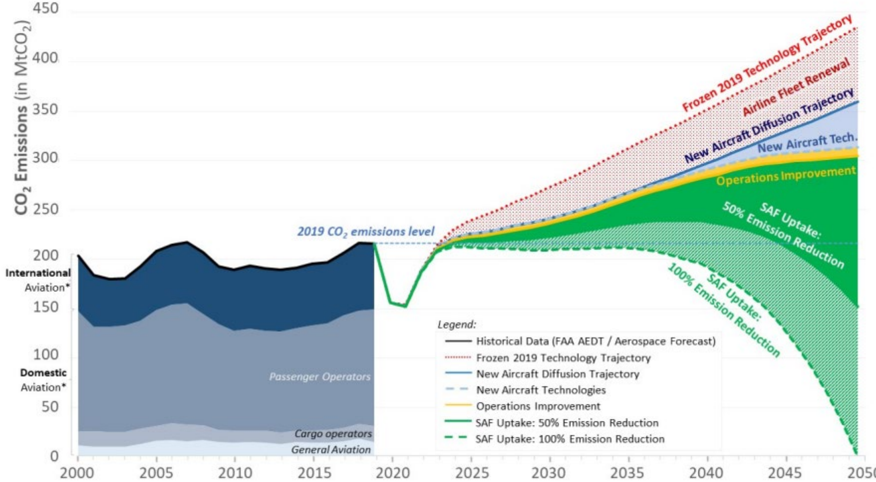
SAF and RNG play an important role in decarbonization of the transportation sector

- Decarbonization of the transportation sector requires liquid and gaseous low-carbon fuels that are produced from waste streams and biomass such as municipal solid waste, crop residues, forest residues, and wet wastes.



Source: https://www.epa.gov/lmop/renewable-natural-gas



* Note: Domestic aviation from U.S. and Foreign Carriers. International aviation from U.S. Carriers.

Figure 3. Analysis of Future Domestic and International Aviation CO_2 Emissions[13]

[13] Analysis conducted by BlueSky leveraging R&D efforts from the FAA Office of Environment & Energy (AEE) regarding CO_2 emissions contributions from aircraft technology, operational improvements, and SAF.

- Sustainable aviation fuel (SAF) and Renewable Natural gas (RNG) offer great potential for decarbonization of the transportation sector.

Life-cycle analysis has been the basis for decarbonization programs to boost GHG emission reductions

- Important to adequately estimate emissions for GHG emission reduction targets.

Major GHG Emission Programs

International	ICAO's CORSIA
Federal	Inflation Reduction Act US EPA's RFS
States	CA: LCFS OR: Clean Fuels Program WA: Clean Fuels Program
Other LCA-based programs	EU: RED II, Canada: Clean Fuel Regulations, Brazil: RenovaBio

Life-cycle analysis (LCA)

ICAO: International Civil Aviation Organization
CORSIA: Carbon Offsetting and Reduction Scheme for International Aviation
EPA: Environmental Protection Agency
RFS: Renewable Fuel Standard
CA: California | LCFS: Low Carbon Fuel Standard OR: Oregon
WA: Washington | EU: European Union | RED: Renewable Energy Directive

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R&D GREET LCA Model

Greenhouse gases, Regulated Emissions, and Energy use in Technologies

Argonne's GREET Model
https://greet.anl.gov/

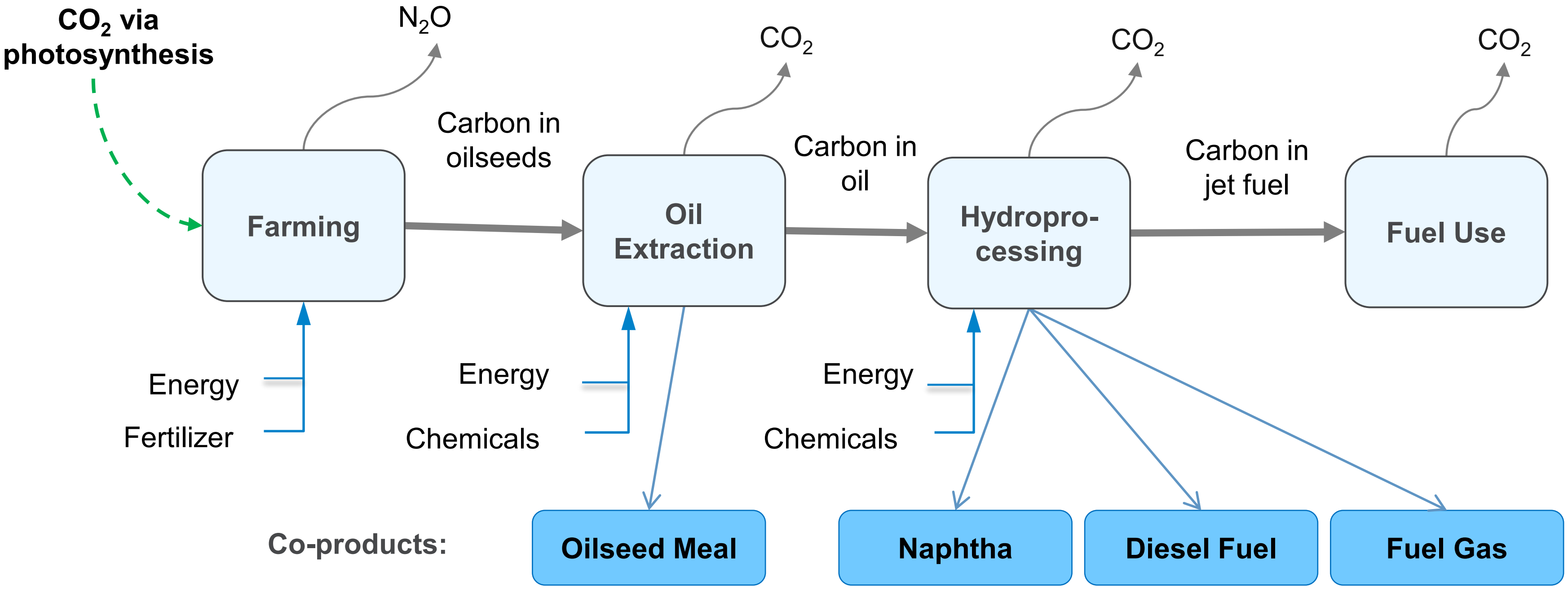
- Tracks life cycle performance of energy and products
  - Used to inform and guide the Department of Energy research
- Argonne has been developing GREET since 1995 with annual updates and expansions.
- Long-term support from U.S. Department of Energy
  - Vehicle Technologies Office (VTO)
  - Hydrogen Fuel-Cell Technologies Office (HFTO)
  - Bioenergy Technologies Office (BETO)
  - Building Technologies Office (BTO)
  - ARPA-E
- Expanded from transportation-focus to include a wide range of technologies (Fuels, Vehicles, Chemicals, Plastics, Agriculture, Metals, Concrete, Buildings, Batteries, Electricity Infrastructure)

SAF Pathways in GREET

Conversion Technology	Feedstocks	Conversion Technology	Feedstocks
FT	Agricultural residues	SIP	Sugarbeet
	Forestry residues		Sugarcane
	Municipal solid waste	ATJ-isobutanol	Agricultural residues
	Short-rotation woody crops		Forestry residues
	Herbaceous energy crops		Corn grain
HEFA	Tallow		Switchgrass
	Used cooking oil		Miscanthus
	Palm fatty acid distillate		Molasses
	Corn oil	ATJ-ethanol	Sugarcane
	Soybean oil		Corn grain
	Rapeseed oil		Agricultural residues
	Camelina		Forestry residues
	Palm oil		Switchgrass
	Brassica carinata		Miscanthus
	Sugarcane		Waste gases

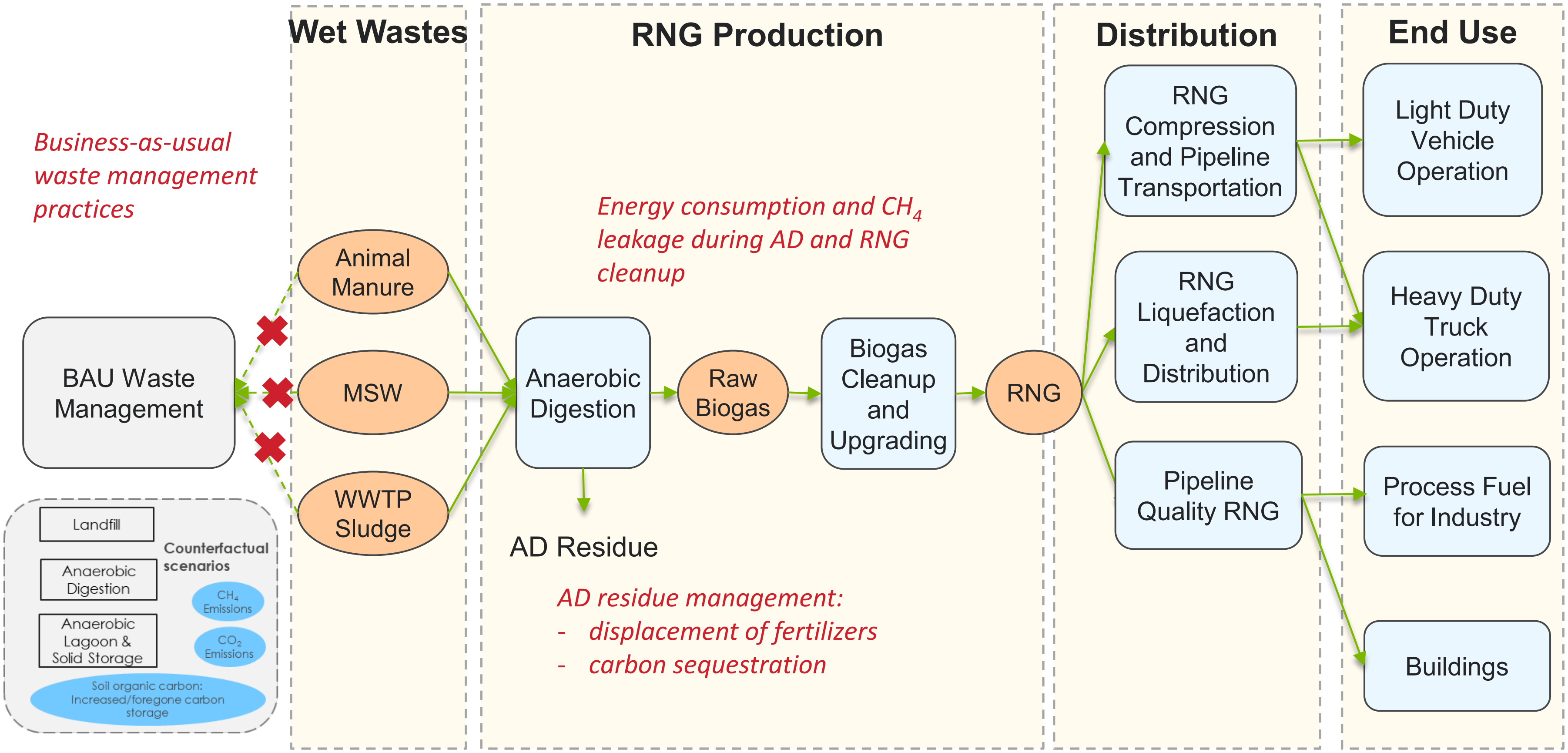
FT: Fischer-Tropsch;
SIP: Synthesized iso-paraffins;
HEFA: Hydroprocessed esters and fatty acids;
ATJ: Alcohol-to-jet

System Boundary: HEFA SAF



- Co-product handling method: process-level allocation
  - Oil extraction: Mass-based allocation
  - Hydroprocessing: energy-based allocation

System Boundary: Waste to RNG Pathways



GHG Emission Accounting in WTE Pathways

- **Biogenic carbon**
  - CO_2 emissions: carbon neutral
  - Sequestered CO_2: negative CO_2
  - CH_4 emissions: CH_4 x GWP_{bioCH4}
- **Fossil carbon**
  - CO_2 emissions; positive CO_2
  - Sequestered CO_2: carbon neutral
  - CH_4 emissions: CH_4 x $GWP_{fossilCH4}$

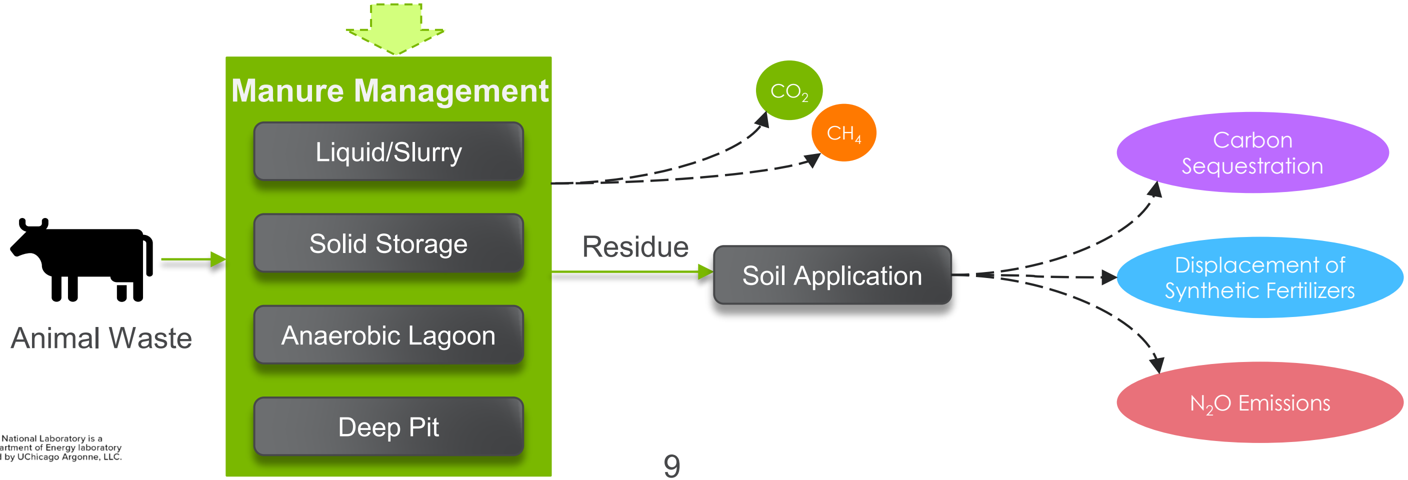
- Functional unit: MJ of fuel output
- Life-cycle GHG emissions considering the impact of avoided business-as-usual (BAU) case:

$$CI\ [gCO_{2e}/MJ] = \left(\underbrace{\frac{GHG_{production} + GHG_{combustion}}{M_{waste}}}_{\text{Fuel Production/Use}} - \underbrace{\frac{GHG_{BAU}}{M_{waste}}}_{\text{BAU (Avoided Emissions)}} \right) \times \underbrace{\left(\frac{M_{waste}}{F} \right)}_{\text{Fuel Yield}}$$

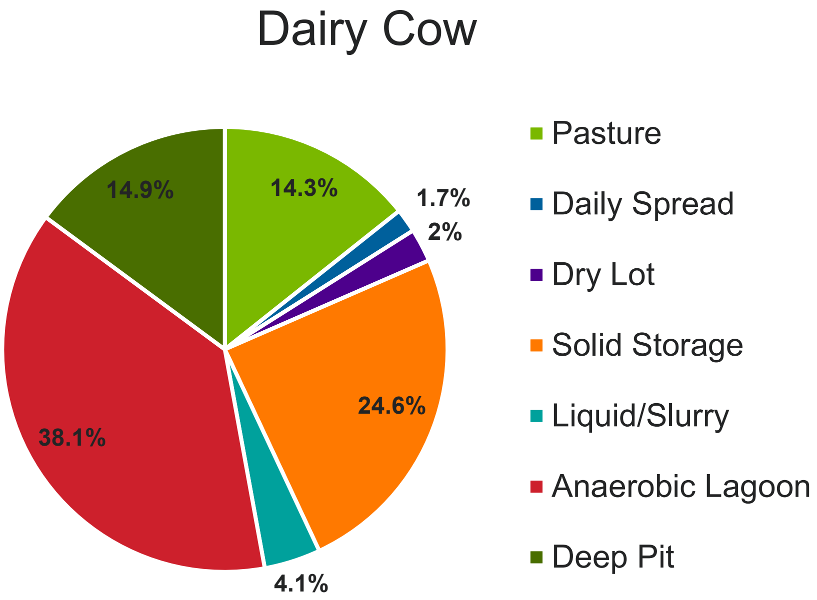
BAU Animal Manure Management in the United States

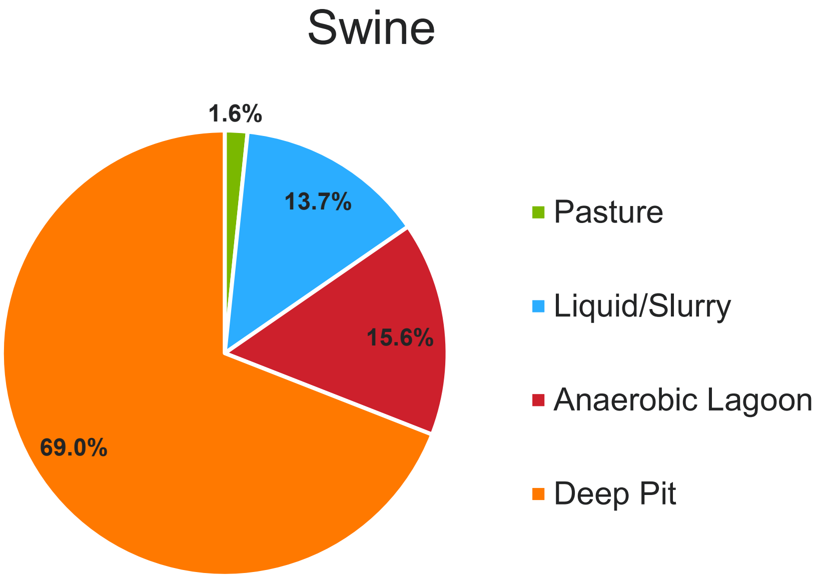
- Emissions from business-as-usual (BAU) management of various animal manure are modeled
  - Beef, dairy cow, dairy heifer, swine, layer, and broiler and turkey
- Manure management data are collected from different sources to estimate the emissions from manure management

Key Parameters:	Manure Characteristics	Livestock Population	Waste Management Share	Maximum CH4 Generation Potential	Methane Conversion Factor
Data Source:	**USDA**	**USDA**	**EPA**	**EPA**	**IPCC & EPA**



BAU Animal Manure Management

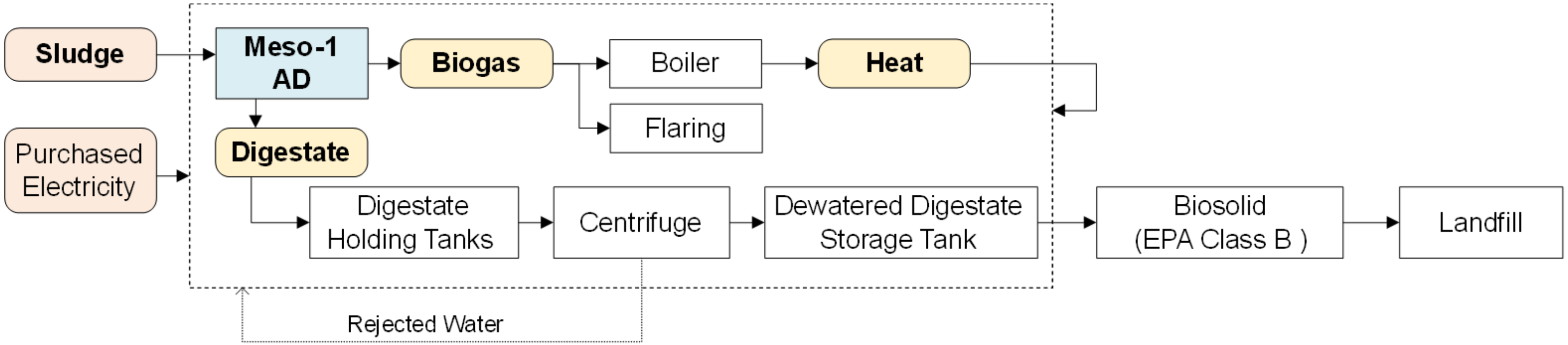




State-level manure management data are included for various animal types and management practices.

BAU Wastewater Sludge Management in R&D GREET

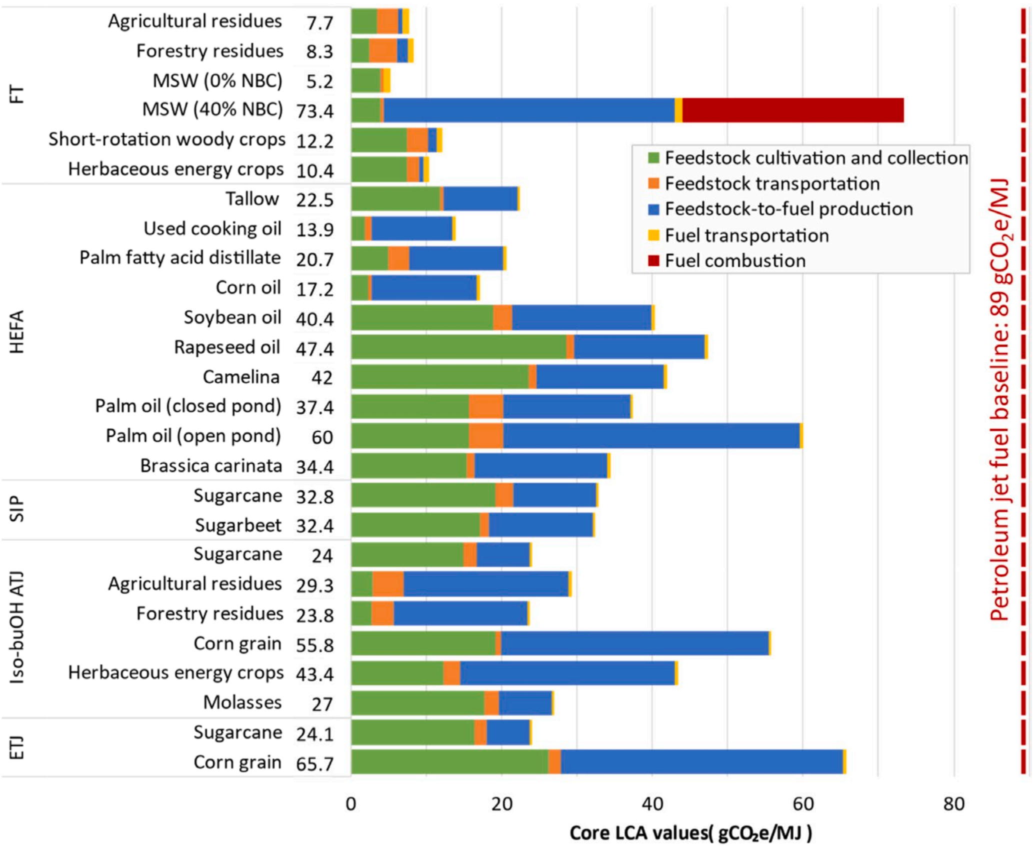
- **Assumptions:**
  - *Single-stage mesophilic AD*
  - *Biogas yield from AD provides the onsite thermal demand; excess biogas is flared*
  - *Purchased grid electricity to satisfy electricity demand*



Flow diagram for counterfactual scenario of sewage sludge AD treatment in R&D GREET

Carbon Intensities Of Waste-to-RNG Pathways

- The GHG reduction benefits of SAFs compared to fossil-derived jet fuels are due to the CO_2 uptake of biomass feedstocks.
- In general, FT pathways have low conversion-related emissions, mainly because the process uses heat from syngas combustion (biogenic carbon emissions), except when the feedstock is MSW with non-biogenic carbon.
- Feedstock has a considerable contribution to the life-cycle GHG emissions. Use of waste and residual feedstocks is key to achieve low-GHG aviation fuels.



Ref: Prussi et al. 2021. CORSIA: The first internationally adopted approach to calculate life-cycle GHG emissions for aviation fuels." Renewable and Sustainable Energy Reviews 150 (2021): 111398.

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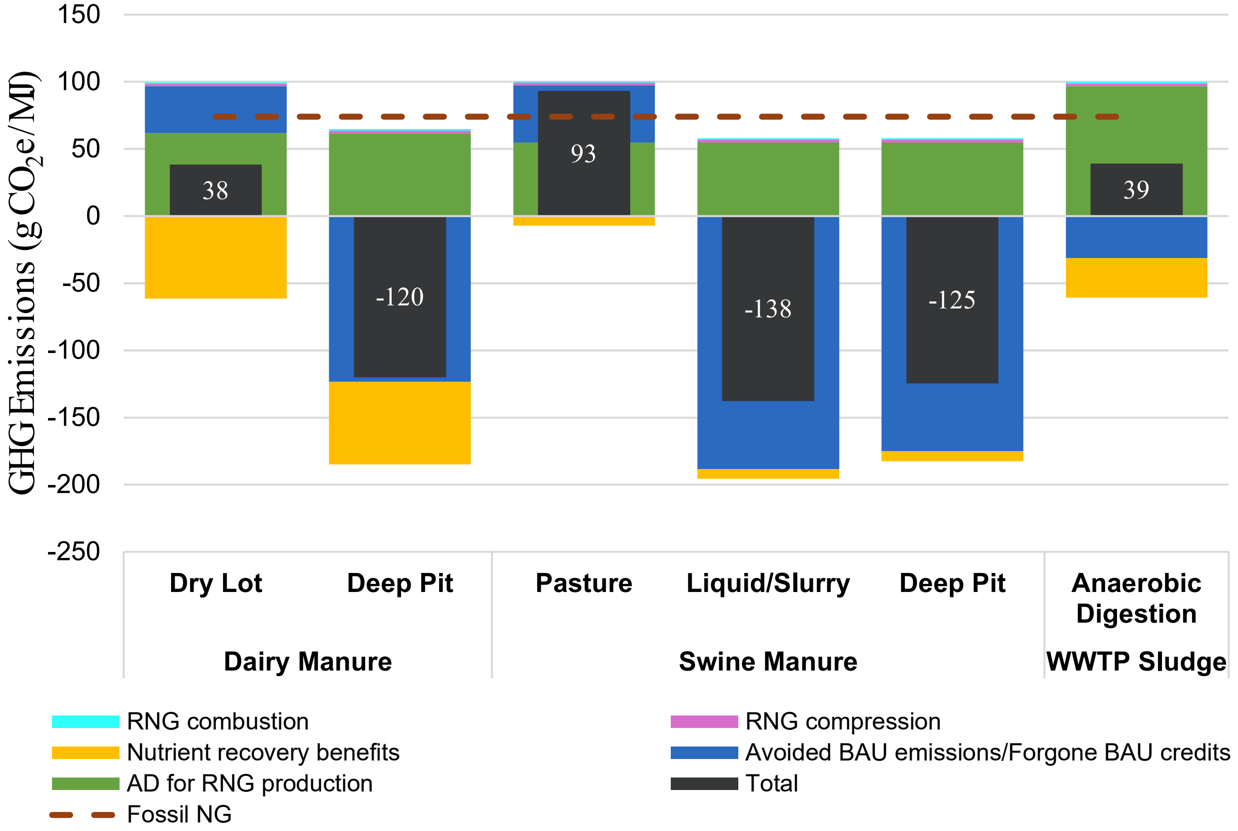
Carbon Intensities Of Waste-to-RNG Pathways

- The avoided BAU emissions greatly impact the carbon intensities of waste-to-RNG pathways.

- For animal manure pathways, the BAU emissions depend on the manure management practice and manure characteristics.
  - A large amount of methane is released from deep pit and liquid/slurry management, leading to significant GHG credits.



Summary

- Carbon cycle via photosynthesis provides key CO_2 benefits for SAF and RNG pathways.
- Counterfactual scenarios have significant impact on the carbon intensity of waste-to-RNG pathways.
  - Waste feedstock characteristics, regional parameters, and operational conditions affect the emissions from counterfactual waste management.
- R&D GREET includes dedicated SAF and RNG modules for LCA results of these pathways.
  - R&D GREET can be used to identify opportunities for further decarbonization.

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Thank you!

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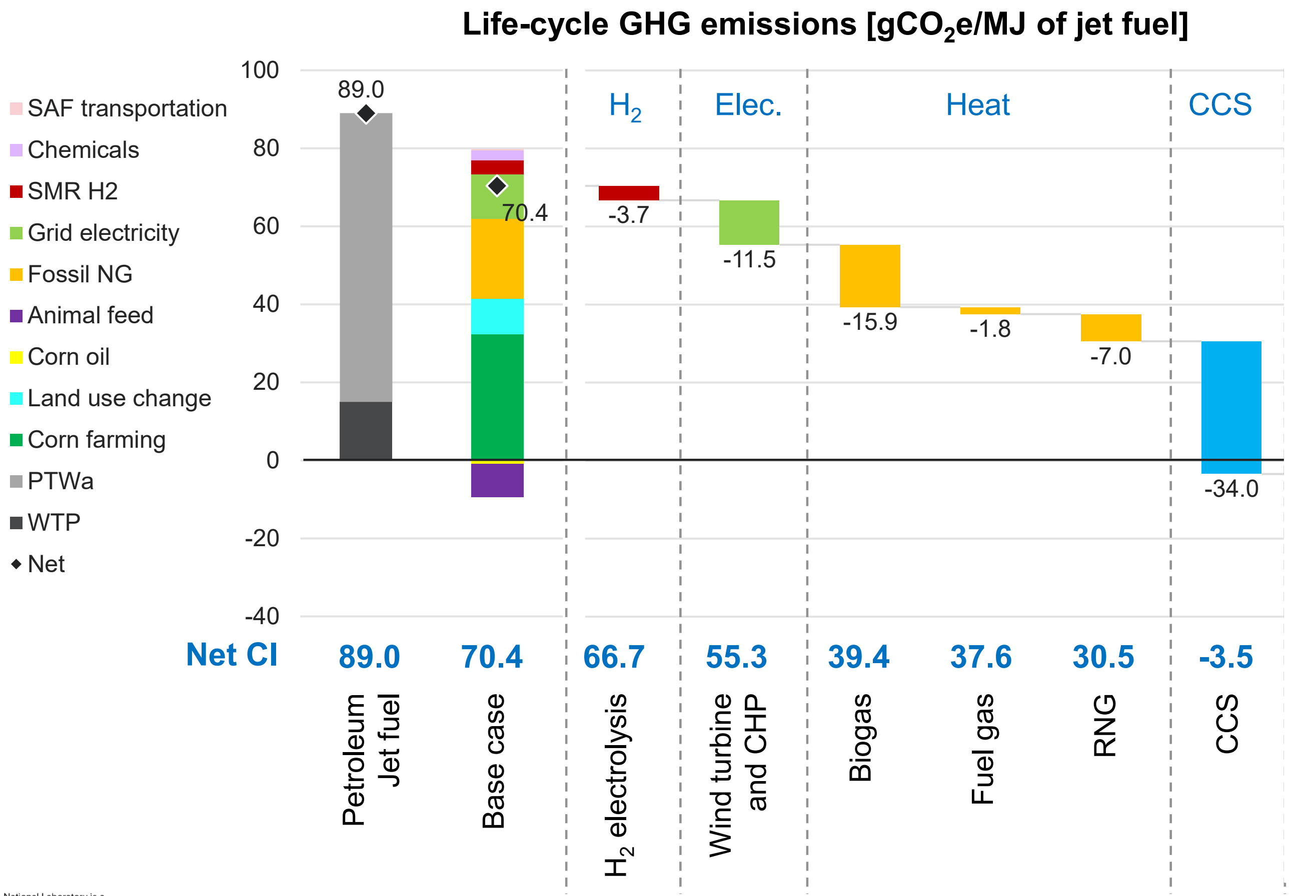
CI reduction through deep decarbonization

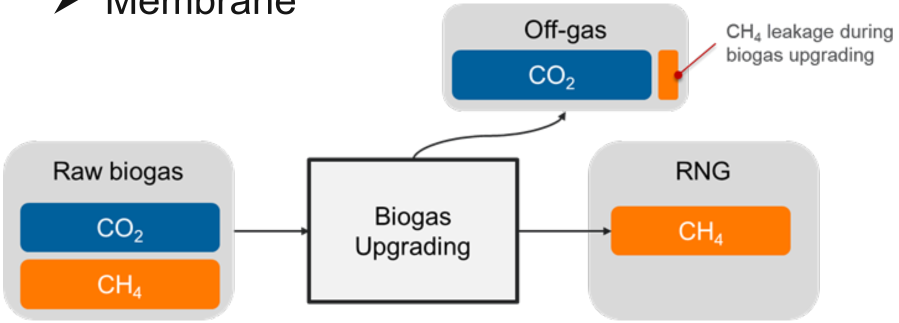


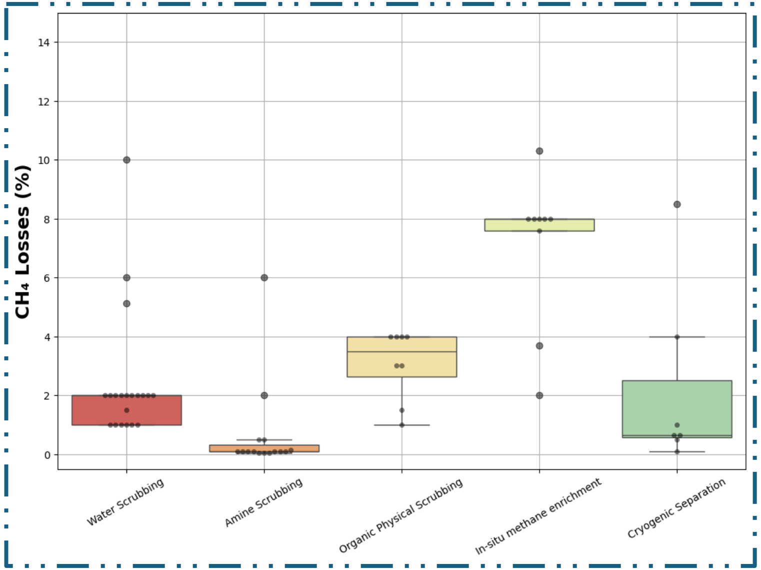
(Yoo et al. 2022)

CHP: combined heat and power | RNG: renewable natural gas
CCS: carbon capture and sequestration | SOC: soil organic carbon

Methane Leakage From Biogas Upgrading

- **Raw biogas produced from AD contains CH_4 and CO_2**
- **CO_2 is separated in raw biogas upgrading to increase the CH_4 concentration**
- **In biogas upgrading, a fraction of CH_4 ends up in off-gas, leading to CH_4 loss**
- **CH_4 loss rate mainly depends on the separation technology:**
  - Pressure swing adsorption (PSA)
  - Water scrubber
  - Chemical (amine) scrubber
  - Membrane



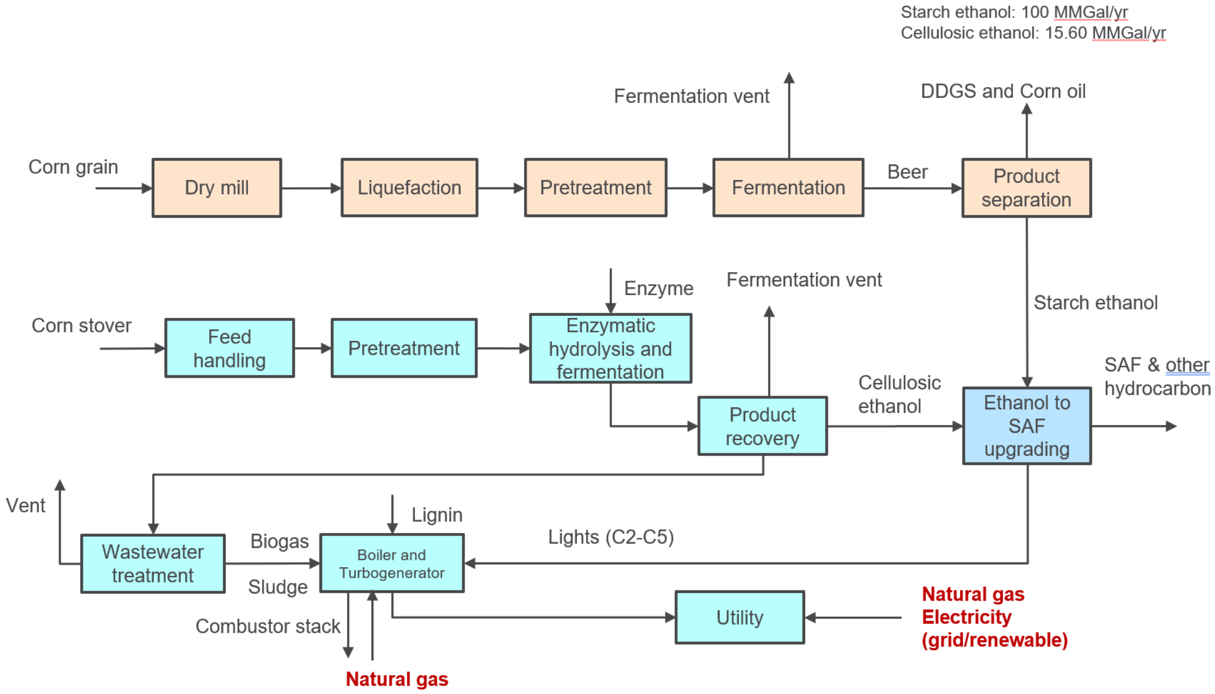


Preliminary literature review

Ethanol-to-Jet

From first- and second-generation ethanol

- Corn grain and corn stover ethanol-to-jet pathways
- Comparing stand-alone and integrated corn grain + corn stover designs
- Evaluating measures for deep decarbonization of the ethanol-to-jet pathway.
  - NG to biomass/RNG
  - Renewable electricity
  - Low carbon farming

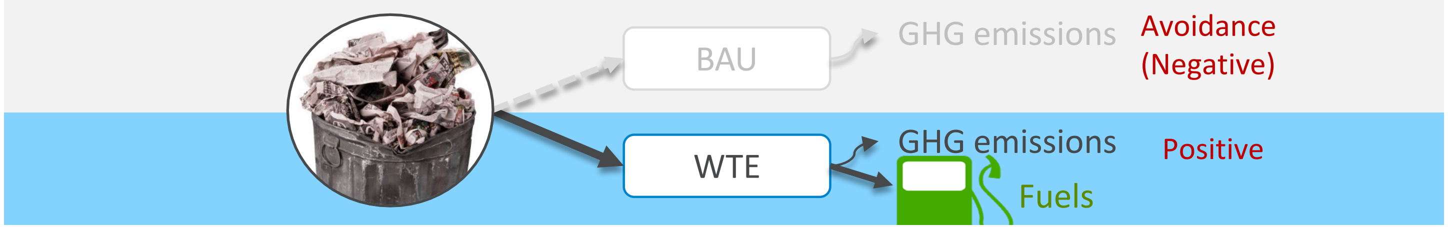


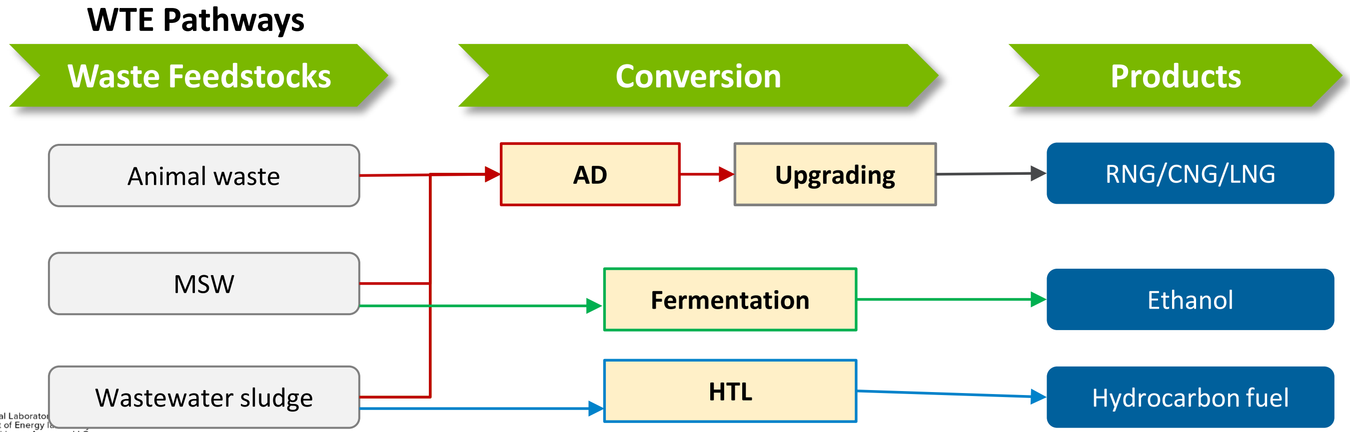
Key parameters affecting feedstock CI

- Crop yield
  – Determines the material/energy inputs per kg oilseed
- Oil content in seed
  – Determines the amount of oil produced from an acre of land
- Farming inputs
  – Fertilizer/chemical use: embodied GHGs in fertilizers and chemicals and N2O emissions of N fertilizers
  – On-farm energy consumption in various farming activities (i.e. tilling, planting, fertilizing, harvesting, and drying)
- Farming practices
  – Conventional vs no tillage for field preparation
  – Manure vs synthetic fertilizer as nitrogen source

WTE Pathways Could Provide Significant GHG Reductions

- Wet wastes can be used for produce a variety of energy products (RNG, hydrocarbon fuels, etc.).
- LCA of WTE pathways should account for the emissions from business-as-usual (BAU) waste management that may be avoided when the waste is diverted to WTE.





Waste-to-Energy and Waste-to-Product Studies

Landfill Gas	Animal Waste	Wastewater Sludge	MSW

Argonne NATIONAL LABORATORY — ANL/ESD/10-3
Well-to-Wheels Analysis of Landfill Gas-Based Pathways and Their Addition to the GREET Model
Energy Systems Division

Argonne NATIONAL LABORATORY — ANL/ESD/11-6
Waste-to-Wheel Analysis of Anaerobic-Digestion-Based Renewable Natural Gas Pathways with the GREET Model
Energy Systems Division

Argonne NATIONAL LABORATORY — ANL/ESD-16/19
Lifecycle Analysis of Renewable Natural Gas and Hydrocarbon Fuels from Wastewater Treatment Plants' Sludge
Energy Systems Division

Argonne NATIONAL LABORATORY — ANL/ESD-16/20
Well-to-Wheels Analysis of Compressed Natural Gas and Ethanol from Municipal Solid Waste
Energy Systems Division

Journal of Cleaner Production
Evaluation of landfill gas emissions from municipal solid waste landfills for the life-cycle analysis of waste-to-energy pathways
Uisung Lee, Jeongwoo Han, Michael Wang

CHAPTER 8
Life cycle analysis of waste-to-energy pathways
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Waste-to-Energy

Waste-to-products

Waste gas-to-liquid fuels (CO_2 utilization)

Journal of Cleaner Production, Volume 382, 1 January 2023, 135114
Life cycle analysis of gasification and Fischer-Tropsch conversion of municipal solid waste for transportation fuel production
Uisung Lee, Hao Cai, Longwen Ou, Pahola Thathiana Benavides, Yixuan Wang, Michael Wang
https://doi.org/10.1016/j.jclepro.2022.135114
Highlights
- Evaluated carbon intensities of liquid fuels produced from municipal solid

Fuel
Life-cycle analysis of fuels from post-use non-recycled plastics
Pahola Thathiana Benavides, Pingping Sun, Jeongwoo Han, Jennifer B. Dunn, Michael Wang

Journal of Cleaner Production, Volume 311, 15 August 2021, 127653
Life cycle analysis of renewable natural gas and lactic acid production from waste feedstocks
Uisung Lee, Arpit Bhatt, Troy Robert Hawkins, Ling Tao, Pahola Thathiana Benavides, Michael Wang
https://doi.org/10.1016/j.jclepro.2021.127653

Abstract
Producing fuels and chemicals from waste is considered economically favorable, due to low feedstock cost, and environmentally favorable, due to avoided emissions from conventional waste management practices. In this study, we evaluate the life cycle greenhouse gas (GHG) emission reduction benefits of renewable natural gas (RNG) and lactic acid (LA) production from four types of wet waste feedstocks (wastewater sludge, food waste, swine manure, and fats, oil, and grease [FOG]) via anaerobic digestion (AD) and LA fermentation, respectively. RNG can be used as an alternative to fossil natural gas, while LA from waste feedstocks can displace conventional LA production pathways

Journal of Cleaner Production, Available online 3 September 2020, 124010
Life Cycle Greenhouse Gas Emissions and Energy Use of Polylactic Acid, Bio-Derived Polyethylene, and Fossil-Derived Polyethylene
Pahola Thathiana Benavides, Uisung Lee, Omid Zare-Mehrjerdi
https://doi.org/10.1016/j.jclepro.2020.124010
Highlights
- Bioderived PE can offer lower GHG emissions and FEC than the fossil-based counterparts.

Modeling and Analysis — Biofpr
Using waste CO_2 from corn ethanol biorefineries for additional ethanol production: life-cycle analysis