Argonne GREET LIFE-CYCLE MODEL

GREET Life Cycle Analysis of Plastic Pathways to Support a Circular Economy

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Systems Assessment Center

Analyzing the benefits and challenges of technologies to make the U.S. more sustainable, secure, and resilient.

- Assess technologies and programs against sustainability goals
  - Focus on greenhouse gas, criteria pollutants, and resource use.
  - Identifying opportunities for improvement.

- Diverse group of ~65 engineers, economists, analysts, modelers, and planners.

GREET Model Overview

Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies

- **Consistent tracking of the life cycle performance of energy and products**
  - Used to inform and guide DOE research and external policies

- Argonne has been developing GREET since 1995 with **annual updates and expansions**.

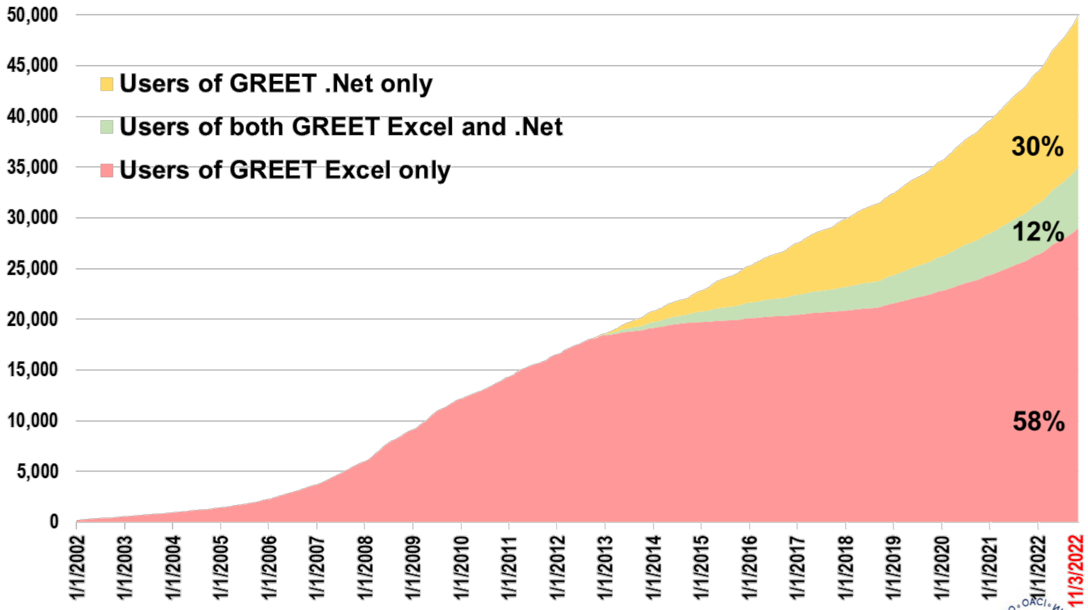
- **Expanded from transportation-focus to include a wide range of technologies**
  - Fuels, Vehicles, Chemicals, Plastics, Agriculture, Metals, Concrete, Buildings, Batteries, Electricity Infrastructure

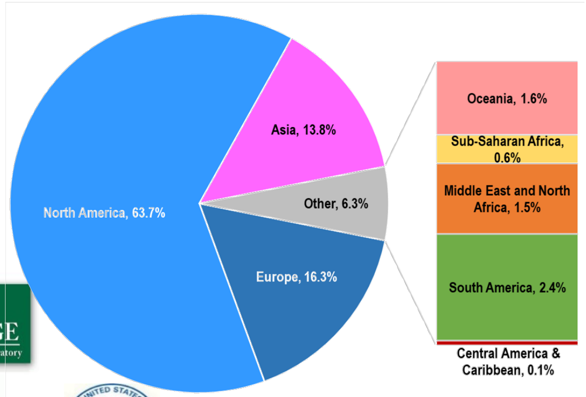
GREET Scope

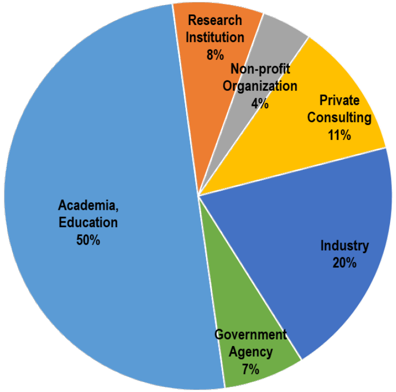
Key LCA metrics

Greenhouse Gases	Criteria Air Pollutants	Energy Use	Water Consumption
• Carbon dioxide • Methane • Nitrous Oxide • Black carbon • Albedo Characterized by global warming potential (CO_2-eq.) based on IPCC AR5	• Sulfur Oxides • Particulate Matter • Nitrogen Oxides • Volatile Organic Compounds • Carbon Monoxide Distinguished between urban and non-urban	By type: • Petroleum • Natural gas • Coal • Biomass • Nuclear • Hydro • Wind • Solar	Withdrawals less local releases AWARE-US model estimates regional and seasonal water stress

~50,000 Registered Users







GREET Informs Policy and Regulation

- **California-GREET** is an adaptation of Argonne's GREET model
- Specified in **Inflation Reduction Act** related to the **Clean Fuel Production Credit** and the **Clean Hydrogen Credit**
- **U.S. EPA** uses GREET with other sources for **Renewable Fuels Standard** pathway evaluations
- **Oregon Clean Fuels Program** also uses an adaptation of Argonne's GREET model
- **National Highway Traffic Safety Administration** for fuel economy regulation
- **Federal Aviation Administration** and **International Civil Aviation Organization** using GREET to evaluate aviation fuel pathways
- **U.S. Maritime Administration - renewable marine fuel options for IMO 2020 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

Plastics in GREET

GOAL:
Conduct analysis of advanced technologies to enable bioplastics and a circular economy for plastics. Provide scientific research and build consensus around technologies to address plastic waste and improve sustainability.

- LCA of bioplastics, plastic re-/upcycling, and plastic-to-fuels.
- Develop a circular economy sustainability analysis framework.
- Stakeholder engagement and consensus building.

Key issues:
- Establish technologies to enable a sustainable future for plastics.
- Understand the potential for chemical recycling vs. pyrolysis vs. waste-to-energy.
- Improve the environmental performance and economics of biofuels with co-products.
- Build consensus around the sustainability implications of circular economy strategies.

Plastics

GREET contains plastics supply chains to help address environmental concerns related to the production and use of plastics

Feedstock	Conversion	Manufacturing & Processing	Products	End-of-Use

• Fossil-based
  • Chemical precursors (ethylene, propylene, naphtha, etc.)
• Bio-based
  • Cellulosic
  • Woody
  • Waste
  • Biochemical precursors: adipic acid, acrylic acid, bio-ethylene, etc.)
	• Chemical
	• Thermochemical
	• Biochemical
		• Extrusion
		• Compression molding
		• Blow molding
		• Calendaring
		• Injection molding
			• Fossil-based
			  • PET
			  • HDPE/LDPE
			  • Nylon 6, 66
			  • PC
			  • PP
			  • PUR
			  • PVC
			• Bio-based
			  • Bio-PE
			  • Bio-PET
			  • PLA
			  • PEF
				• Landfill
				• Composting
				• Combustion with energy recovery
				• Recycling
				  • *Mechanical recycling*
				  • *Chemical recycling*
				  • *Biochemical recycling*

Circular Economy Sustainability Analysis Framework of Plastics

- **Objectives**
  - Quantify and compare energy and environmental metrics for conventional and circular plastic packaging pathways by extending the life cycle analysis (LCA) framework to address circular/upcycling pathways
  - Specify a framework for analysis of plastic in circular economy, building on established LCA methods
- **Analysis**
  - The study compares the production of PET bottles through different technologies
  - A circular economy sustainability analysis framework was developed in GREET
  - The framework integrates LCA with Material Flow Analysis (MFA) to simultaneously estimate environmental and circularity metrics
  - Four case studies were designed to evaluate the interactions between the conventional and circular PET production pathways

Life Cycle Analysis

Conventional pathways
- Virgin PET - PTA & EG route
- Virgin PET - DMT & EG route

Circular pathways
- Mechanical recycling
- Enzymatic hydrolysis

1) Current state
2) Max. mechanical recycling
3) Mechanical & Chemical
4) Mechanical, Chemical & Upcycling

*Greenhouse Gases, Regulated Emissions, and Energy Use in Technologies (**GREET**) Model*

Material Flow Analysis

Estimation of material flow factors
- Recycling rates
- Yields of operations
- Recycled content
- Co-product shares
- Technology shares

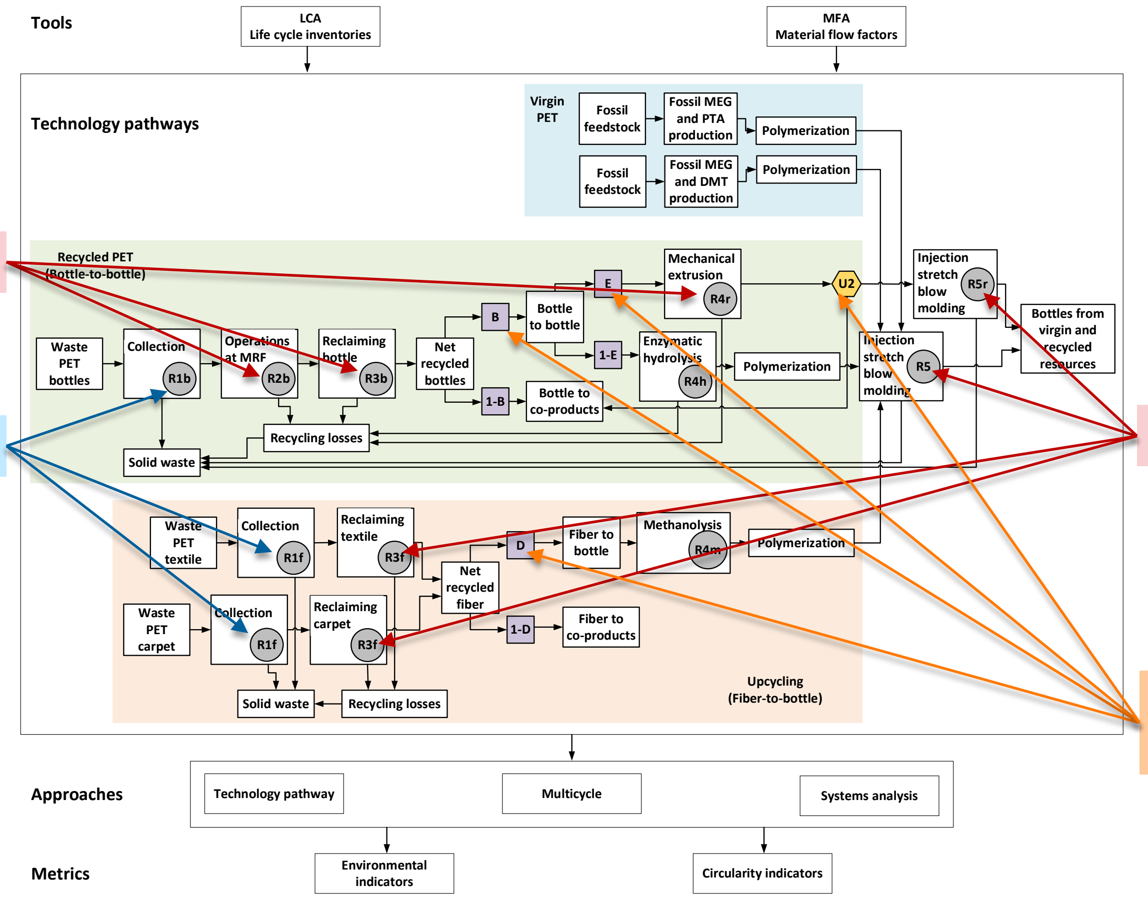
Estimation of flows in the supply chain

PET: Polyethylene terephthalate
PTA: Purified terephthalic acid
DMT: Dimethyl terephthalate
EG: Ethylene glycol

Environmental metrics
- GHG emissions
- Total energy consumption
- Water consumption

Circularity metrics
- Virgin material use
- Solid waste generation

Circular Economy Sustainability Analysis for Plastics



Yields

Recycling rates

Yields

Determine the Mass flows

New plastic recycling pathways for PET (bottle) production:

- Mechanically-recycled PET
- Chemically-recycled PET (via enzymatic hydrolysis)

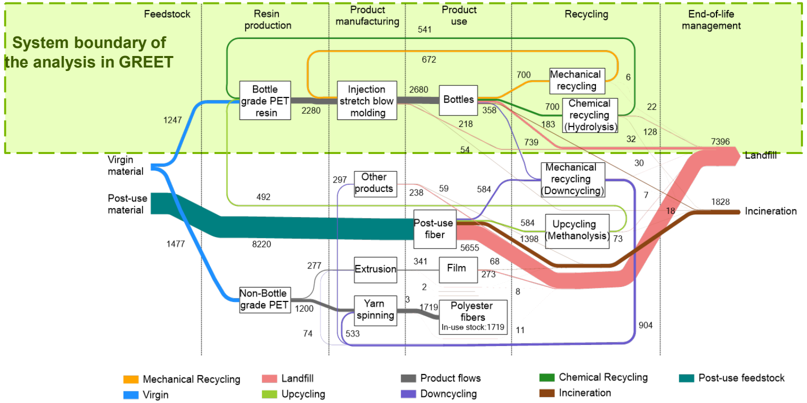
Gracida et al., 2022. ***A Circular Economy Sustainability Analysis Framework for Plastics: Application for Polyethylene Terephthalate (PET). Under review.***

Circular Economy Sustainability Analysis for Plastics

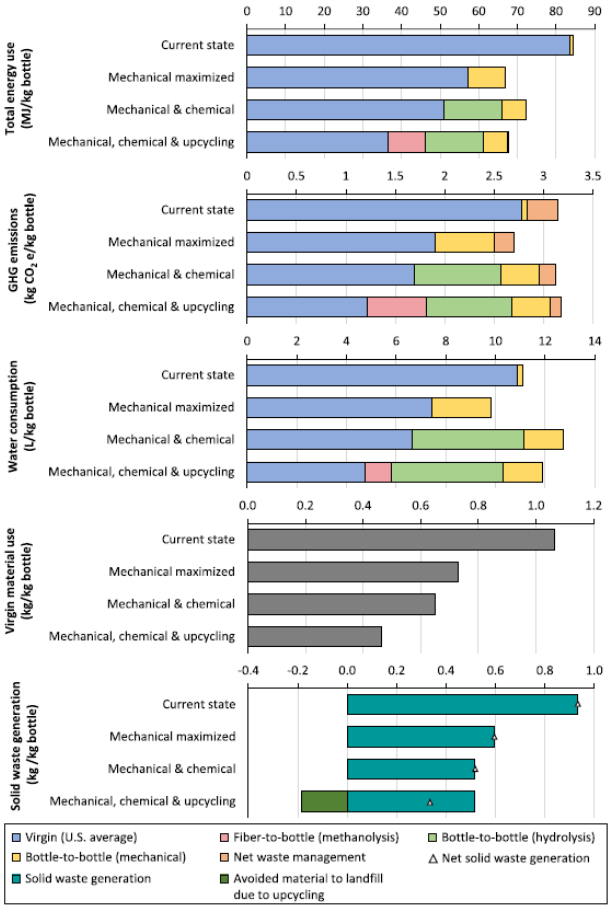
Major findings of the study

- Trade-offs between the environmental and circularity indicators of the recycling technologies were identified
- Recycling technologies with lower GHG emissions increase the reliance on virgin materials and vice versa
- Reclaiming operations are the major drivers of GHG emissions in the recycling pathways
- Chemical recycling and upcycling do not reduce the life-cycle impacts of the current supply chain but reduce virgin material use and solid waste generation

Sankey diagram of the U.S. supply chain of PET bottles when applying simultaneous circular economy strategies



Life cycle impacts and circularity metrics of the supply chain of PET Bottles by applying different circular economy strategies

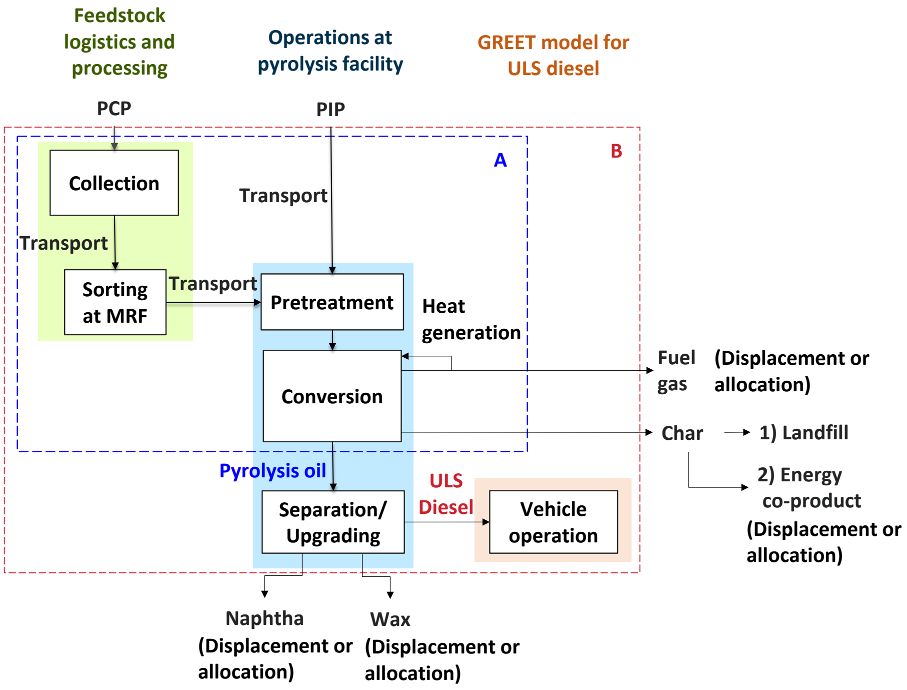


Post-Use Plastic (PUP) conversion to products

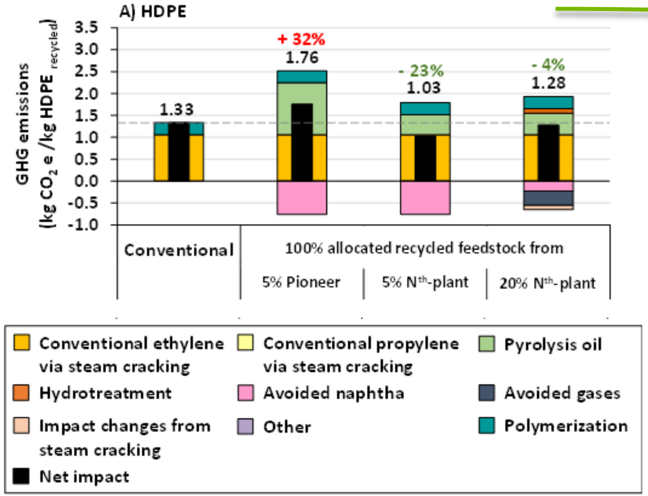
- **Updated version of post-use plastic conversion via pyrolysis**
  - Industry data collected to characterize post-use plastic pathways
  - Included production of intermediate product such as ***pyrolysis oil*** and fuel such as ***ultra-low sulfur (ULS)*** diesel.
  - Presented the data for two types of facilities: (1) pioneer, and (2) Nth-plant.

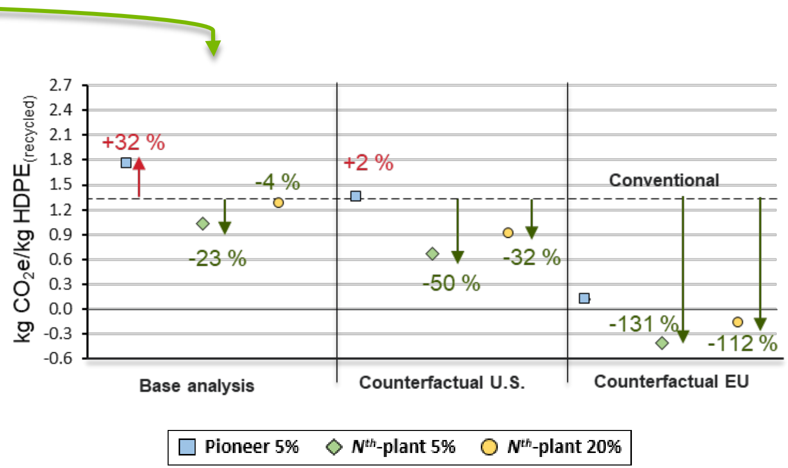
- **New inventories**
  - **PET reclaiming operations** (PET bottle-to-PET flake),
  - **Mechanical extrusion** (PET flake-to-mechanically recycled resin),
  - **Enzymatic hydrolysis** (PET flake to purified terephthalic acid and ethylene glycol).

- **New lubricant pathways**
  - Plastic Upcycling to Lubricant Product: (Cappello, V. et al. 2022)



Life cycle analysis of plastic-to-plastic pathways via pyrolysis





- Evaluate the impacts of producing polyolefins through cofeeding of PUP-derived pyrolysis oil with conventional feedstocks (naphtha and natural gas liquids)
- Use the mass balance approach to estimated GHG Emission reductions of different scenario including 5% and 20%, Plant capacity of the pyrolysis conversion facility (Pioneer vs Nth-plant), Counterfactual scenarios (U.S. vs. E.U), composition of the baseline feedstock of crackers
- HDPE with 100% allocated recycled feedstock showed up to 23% reductions in GHG emissions compared to conventional production of HDPE
- Inclusion of the avoided emissions from traditional end-of-life management in the United States reduced in up to 50% the GHG emissions compared of the conventional production of HDPE

Cross-database comparisons for plastics LCA: goal and scope

- Different plastics LCA databases have significant cross-database discrepancies
- **To identify the sources and quantify the degree of the discrepancy**, multiple LCA databases are investigated for five popular resin products and three post-use phases.
- The outcomes can help governmental agencies implement environmental regulations and other policies to plastics industry using the LCA approach

Database	GREET	USLCI	Ecoinvent	GaBi	
Software	GREET	OpenLCA	OpenLCA	GaBi	
Version	2021*	2021 Spring Quarter	v.3.7.1	v.10	
Publisher	ANL	NREL	Ecoinvent	Sphera	
Access	Free public access	Free public access	One-time purchase	Subscription-based	
PET	O (dataset available)	O	O	O	Resin production
HDPE	O	O	O	O	
PP	O	O	O	O	
bio-PE	O	X (not available)	X	O	
PLA	O	O	O	O	
Landfill	O	X	O	O	Post-use phase
Incineration	O	X	O	O	
Mech. Recycling	O	O	O	X	

*Some of the significant updates in GREET 2022 are reflected in the current analysis

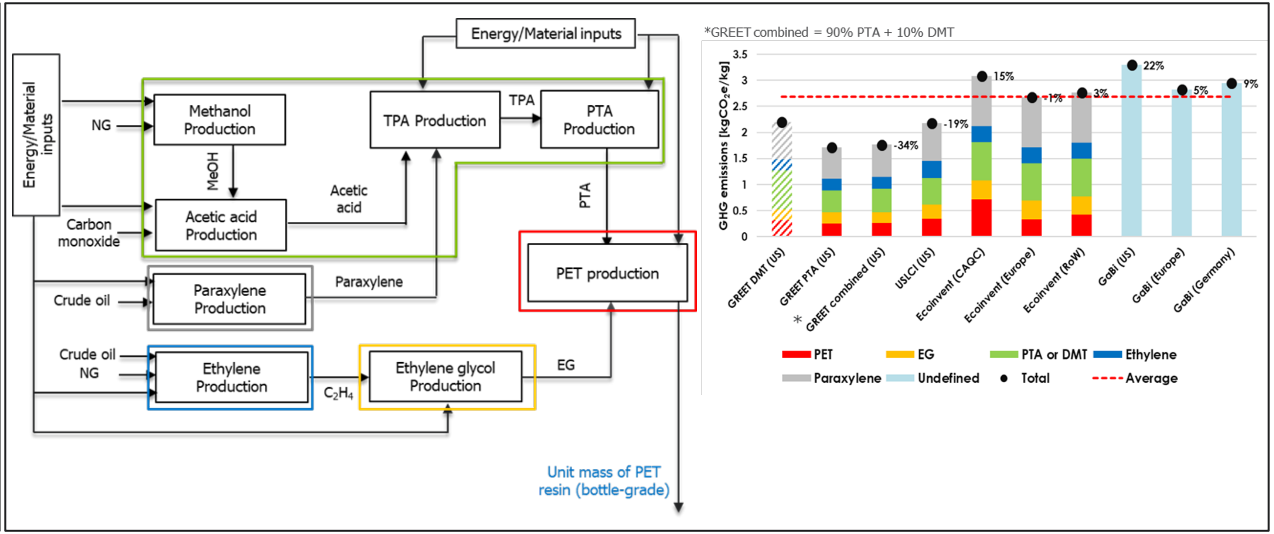
Cross-database comparisons for plastics LCA: metrics investigated

- Metadata comparisons and breakdown analysis are conducted to quantify the degree and identify the sources of discrepancy.

Metadata characteristics comparisons

- Datasets (UUID)
- LCI references
- Temporal representation
- Geographical representation
- System boundary
- Final product and functional unit
- Technology coverage and details
- Degree of representation
- Number of plants (and/or producers)
- Foreground co-products and allocation methods
- Granularity (or Transparency)

Breakdown analysis



- Life cycle impact assessment (LCIA) results are compared across the databases on the consistent impact category and factors for valid comparisons.

Accomplishments

Series of publications providing LCA results for biobased plastics and plastic-to-energy pathways.

- Environmental benefits of bio-based PET and recycled PET bottles
- Incorporating biodegradation of compostable plastic into LCA of bioplastics
- LCA of non-recycled plastics to fuels
- LCA comparison of biobased and conventional chemicals
- LCA of stover-derived lactic acid and ethyl lactate
- LCA of new bioplastic
- New feedstocks, alternative feedstocks
- Data collection from industry waste plastic conversion process

– Expansion of GREET® to include biobased plastics, conventional virgin and recycled plastics, biochemical co-products from biorefineries, and conventional chemicals.

ACS Sustainable Chemistry & Engineering
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Exploring Comparative Energy and Environmental ... Virgin, Recycled, and Bio-Derived PET Bottles
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Supporting Information

Environmental Science & Technology
Article
pubs.acs.org/est
Life-Cycle Fossil Energy Consumption and Greenhouse Gas Emissions of Bioderived Chemicals and Their Conventional Counterparts
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Argonne National Laboratory, 9700 S. Cass Avenue, Argonne, Illinois 60439, United States

Contents lists available at ScienceDirect
Fuel
journal homepage: www.elsevier.com/locate/fuel
Full Length Article
Life-cycle analysis of fuels from post-use non-recycled plastics
Pahola Thathiana Benavides, Pingping Sun, Jeongwoo Han, Jennifer B. Dunn, Michael Wang
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Journal of Cleaner Production 277 (2020) 124010
Contents lists available at ScienceDirect
Journal of Cleaner Production
journal homepage: www.elsevier.com/locate/jclepro
Life cycle greenhouse gas emissions and energy use of polylactic acid, bio-derived polyethylene, and fossil-derived polyethylene
Pahola Thathiana Benavides, Uisung Lee, Omid Zarè-Mehrjerdi

Argonne NATIONAL LABORATORY
ANL-22/37
Life-cycle Analysis of Conversion of Post-Use Plastic via Pyrolysis with the GREET Model

Contents lists available at ScienceDirect
Journal of Cleaner Production
journal homepage: www.elsevier.com/locate/jclepro
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
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Journal of Cleaner Production xxx (xxxx) 135110

ACS Sustainable Chemistry & Engineering
pubs.acs.org/journal/ascecg
Research Article
Life Cycle Greenhouse Gas Emissions and Water and Fossil-Fuel Consumptions for Polyethylene Furanoate and Its Coproducts fr... Wheat Straw
Taemin Kim, James Bamford, Ulises R. Gracida-Alvarez, and Pahola Thathiana Benavides
Cite This: ACS Sustainable Chem. Eng. 2022, 10, 2830–2843
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journal homepage: www.elsevier.com/locate/jclepro
Life cycle analysis of polylactic acids from different wet waste feedstocks
Taemin Kim, Arpit Bhatt, Ling Tao, Pahola Thathiana Benavides

Thank you!

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GREET 2022 Updates

GREET 1

- Updated and expanded hydrogen production pathways with GUI in GREET Excel version
- Updated CO_2 utilization simulations: carbon accounting, detailed modeling of CO_2 capture, compression, and transportation, direct air capture
- Included offshore macroalgae production technologies
- Updated and expanded marine fuel production pathways, with a GREET marine module
- Updated and expansion of biodiesel and renewable diesel: used cooking oil is added.
- Updated post-use plastic pyrolysis conversion
- Updated and expanded waste to polylactic acid (PLA) and plastic modeling
- Updated and expanded of ammonia production pathways (conventional, blue, and green ammonia)
- Added post-use plastic to lubricant product pathways (including synthetic lubricants poly-alpha olefins)
- Added an air separation unit to O_2 and N_2 production

GREET 2

- Updated infrastructure LCA for nuclear power, hydropower, wind turbines, solar photovoltaics
- Updated and expanded LCA of electrolyzers (solid oxide, alkaline, and proton exchange membrane)
- Updated light-, medium-, and heavy-duty vehicle components
- Updated and expanded the battery LCA module with new materials and domestic lithium production
- Updated inventory data for aluminum production
- Updated LCA of critical materials (Ni, Cu, Ti, and rare earth elems)
- Added the end-of-life credit approach of vehicle recycling (steel and aluminum)

Background Data

- Global warming potentials of AR6
- US electricity generation mix and crude oil mix
- Methane leakage of natural gas supply chain
- Fuel use for natural gas recovery
- Expansion of plastic inventory
- Energy intensity of rail movement of passengers
- Aviation payload energy intensities and combustion emissions
- HD hybrid electric vehicle fuel economy
- Feedstock slate for U.S. steam crackers