

NOVEMBER 7 2022
GREET TRAINING WORKSHOP



GREET LCA of Building Materials, Chemicals, Bioproducts, Plastics, and Catalysts

Hao Cai, Ph.D.

P. Thathiana Benavides, Ph.D.

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



Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.



75
1946–2021



GREET LCA OF BUILDING MATERIALS, COMPOSITES, AND WHOLE BUILDINGS



Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.

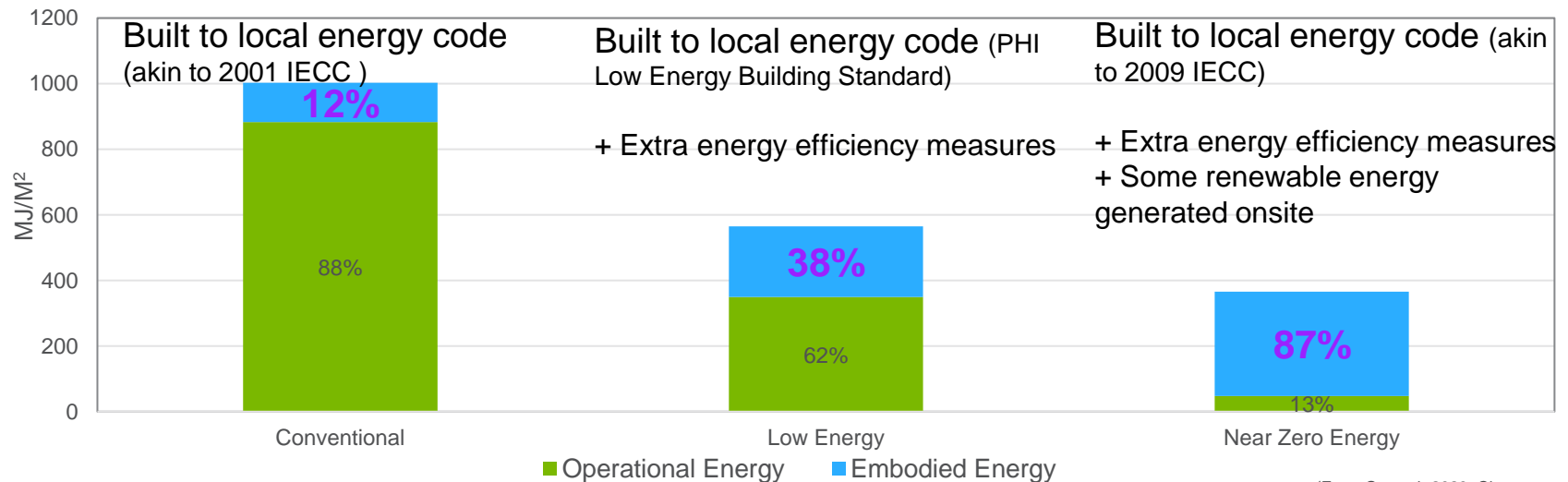
Argonne 
NATIONAL LABORATORY

75
1946–2021

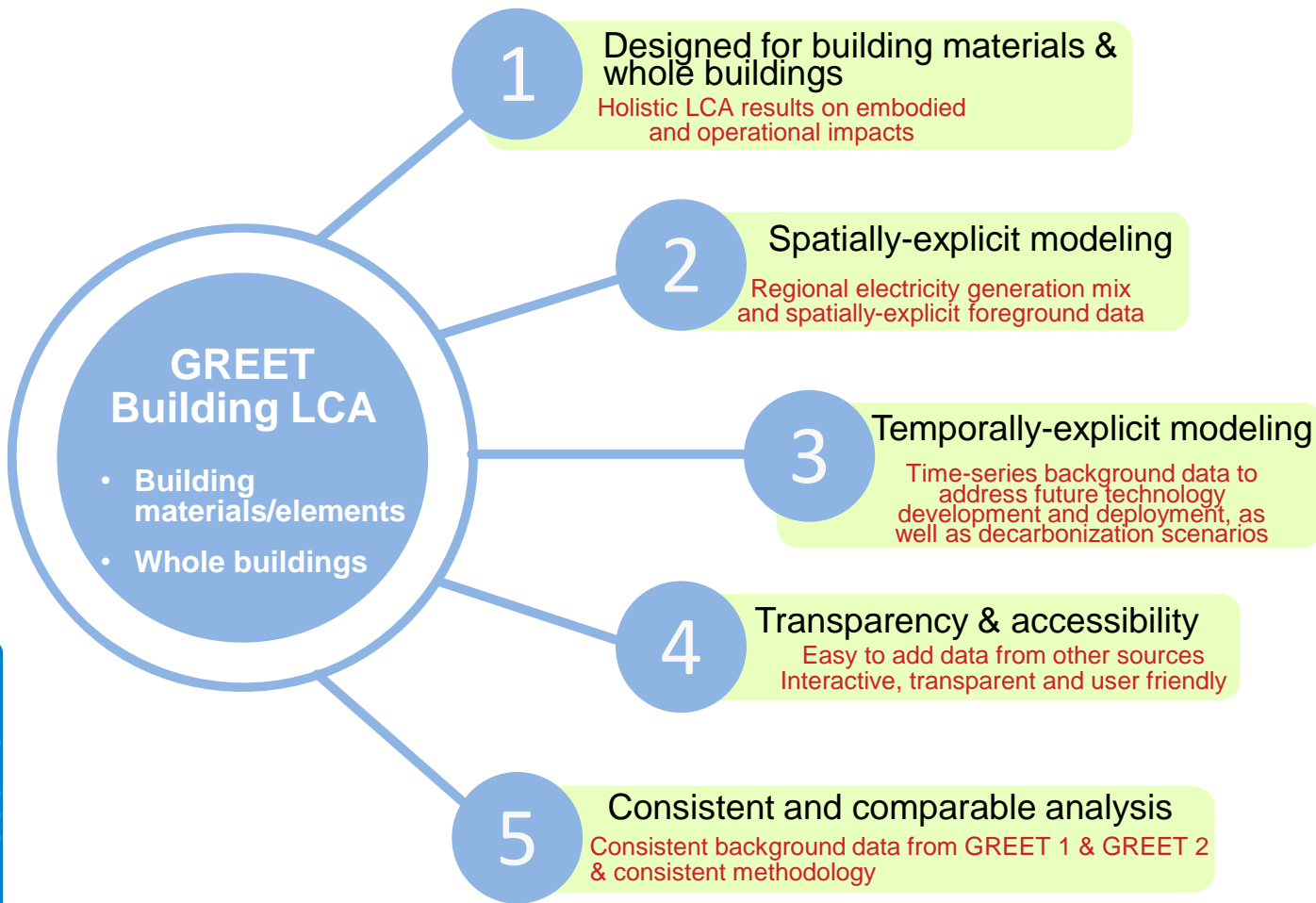
Addressing Embodied Energy and Carbon Impacts Becomes Critical to Sustainable Buildings

As the building sector continues to improve energy efficiency to reach net zero energy buildings, embodied energy/GHGs could become the **“elephant in the room (or buildings)”**.

Illustrative Tradeoffs Between Embodied Energy and Operational Energy: MJ/M²



(From Goetsch 2020; Chastas et al, 2016)



Argonne building LCAs inform building technology R&D of opportunities to improve embodied and operational GHG performance for deep-decarbonization of building materials and whole buildings.

GREET Building LCA Module Released To Public

GREET®

Publications

Databases

GREET Model Platforms

GREET .Net

GREET Excel

Fuel-Cycle Model

Vehicle-Cycle Model

GREET Tools

WTW Calculator

AFLEET Tool

AWARE-US Model

FD-CIC Tool

Refinery Products VOC

GREET Building Module

GREET Building LCA Module

Click to save and extract the .7z archive [GREET_Building_LCA_Module_2022.7z](#) to your hard drive.

GREET Building LCA Module 2022

The GREET team of Systems Assessment Center at Argonne National Laboratory is pleased to announce release of a new GREET Building LCA Module.

The GREET Building LCA Module is designed to conduct and compare detailed and transparent LCA of building materials/components/technologies, as well as whole buildings and building designs.

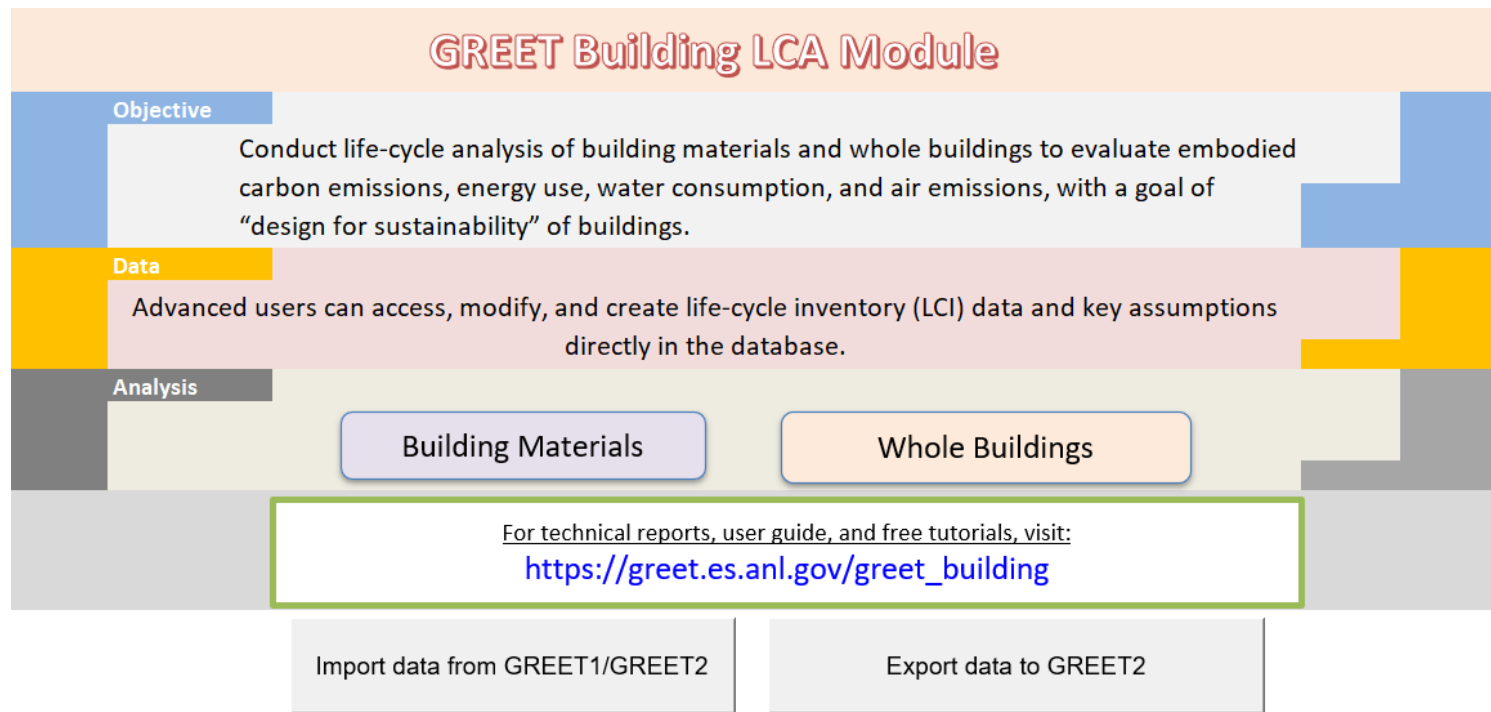
A Transparent, Standardized Tool to Address Building Technologies and Inform R&D, Building Designs, and Technology Integration

- The Whole Building Analysis Module has been augmented to enable sensitivity analysis. A Bill of Materials for a building, whence run through the initial LCA, can be set up for sensitivity analysis. The quantity, material type, loss factor, replacement period, and adjustment factor can be set up for each individual material, and the changes in emissions analyzed for each separate factor
- The Whole Building Analysis module has been augmented to allow for disaggregated life cycle results. Life Cycle Analysis results can be aggregated to the system boundary or disaggregated and calculated at each life cycle stage
- The LCProfiles database has been expanded into two worksheets to handle the disaggregated whole building

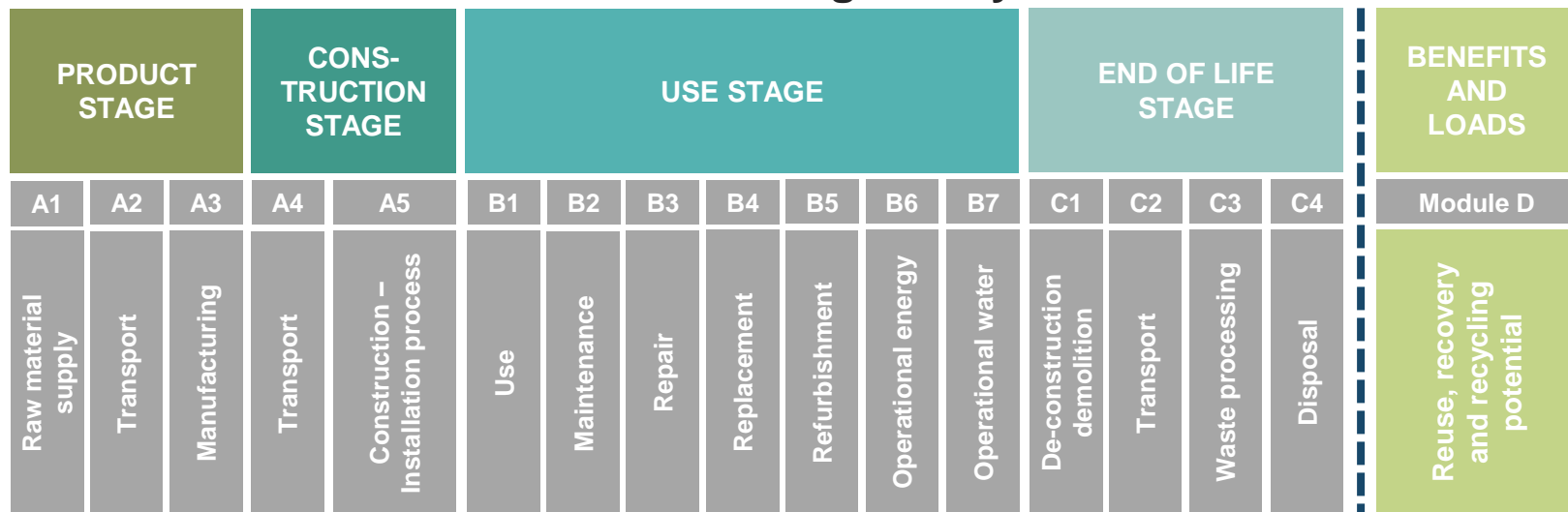
https://greet.es.anl.gov/greet_building

How does the GREET Building LCA Module look like?

Designed to address embodied and operational impacts of building materials and whole buildings with dynamic linkages to GREET 1 and GREET 2



Building Materials & Whole Building Life-cycle



EN 15978 (2011)

Background data from GREET;
Detailed transportation modeling
 capabilities: modal (truck, rail, barge, and tanker), share of fuel type, distance, and payload;
Custom electricity generation mix & Regionalized electricity
 generation mix at the state level.

Energy and water consumption **during use phase;**
Custom electricity generation mix;
Replacement schedule;
Temporal effects with time-series emission factors to reflect effects of technology advancement over time.

Materials, energy and water for **demolition;**
Detailed Transportation modeling: modal (truck, rail, barge, and tanker), share of fuel type, distance, and payload.
Waste processing modeling;
End-of-life impact modeling.

Building LCA: Cradle-to-Grave consideration of a building to address its energy and environmental footprints

Making and Supply of Raw Material:

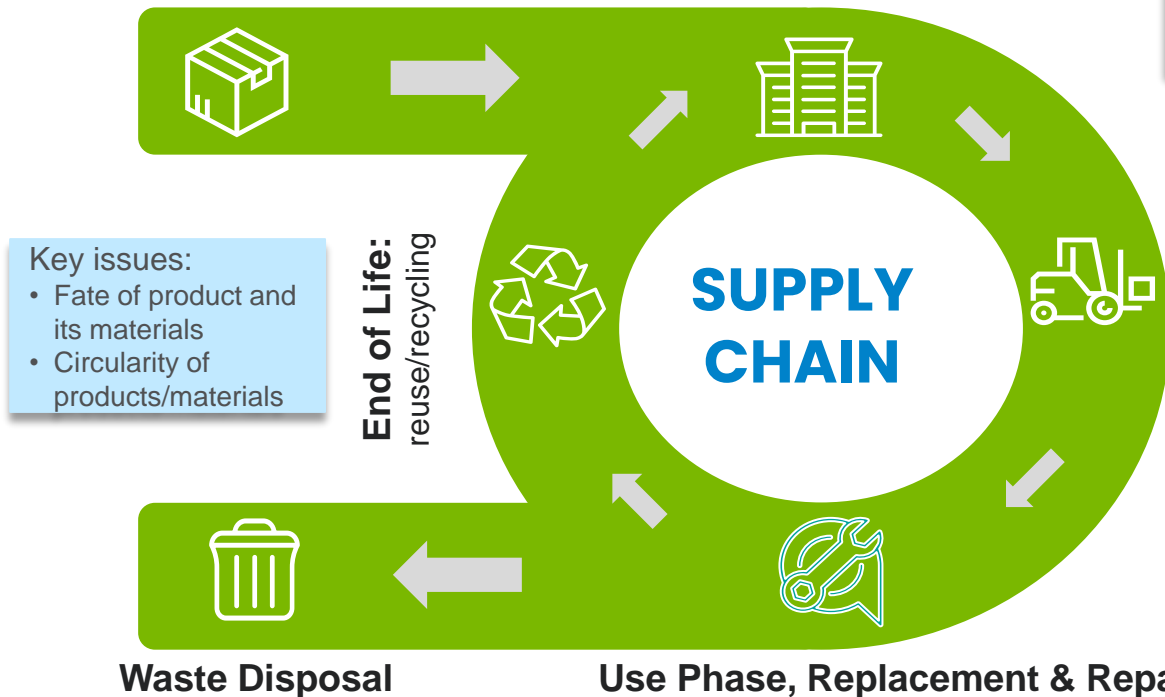
- Material & energy & inputs
- Direct/embodied energy/emissions

Making of Building Components:

- Energy & material inputs
- Direct/embodied energy/emissions

Key issues:

- Material composition
- Manufacturing processes
 - ✓ Energy efficiency: how much used
 - ✓ Type of energy used: natural gas, electricity, etc.



Distribution

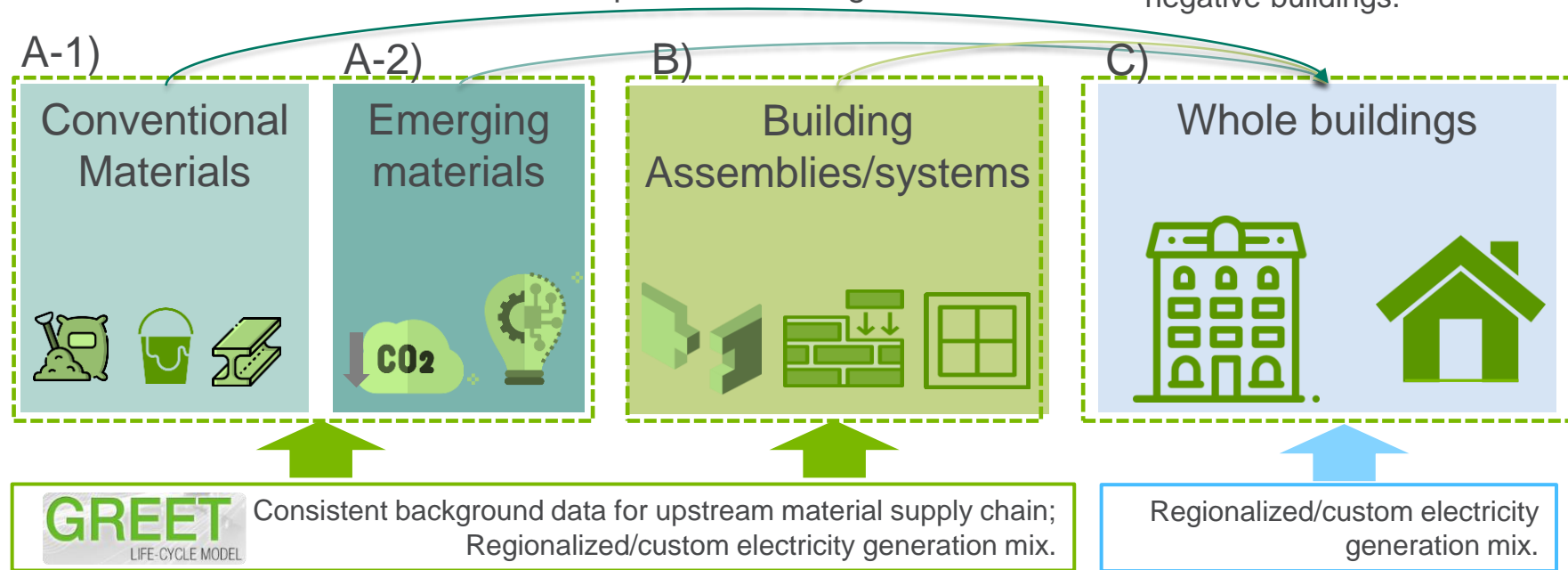
Key issues:

- Volume- or mass-limited transportation
- Logistics details: transportation modes, distances, losses, etc.

All inputs (materials and energy) across the supply chain have their own life cycles and footprints!

GREET Building LCA Address Building Materials and Whole Buildings Holistically

- ✓ Bottom-up approach.
- ✓ Embodied GHG hotspots.
- ✓ Weigh options to achieve both embodied and operational performance targets.
- ✓ Holistic embodied and operational impact modeling;
- ✓ Identify opportunities towards net zero carbon/carbon-negative buildings.



A-1) Concrete LCA With GREET

Select Material to Model: Create New Component Import Component from Another File Mark Material as Updated

Concrete, light weight, US national benchmark mix, 4000 psi Address Data Gaps for the Current Material Address All Data Gaps for All the Materials

Create a Copy Delete

Component Properties

Functional Unit: System Boundary: Component Category:

Modeling Year: Set Modeling Year

Life Cycle Details Define Context for system boundary past Cradle to Gate Define Context

Manufacturing Processes

A1 - Raw Material Supply A2 - Raw Material Transportation A3 - Manufacturing

A1+A2+A3: User Manual Entry

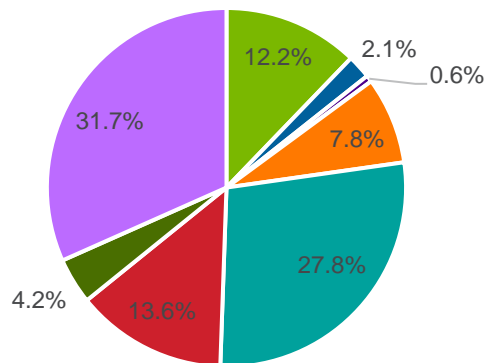
A4 - Finished Product Transportation A5 - Construction & Installation B - Use, Maintenance, Repair, Replacement, Refurbishment C1 - Deconstruction C2 - Waste Transportation C3 - Waste Processing C4 - Disposal D - Re-X

Run Simulation View Results in Dashboard Show/Edit LCI Database Run Forward Propagating LCA Run Recursive Simulation

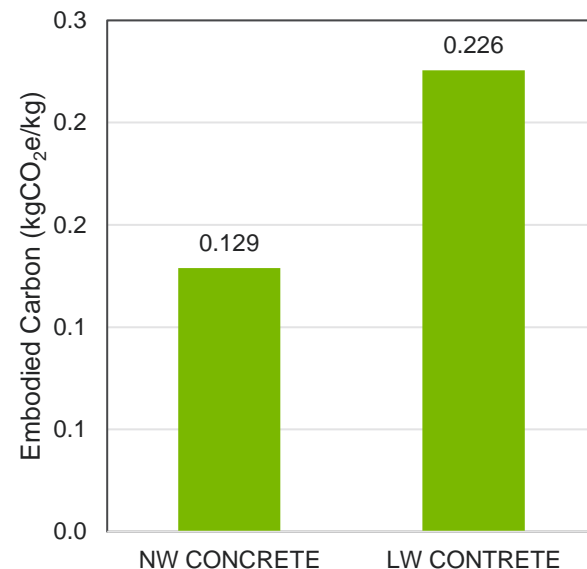
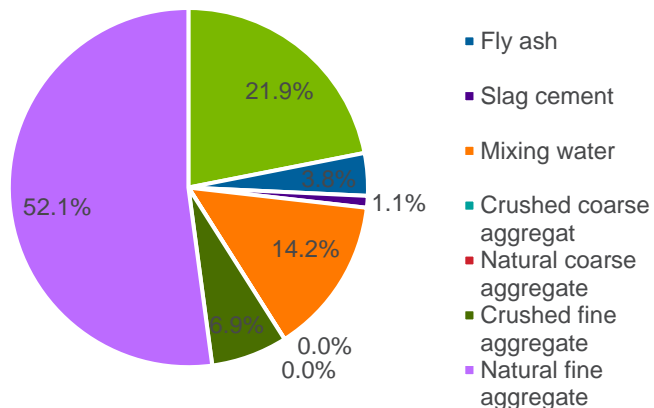
Process-level LCA produces reliable embodied GHG emissions results with detailed foreground data across the supply chain.

A-1) Concrete LCA With GREET

Normal weight concrete (4000 psi) mix design



Light weight concrete (4000 psi) mix design



- Process-level LCA results pinpoints key drivers of ready-mixed concrete products of different formulations;
- Lightweight (LW) concrete contains a greater share of Portland cement than normal weight (NW) concrete, leading to much greater embodied GHG emissions.

B) Wall Assembly LCA with GREET

GREET Building LCA Data Entry

Select Category to Filter Component List

Create New Component

Select Material to Model



Reynolds, 2021

Retrofit Wall Panel_Baseline

Create a Copy Delete

Component Properties

Functional Unit: System Boundary: Component Category:

Life Cycle Details

Manufacturing Processes

A1 - Raw Material A2 - Raw Material Transportation A3 - Manufacturing A4 - Finished Product Transportation A5 - Construction & Installation B - Use, Maintenance, Repair, Replacement, Refurbishment C - End of Life D - Re-X

Run Simulation View Results in Dashboard Show/Edit LCI Database

Enter Manufacturing Process Information...

Retrofit Wall Panel_Baseline

Process Steps

- Housewrap
- Tape
- Vinyl siding
- Dense pack cellulose
- Furring Strips
- 3/4" XPS Furring Infill
- 2" Exterior XPS Foam
- Fasteners
- Retrofit Wall Panel_Baseline

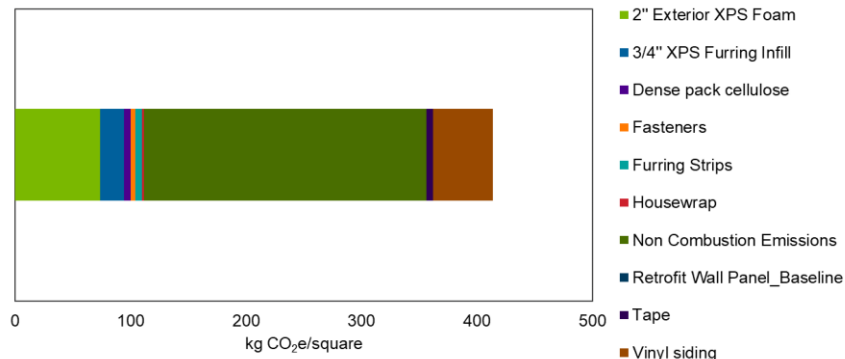
Insert New Remove

Primary Output: Functional Unit: Location:

A1 - Raw Material Sourcing A2 - Raw Material Transport A3 - Manufacturing

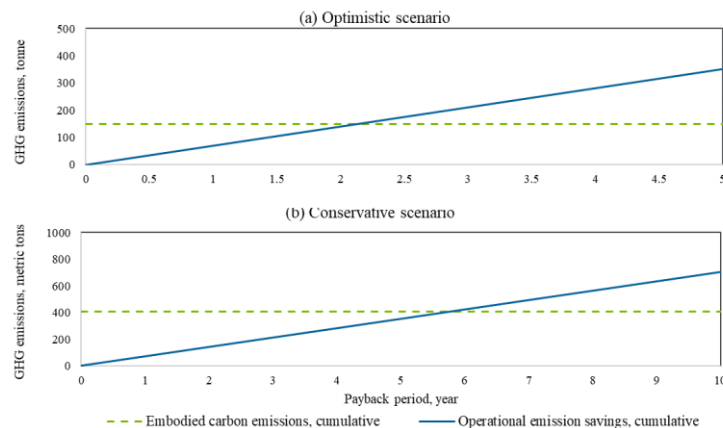
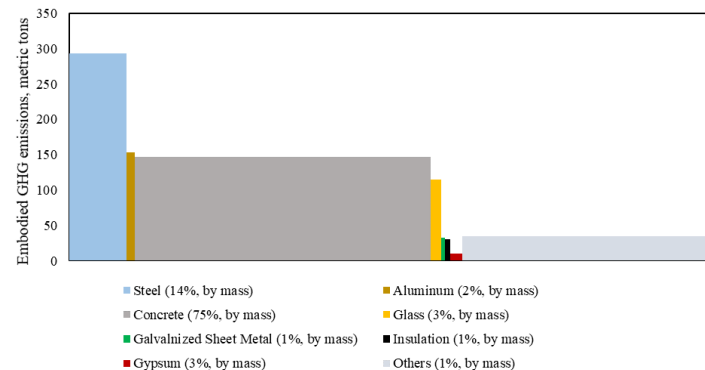
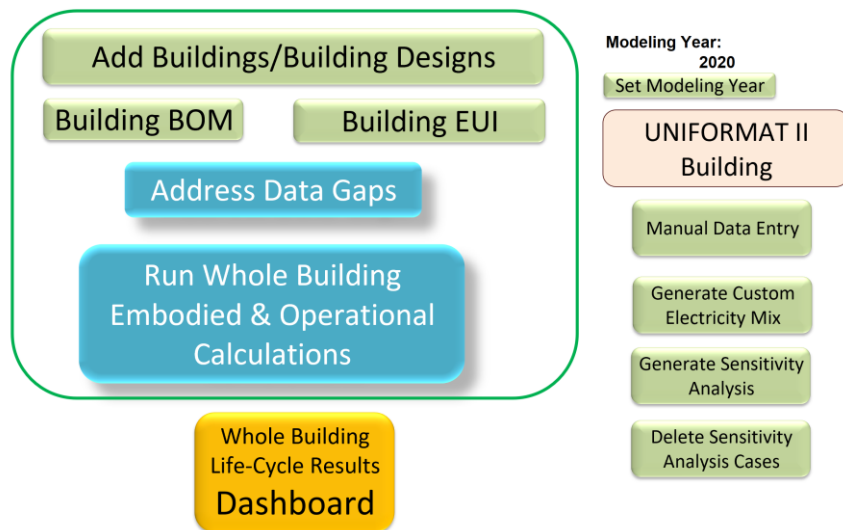
Notes

OK



Process-level, integrated, and transparent modeling of building composites (wall panels) with consistent methodologies and background data.

c) Whole Building LCA With GREET: Chicago Chinatown Public Library





GREET LCA OF PRODUCTS, PLASTICS, AND CATALYSTS



U.S. DEPARTMENT OF
ENERGY

Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.

Argonne 
NATIONAL LABORATORY

75
1946–2021

Steam Cracking

- Two scenarios of co-produced hydrogen treatment
 - Scenario A - Hydrogen is used as internal energy source
 - Scenario B - Hydrogen is sold externally
- 2. Three co-product allocation including: Mass, market-value and energy allocation
- 3. Emissions factors (EF) based on feedstock slate carbon content
 - Feedstock cracking EFs come from industry reported data
 - Cracking CO₂ emissions are adjusted based on the carbon content of feedstocks. Taken from GHGRP & NEI
- 4. Updated the feedstock slate of steam crackers in the United States

U.S average feedstock slate (Lippe, 2020) ^a

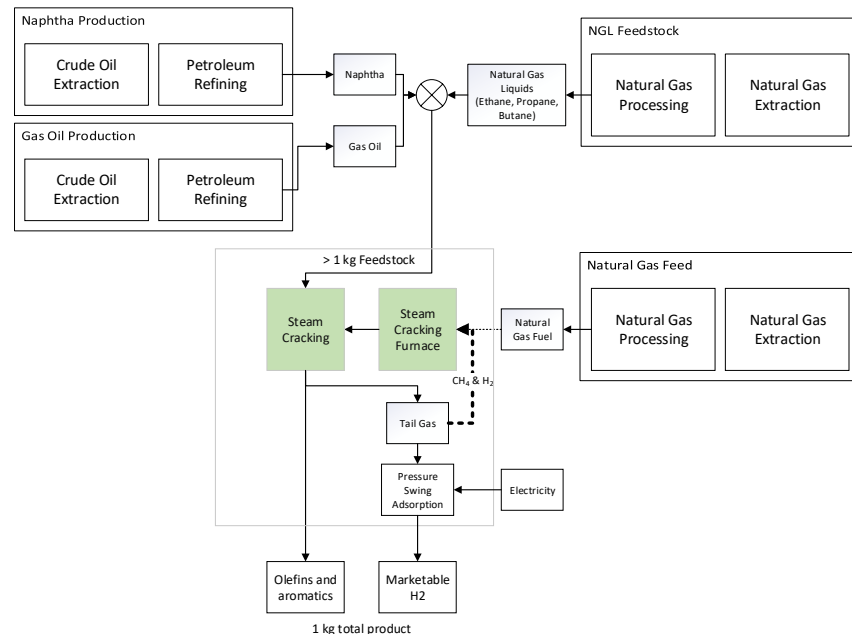
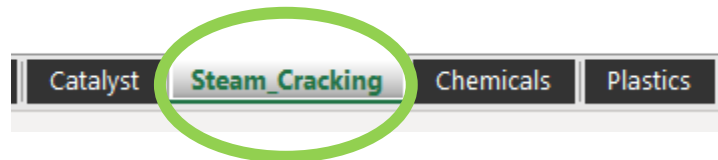
	Ethane	Propane	Butane	Naphtha
Feedstock Slate (Mass Ratio)	75.6%	15.5%	2.8%	6.1%

^a Lippe, D., 2020. US ethylene producers evaluate post-pandemic capacity additions. Oil & Gas Journal

118, 56–64

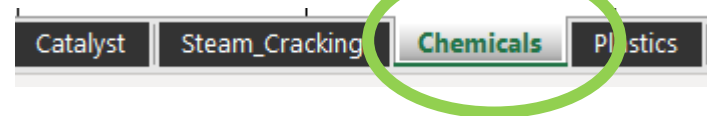


Argonne National Laboratory is a U.S. Department of Energy laboratory managed by UChicago Argonne, LLC.



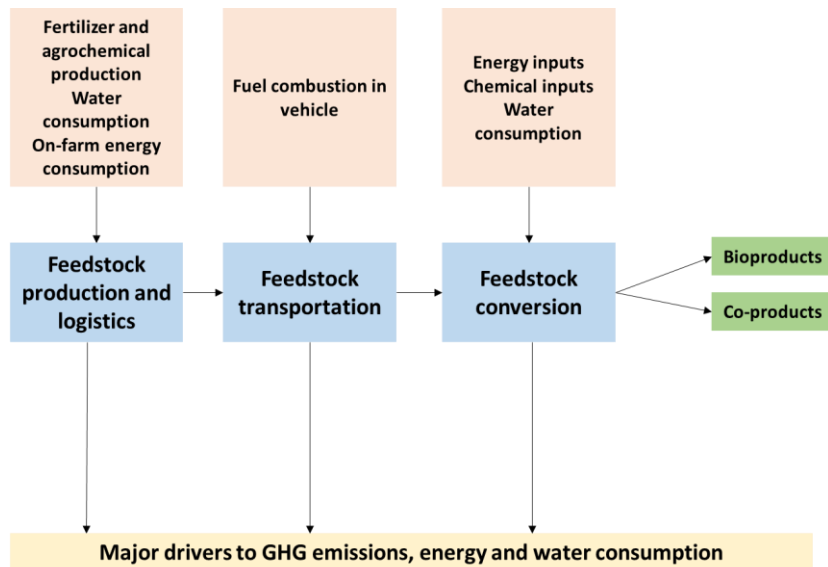
Chemicals

- Comprehensive collection of inventories that can be easily applied in downstream production processes.
- Information regarding the U.S. shares of production for chemicals with multiple production pathways
- The conversion pathway and reference source are now specified as notes in the calculations section for all chemicals for which this information was available
- Calculations and results are separated by fossil-based and bio-based products
- Commonly used chemicals, such as the olefins from the Steam_Cracking tab are exported to the results section in the new Chemicals tab.
- New production pathways were added for 9 fossil-based chemicals*



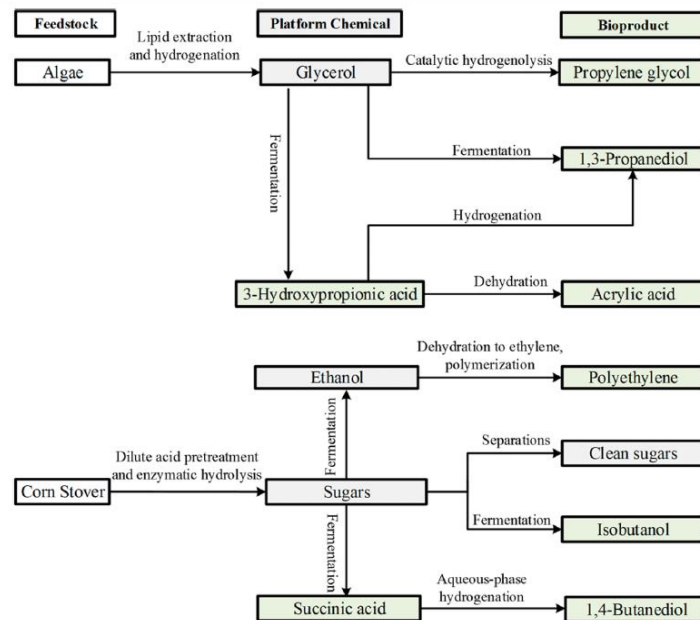
Fossil-based pathways		Bio-based pathways
	1,4-butanediol	
Oxygen		Bio Propylene Glycol
Benzene	Cyclohexane	Bio 1,3-Propanediol (glycerol)
Ethylene Oxide	Adipic Acid	Bio 1,3-Propanediol (3-HP)
Syngas from Coal and NG	Barite*	Bio 3-Hydroxypropionic acid (3-HP) (Distillation)
Propylene Oxide	Fossil Mono Ethylene Glycol (MEG)*	Bio 3-Hydroxypropionic acid (3-HP) (EDI)
Propylene Glycol	Carbon monoxide*	Bio Acrylic Acid
Acrylic Acid	Mixed Xylenes*	Bio Ethylene
	Fossil Purified Terephthalic Acid (PTA)*	
Formaldehyde	Paraxylene*	Bio Sugars
Acetylene	Aluminum Sulfate (liquid)*	Bio Isobutanol
1,3-Propanediol (Syngas from Coal)		Bio Succinic Acid (LLE) and (EDI)
1,3-Propanediol (Syngas from NG)	Ferric Chloride*	Bio 1,4-butanediol
Isobutanol (Syngas from Coal and NG)	Defoamant*	Lactic acid (From Corn, corn stover, wet wastes)
	Fossil Dimethyl Terephthalate (DMT)*	Ethyl Lactate (corn and corn stover derived lactic acid)
Ethyl Acetate		Bio Ethylene Oxide
Nitrogen		Bio Ethylene Glycol
Hydrogen		Bio Terephthalic acid (TPA) via isobutanol intermediate
Methane		
Olefins including ethylene, propylene, etc.		

Life cycle of products



Environmental Science & Technology

Article



Adom et al 2014. *Environ. Sci. Technol.* 2014, 48, 24, 14624–14631
<https://doi.org/10.1021/es503766e>

Plastics

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

Feedstock

- Fossil-based
 - Chemical precursors (ethylene, propylene, naphtha, etc.)
- Bio-based
 - Cellulosic
 - Woody
 - Waste
 - Biochemical precursors: adipic acid, acrylic acid, bio-ethylene, etc.)



Conversion

- Chemical
- Thermochemical
- Biochemical



Manufacturing & Processing

- Extrusion
- Compression molding
- Blow molding
- Calendaring
- Injection molding



Products

- Fossil-based
 - PET
 - HDPE/LDPE
 - Nylon 6, 66
 - PC
 - PP
 - PUR
 - PVC
- Bio-based
 - Bio-PE
 - Bio-PET
 - PLA
 - PEF



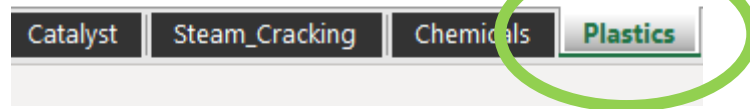
End-of-Use

- Landfill
- Composting
- Combustion with energy recovery
- Recycling
 - *Mechanical recycling*
 - *Chemical recycling*
 - *Biochemical recycling*



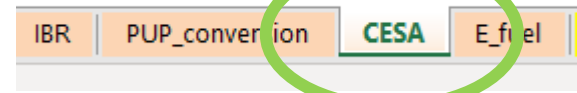
Plastics

- New “Plastics” tab in GREET1 that contains inventories for several fossil-based and bio-based plastic resins, transformation processes, and final plastic products
- Inventories are drawn from those already contained in the GREET2 Plastics tab
- Tab contain characteristic like heating value, carbon content, biodegradability, and the percent of carbon that is biogenic
- Details the U.S. shares of production for plastics that have multiple production pathways and allocation methods options
- Updated inventory for major plastic pathways*
- Transformation technologies include:
 - Compression molding
 - Calendaring
 - Extrusion
 - Injection molding
 - Blow molding
 - Yarn Spinning

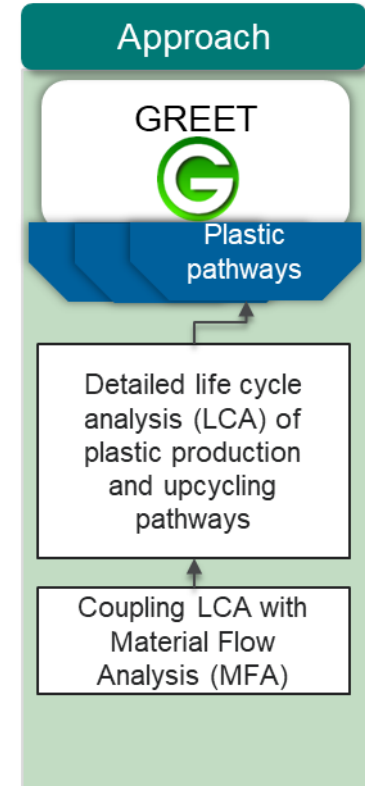


Fossil-based pathways		Bio-based pathways
Fossil Acrylonitrile-Butadiene-Styrene (ABS)	Fossil Nylon 6 and 66	Bio Polyethylene (PE)
Ethylene Propylene Diene Monomer (EPDM)	Fossil Polycarbonate (PC)	Polylactic Acid (PLA) - From Corn
Fossil General purpose polystyrene (GPPS)	<i>Fossil Polyethylene Terephthalate (PET)* via PTA and EG and DME and EG</i>	Bio Polyethylene Terephthalate (PET)
Fossil High-Impact Polystyrene (HIPS)	<i>Fossil Polypropylene (PP)*</i>	Polyethylene Furanoate (PEF)
<i>Fossil High-Density Polyethylene (HDPE)*</i>	Fossil Polyurethane (PUR) Flexible Foam	Polylactic acid (PLA) from wastewater sludge
<i>Fossil Low-Density Polyethylene (LDPE)*</i>	Fossil Polyurethane (PUR) Rigid Foam	Polylactic acid (PLA) from food waste
Fossil Linear Low-Density Polyethylene (LLDPE)	Fossil Polyvinyl Chloride (PVC)	Polylactic acid (PLA) from swine manure

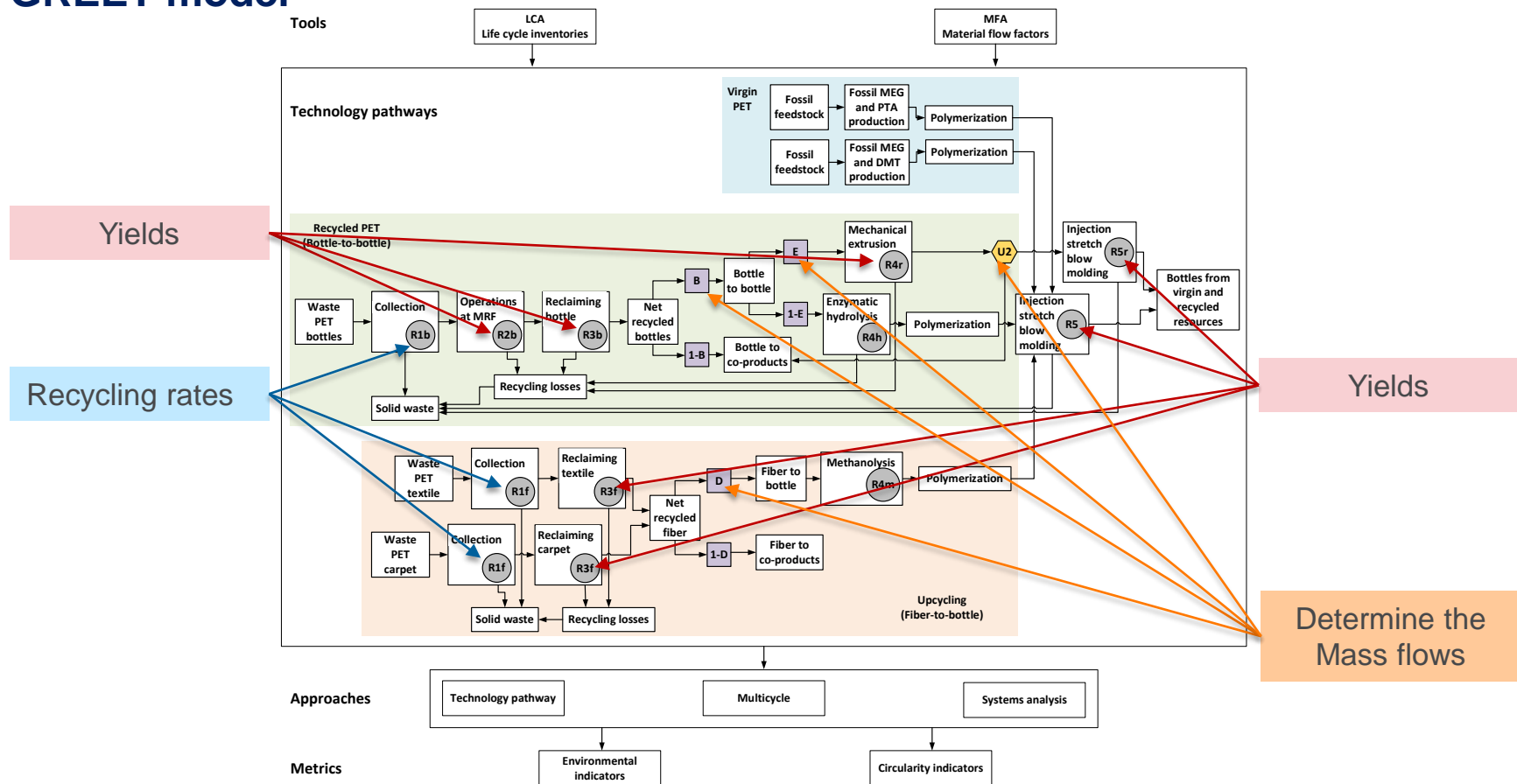
Circular economy sustainability analysis of plastics



- Input information related of post-use PET bottles to recycled bottles
 - Recycling rates
 - Recycling Shares
 - Yields: sorting, reclaiming, chemical conversion hydrolysis, polymerization
 - Material loses
- New recycling plastic technologies pathways for PET (bottle) production added
 - Mechanically-recycled PET
 - Chemically-recycled PET (via enzymatic hydrolysis)
- Cases studies
 - Business as usual
 - User defined
- New metric to assess circularity
 - Virgin material use
 - Solid waste generation

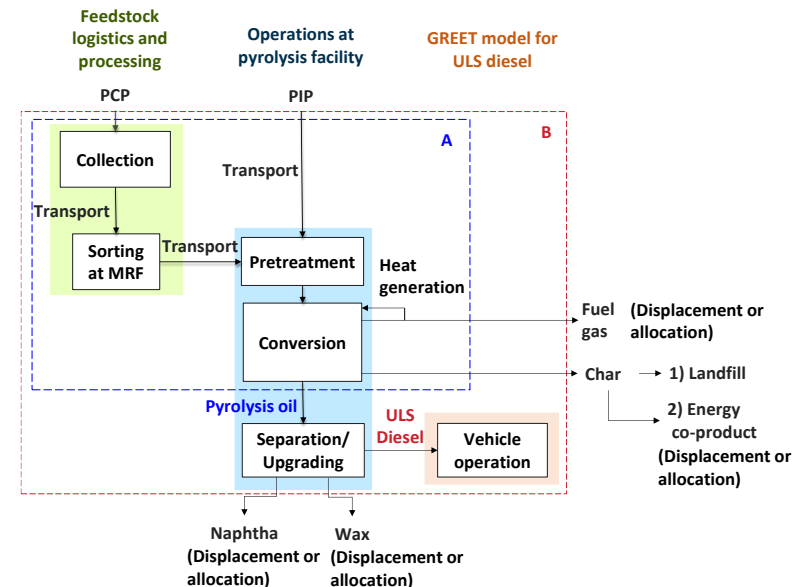


Transparent and Publicly-available Circular Economy of Plastics with the GREET model



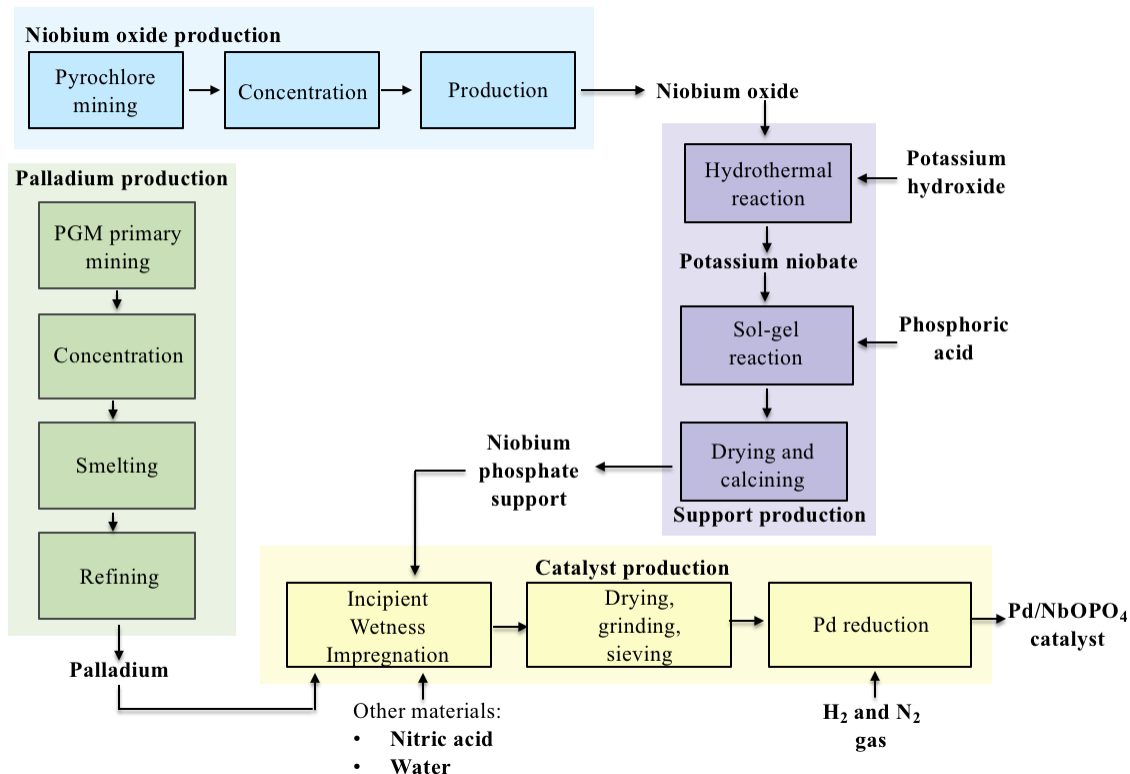
Post-Use Plastic (PUP) conversion

- Updated version of the life-cycle analysis (LCA) of PUP conversion via pyrolysis
 - Industry data was collected and processed to characterize the environmental benefits and tradeoffs of PUP conversion 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: (1) pioneer, and (2) Nth-plant.
- New inventories for recycling of PUP
 - reclaiming operations of PET bottles (PET bottle-to-PET flake conversion),
 - mechanical extrusion (PET flake-to-mechanically recycled PET resin),
 - enzymatic hydrolysis (PET flake converted to purified terephthalic acid and ethylene glycol).
- Added other conversion pathways to produce Lubricants
 - Plastic Upcycling to Lubricant Product: (Cappello, V. et al. 2022)



Catalyst

- Contains material and energy inventories for catalysts that can be applied in LCAs of biofuels or other products
- Added two new catalysts
 - single-phase catalyst composed of palladium metal on a niobium phosphate support: Pd/NbOPO_4
 - Zirconium oxide: ZrO_2
- Added inventories of associated material for catalyst production
 - Nb_2O_5
 - KNbO_3
 - NbOPO_4
 - zircon



Supply chain featuring the primary materials inputs and outputs for production of Pd/NbOPO_4 catalyst (Kingsbury & Benavides 2021)

CONTRIBUTORS

Building LCA:

Hao Cai
Tom Sykora
Michele Morales
Jarod Kelly
Michael Wang

Chemicals LCA:

P. Thathiana Benavides
Amgad Elgowainy
Ulises R. Gracida
Troy Hawkins
Taemin Kim
Pingping Sun
Michael Wang

The GREET research effort at Argonne National Laboratory was supported by the Office of Energy Efficiency and Renewable Energy (EERE) of the US Department of Energy (DOE) under contract DE-AC02-06CH11357. The views and opinions expressed herein do not necessarily state or reflect those of the US government or any agency thereof. Neither the US government nor any agency thereof, nor any of their employees, makes any warranty, expressed or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights.



THANK YOU!



U.S. DEPARTMENT OF
ENERGY

Argonne National Laboratory is a
U.S. Department of Energy laboratory
managed by UChicago Argonne, LLC.

Argonne 
NATIONAL LABORATORY

75
1946–2021