U.S. DEPARTMENT OF ENERGY
Office of ENERGY EFFICIENCY & RENEWABLE ENERGY

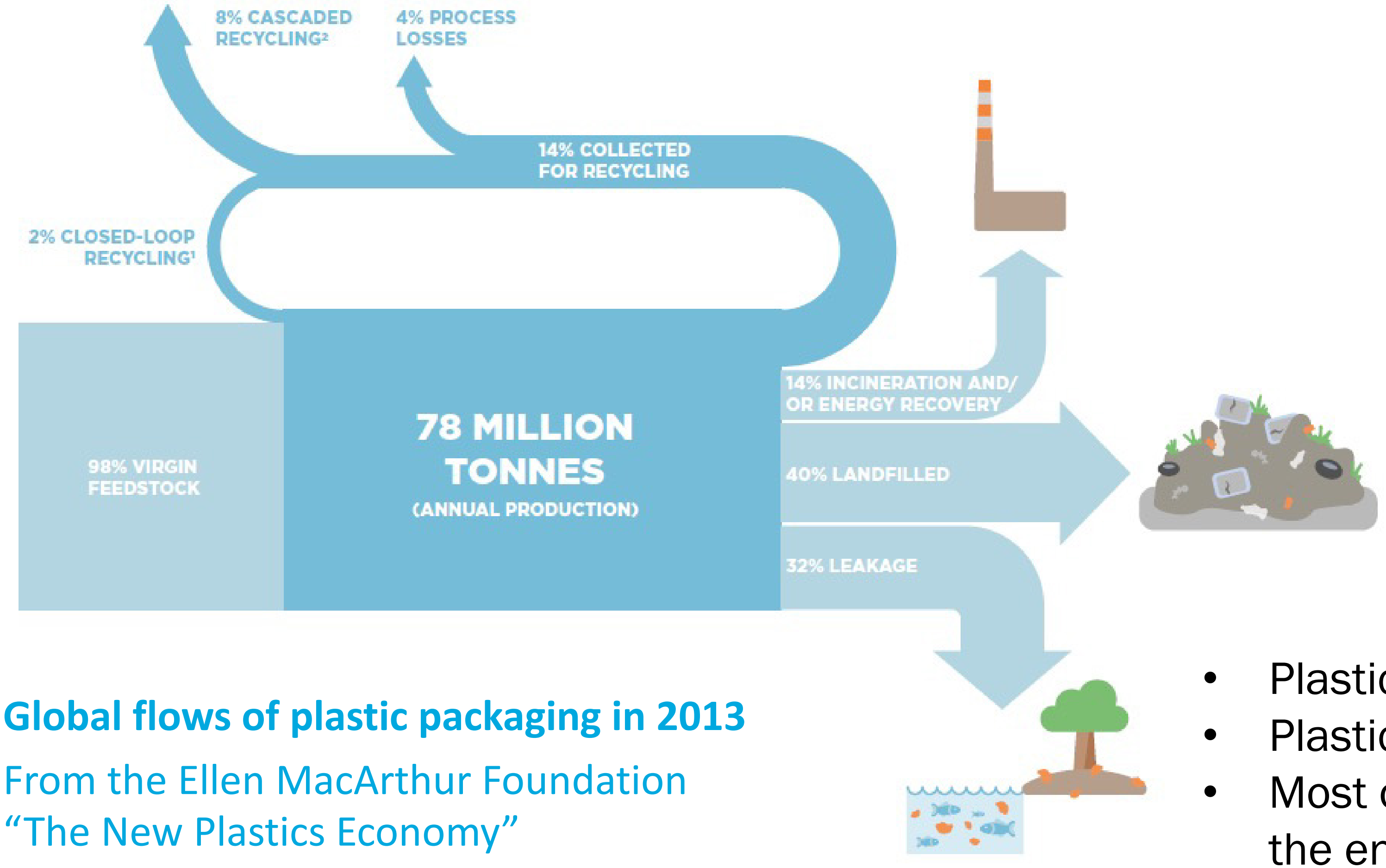
Plastics Special Topic

Gayle Bentley

BETO Peer Review

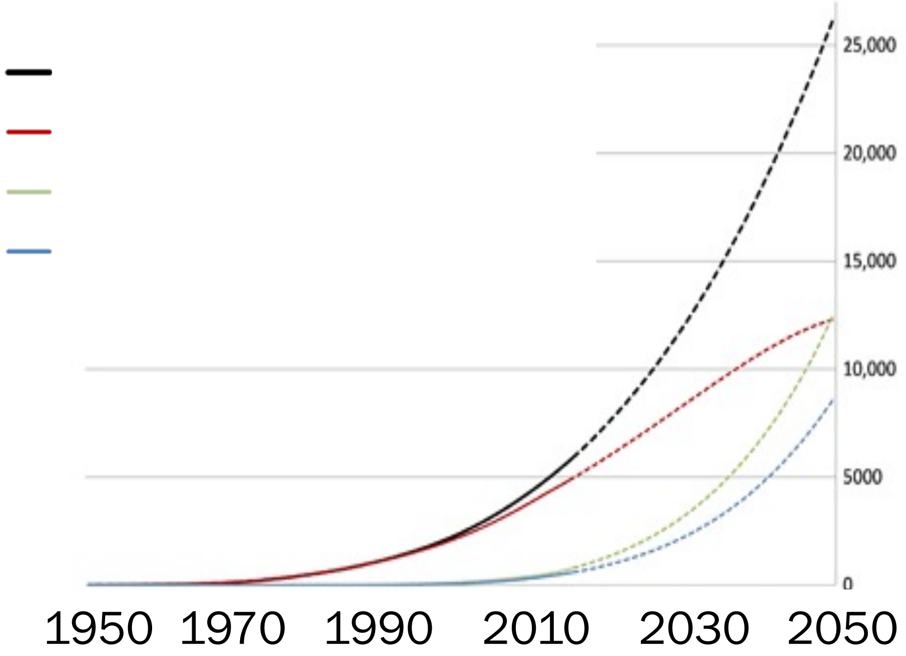
8 March 2021

The Challenge: A linear carbon economy for plastics



Global flows of plastic packaging in 2013

From the Ellen MacArthur Foundation
“The New Plastics Economy”

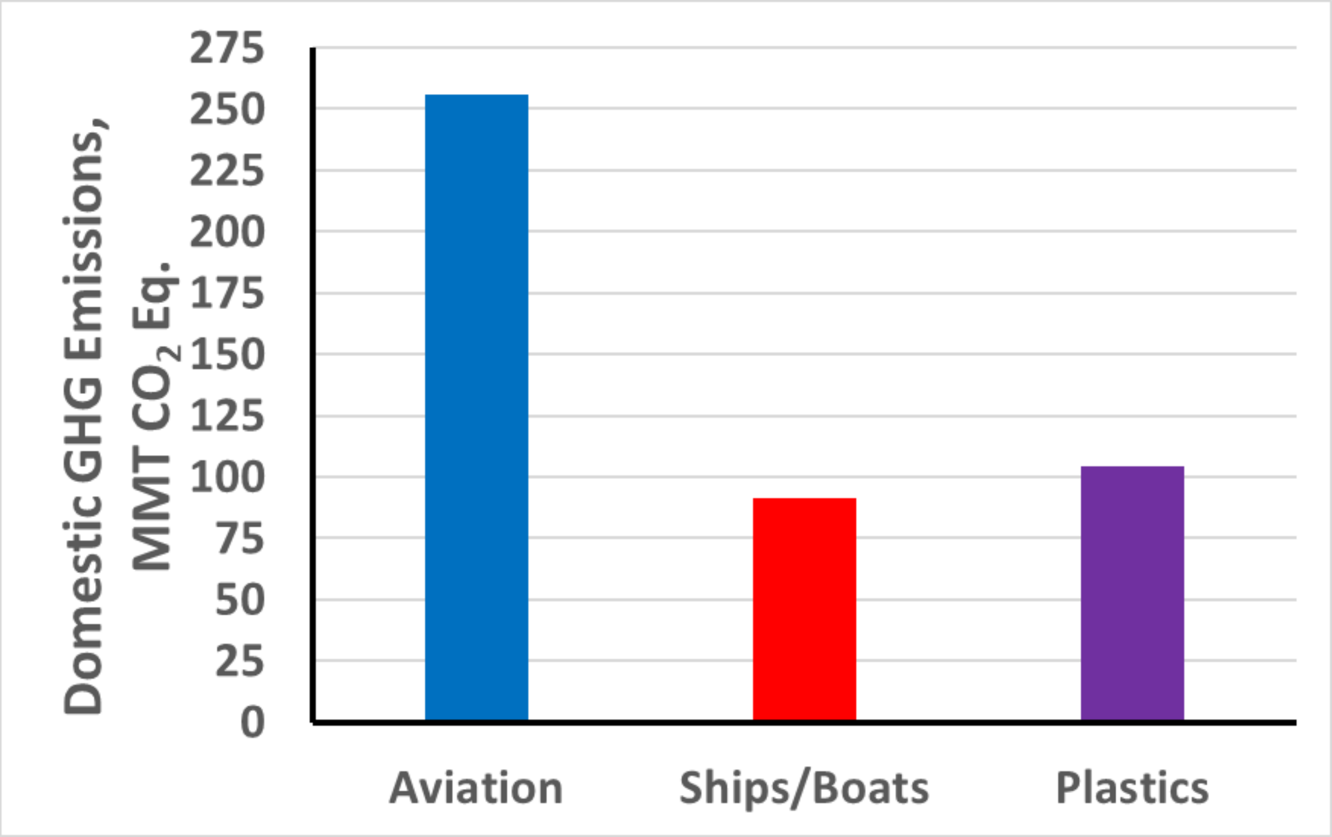


- Plastic is made from non-renewable feedstocks
- Plastic waste is increasingly accumulating[1]
- Most of that plastic waste ends up in landfills and the environment[2]
- Plastic production currently consumes 6% of global oil and is anticipated to increase to 20% of global oil by 2050[3]

[1]Geyer et al. Science Advances 2017
[2]Zheng and Suh. Nature Climate Change 2019
[3]Jambeck et al. Science 2015 and Ellen MacArthur Foundation

Reimagining Plastics Presents a Climate and Energy Opportunity

- Plastic lifecycle consumes 3% total energy US use[1]
- Plastic lifecycle accounts for nearly 3% domestic GHG emissions[1]
- Recycling plastic has large GHG impacts (>60% reductions)[2]



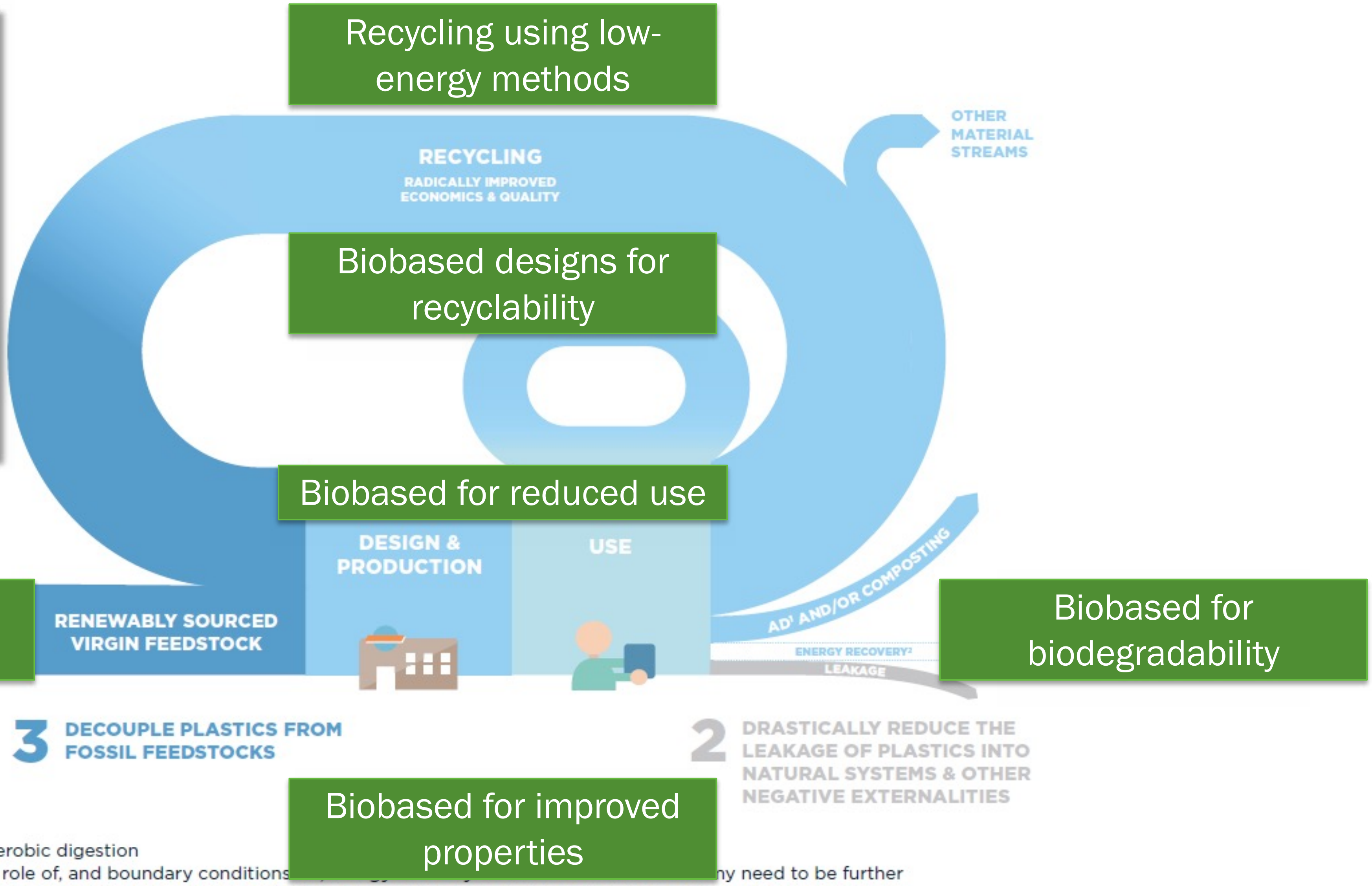
1. Nicholson *et al*. *Joule* 2021, 5, 1–14
2. Virgin vs Recycled Plastic LCA White Paper APR 2020

Aviation and marine from EPA "Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990-2018," presented data reflects 2018 emissions.
Plastics data from Nicholson *et al*, *Joule*, 2021. Data presented reflects 2019 emissions. EIA data reports between 187-256 MMT CO2 for aviation and 91 MMT for marine

The BETO Opportunity: A circular plastics economy

Why BETO?

- ✓ Long history valorizing recalcitrant material.
- ✓ Energy problem and opportunity
- ✓ Emissions problem and opportunity
- ✓ Opportunity to reduce dependence on fossil



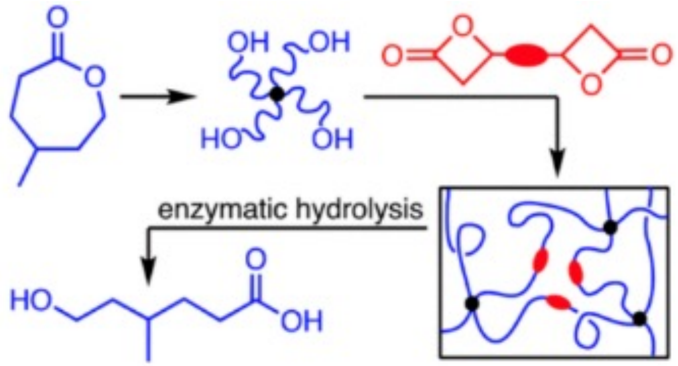
1 Anaerobic digestion
2 The role of, and boundary conditions ... ny need to be further investigated

Opportunities for BETO in Design and Deconstruction

Opportunity: Design

Goal: New biomass-derived plastics with:

- Superior properties
- Recyclability
- Lower GHG impact
- End-of-life considered at design



https://pubs.acs.org/doi/10.1021/jacs.7b10173

Opportunity: Deconstruction

Goal: New chemical and biological methods to break plastic down and upgrade it into new materials

- Reduce existing waste
- Provide economic incentive to recycle current plastic

Microb. Biotechnol. 2015, DOI: 10.1111/1751-7915.12312)

Environ. Sci. Technol. 2014, DOI: 10.1021/es504038a

R&D Highlight: BOTTLE National Lab-Led Consortium

BOTTLE **vision:** deliver selective and scalable technologies that enable cost-effective recycling, upcycling, and increased energy efficiency for plastics.

BOTTLE **mission**: develop robust processes to upcycle existing waste plastics, and new plastics and processes that are recyclable-by-design

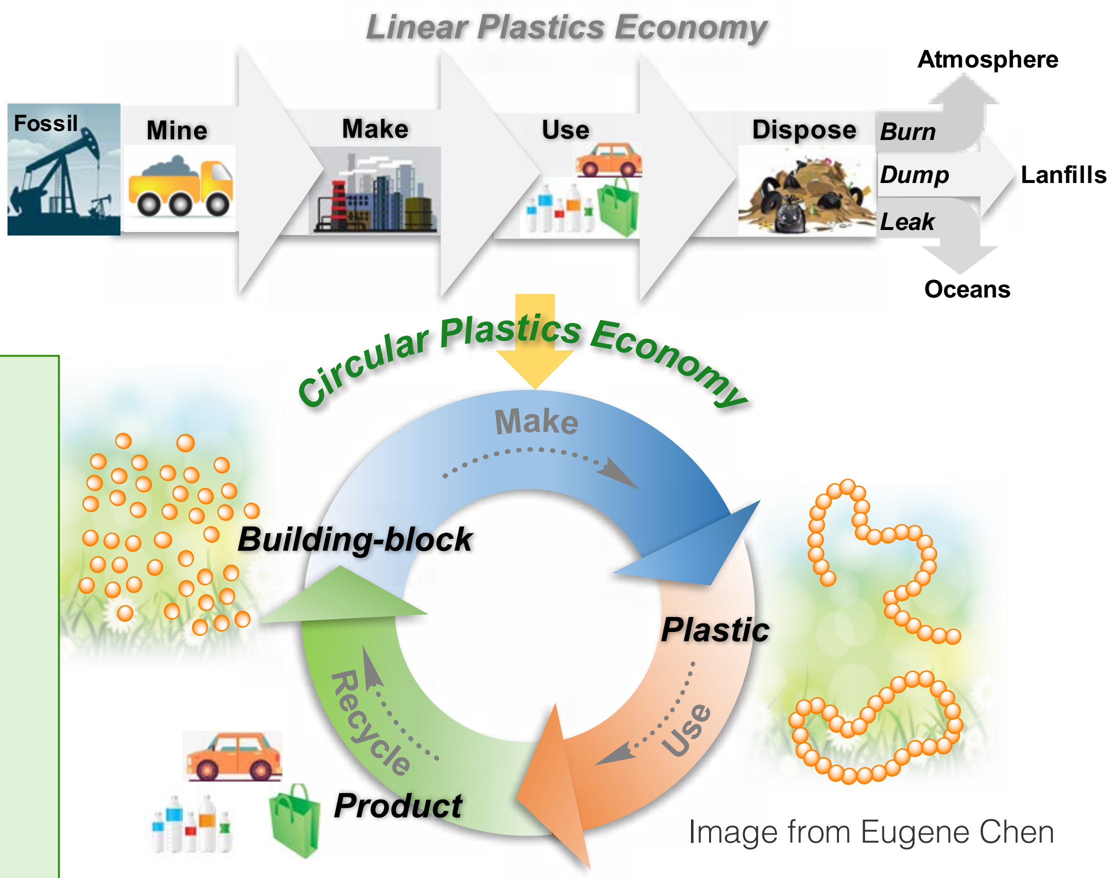


Image from Eugene Chen

METRICS

Energy:

- **≥50% energy savings** relative to virgin material production
- Recycling back to original material can save 40-90% supply chain energy

Carbon:

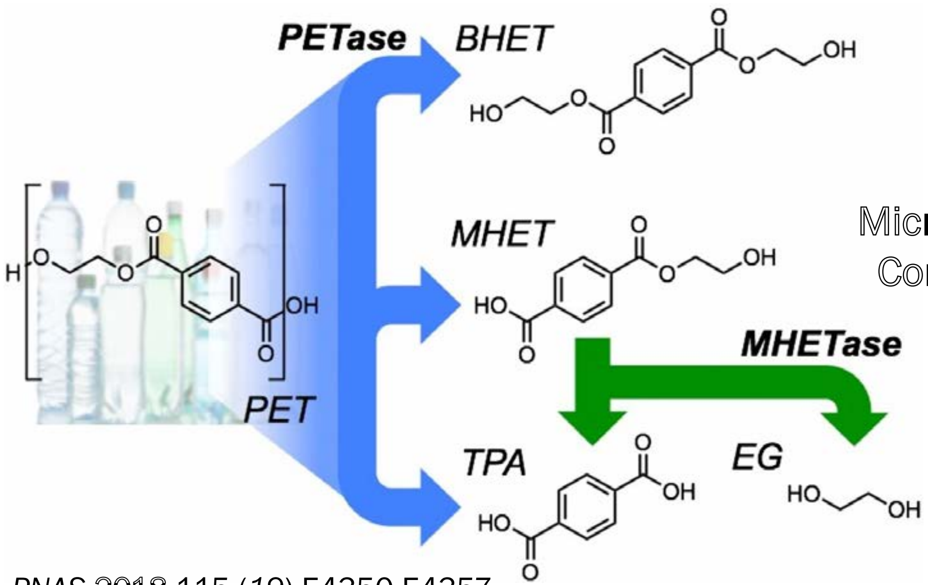
- **≥75% carbon utilization** from waste plastics
- Estimated based on proposed projects on commodity thermoplastics

Economics:

- **≥ 2x economic incentive** above price of reclaimed materials

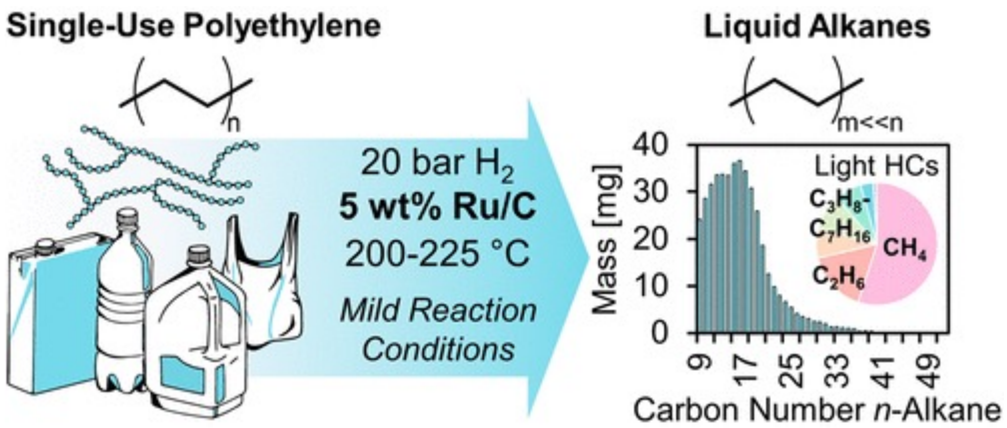
Northwestern University · SLAC National Accelerator Laboratory · NREL Transforming ENERGY · Bottle.org · Oak Ridge National Laboratory · Massachusetts Institute of Technology · Colorado State University · Argonne National Laboratory · Montana State University · Los Alamos National Laboratory Est. 1943 · University of Portsmouth

Early Successes Through BOTTLE



Microbial Recycling of Commodity Plastics

PNAS **2018** 115 (*19*) E4350-E4357

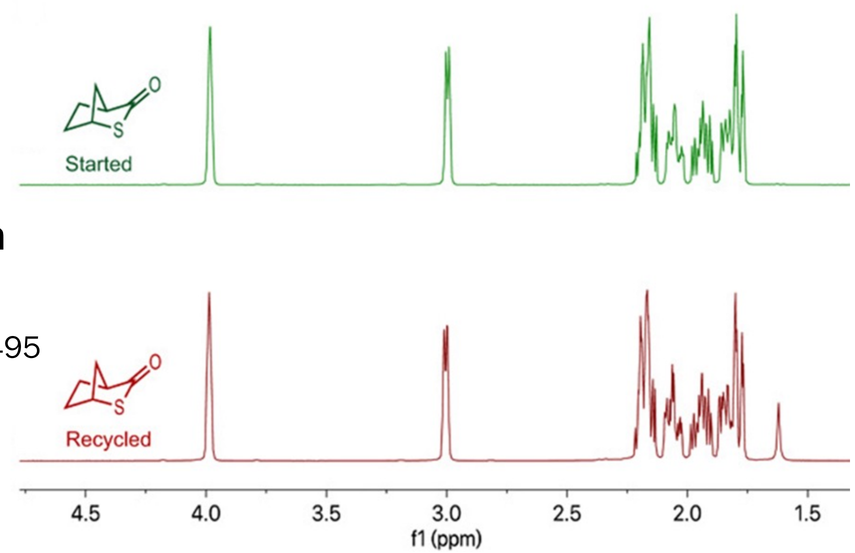


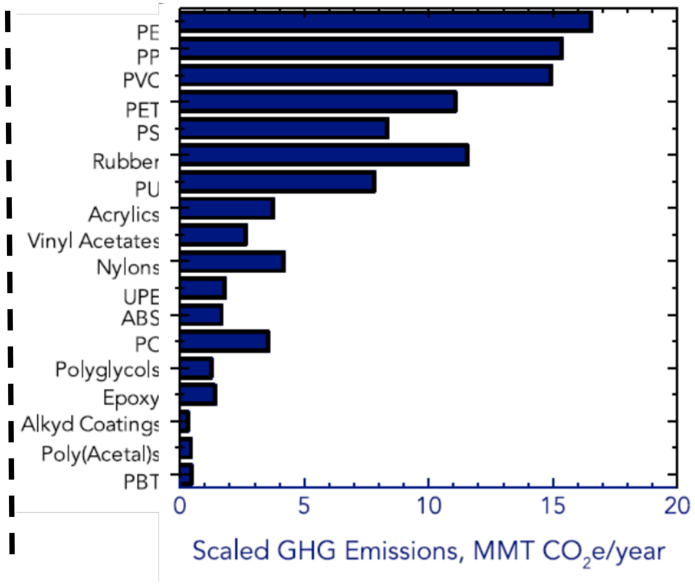
Upcycling Polyolefins to Light, Liquid Alkanes

JACS Au **2021** 1 (1) 8–12

High Performance, Recyclable by Design Polymers

Sci. Adv. **2020** 6 (34) eabc0495





Quantifying the Domestic GHG and Energy Impact of Plastics Production

Joule **2021** 5; 1–14

2020 BOTTLE FOA Topic Areas

Topic Area	Description
1a	Novel **Bio-Based** Plastics: Designing Highly Recyclable or Biodegradable **Bio-Based** Plastics
1b	Novel Plastics: Designing Highly Recyclable or Biodegradable Plastics
2	Novel Methods for Deconstructing and Upcycling Existing Plastic Waste
3	BOTTLE Consortium Collaborations to Tackle Challenges in Plastic Waste

Joint FOA sponsored by AMO and BETO

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy

FY20 BOTTLE Awards

	Topic	Organization	Title
BETO	1a	Iowa State University	Trojan Horse Repeat Sequences for Triggered Chemical Recycling of Polyesters for Films and Bottles
	1a	University of California: San Diego	Production of high-performance biodegradable polyurethane products made from algae precursors
	2	Battelle Memorial Institute	Hybrid Approach to Repurpose Plastics Using Novel Engineered Processes
	2	IBM Almaden Research Center	Upcycling PET via the VolCat process
	3	University of Wisconsin-Madison	Designing Recyclable Biomass Biomass-Based Polyesters
AMO	1b	University of California, San Diego	Degradable Biocomposite Thermoplastic Polyurethanes
	1b	The University of Akron	Highly Recyclable Thermosets for Lightweight Composites
	2	Iowa State University	Modular Catalytic Reactors for Single-Use Polyolefin Conversion to Lubricating Oils for Upcycled Plastics
	2	Case Western Reserve University	Hybrid Chemical-Mechanical Separation & Upcycling of Mixed Plastic Waste
	2	LanzaTech, Inc.	Upscaling of Non-Recyclable Plastic Waste into CarbonSmart™ Monomers
	3	University of Delaware	Circular Economy of Composites enabled by TUFF Technology
	3	University of Minnesota: Twin Cities	BOTTLE – Recyclable and Biodegradable Manufacturing and Processing of Plastics and Polymers based on Renewable Branched Caprolactones

$27.2M in selected projects

DOE investments are coordinated to develop solutions to plastic waste

Thermal Processes

SC · FE · EERE · ARPA-E

Technologies: Pyrolysis, gasification, energy recovery

Aspirational: High carbon efficiency, low energy thermal conversion of plastic waste to plastic oil or syngas

Chemical Processes

SC · EERE

Technologies: Chemical upcycling, depolymerization

Aspirational: Rou[…] high value products from plastic wast[…] majority of comm[…] polymers

[…] Recycling […]ecovery

[…] · EERE

[…]ies: […]sorting, […]izers, […]al recycling

[…]al: High […]rates, […]sorting and […]ling of […]ty plastics

Design for Circularity

SC · FE · EERE

Technologies: Materials redesign, polymer deconstruction

Aspirational: Highly recyclable plastics with cost and utility parity versus conventional materials

Funding Opportunity Announcements | Small Busin[…] Research […] | […] Laboratory Calls | Institute Project Calls

Future Directions in Plastics Design and Deconstruction at BETO

Questions moving forward:

- What can we make when we are no longer limited by the constraints of a petroleum starting material?
- How do we prioritize recyclability vs biodegradability vs less-use vs renewable?
- Can we design “bio-benign?” (recyclable, biodegradable, no microplastics, non-toxic sub-components)
- What is the best combination of chemical and biological treatment of plastics to maximize stream value?
- How tolerant to contaminants can these treatments be?
- How do we design a system to handle extremely heterogeneous streams?

Future Directions:

- Coordinated work across DOE and other agencies
- BOTTLE Consortium
- Plastics design will continue to be a priority for BETO
- Rethink plastics as feedstocks

Synergy with Biden-Harris Administration Goals

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Appendix

Why are biobased approaches good for a circular carbon economy?

- **Biobased feedstocks are renewable, and when collected properly, are sustainable**
- **Biobased capitalizes on the highly functionalized nature of biomass to access products that would be too expensive to make from petroleum**
- **Biobased can play a role in recyclability: designs for modern recyclables include highly functionalized monomers (e.g. vitrimers)**
- **Biobased can be amenable to anaerobic digestion or composting (e.g. polylactic acid (PLA))**
- **Biobased approaches to plastics degradation can be used for breaking down intractable mixtures**

Biobased waste feedstocks

Biobased for reduced use

Biobased for improved properties

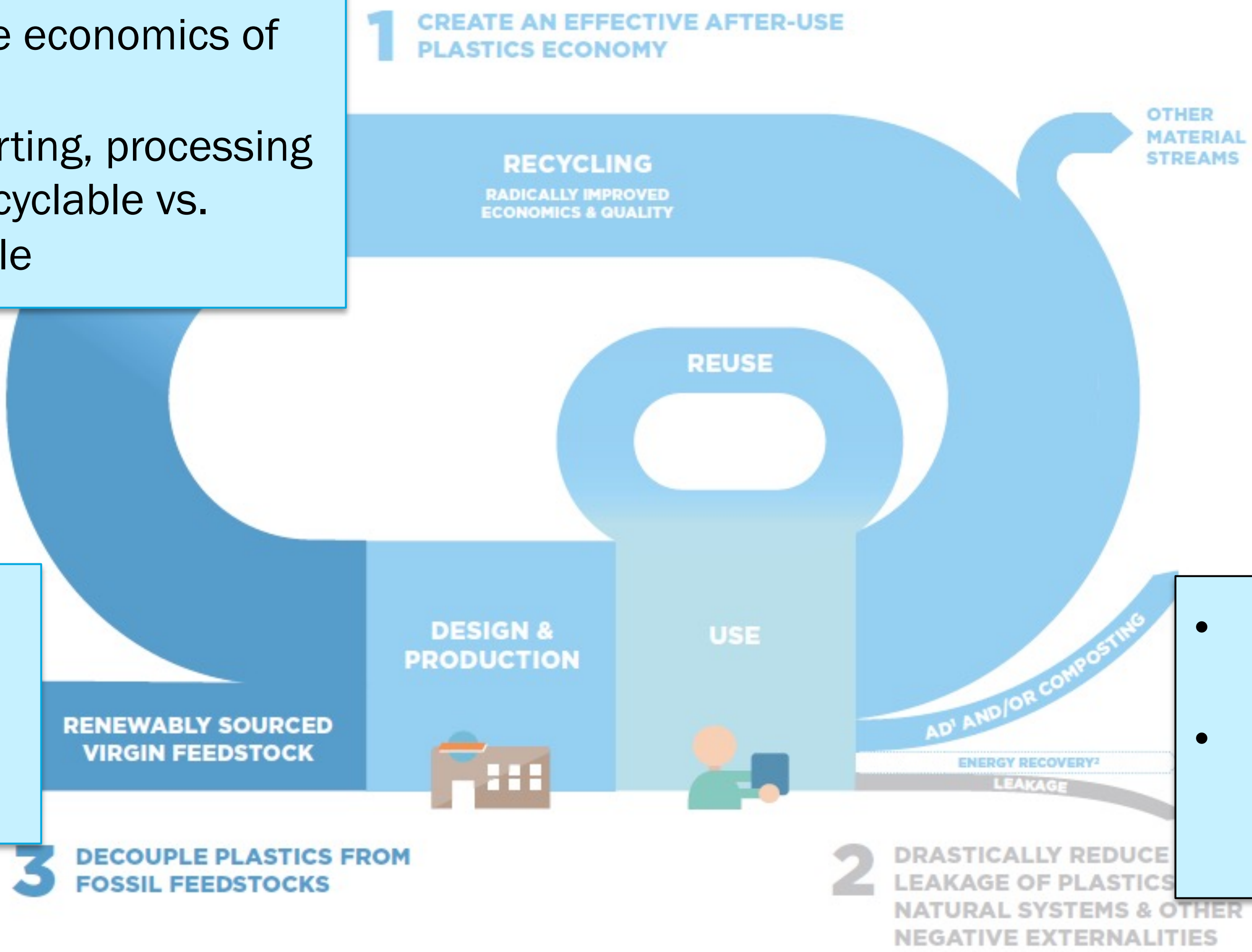
Biobased for recyclability

Biobased for biodegradability

Recycling using low-energy methods

The Solution: A circular carbon economy for plastics

- Improve the economics of recycling
- Improve sorting, processing
- Balance recyclable vs. compostable



- Use GHGs as feedstocks (CO_2 and CH_4)
- Use biomass

- Improve the value of recycling
- Create "bio-benign" plastics; biodegradable, no microplastics, non-toxic

1 Anaerobic digestion
2 The role of, and boundary conditions for, energy recovery in the New Plastics Economy need to be further investigated

Deconstruction Opportunities

Challenge: Mixed Streams

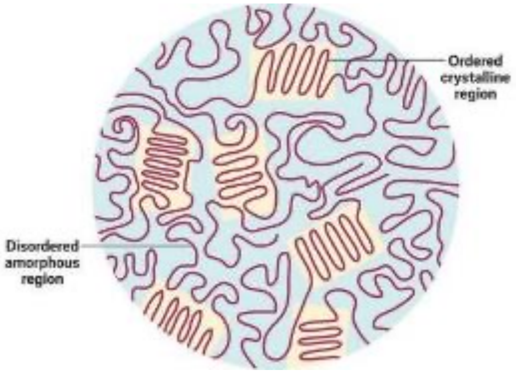
BETO competency: heterogeneous biomass valorization

The Guardian. April 16 2018

- Dirty streams contain catalyst poisons and complex substrate mixtures

Challenge: Crystallinity

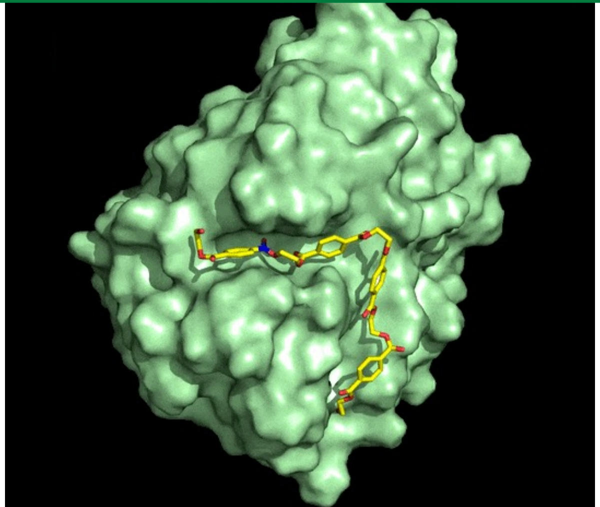
BETO competency: lessons from cellulose



- Enzymes and catalysts can have difficulty accessing highly ordered crystalline polymers leading to slow and incomplete breakdown

Challenge: C-C Breakdown rate/completeness

BETO competency: enzyme, catalyst, and organism engineering



Credit: John McGeehan/University of Portsmouth

- Selective C-C bond breaking chemistry is difficult
- Current enzymes are too slow to be economically competitive
- Plastics are "new," evolutionarily speaking, so enzymes and organisms have not had incentive to evolve

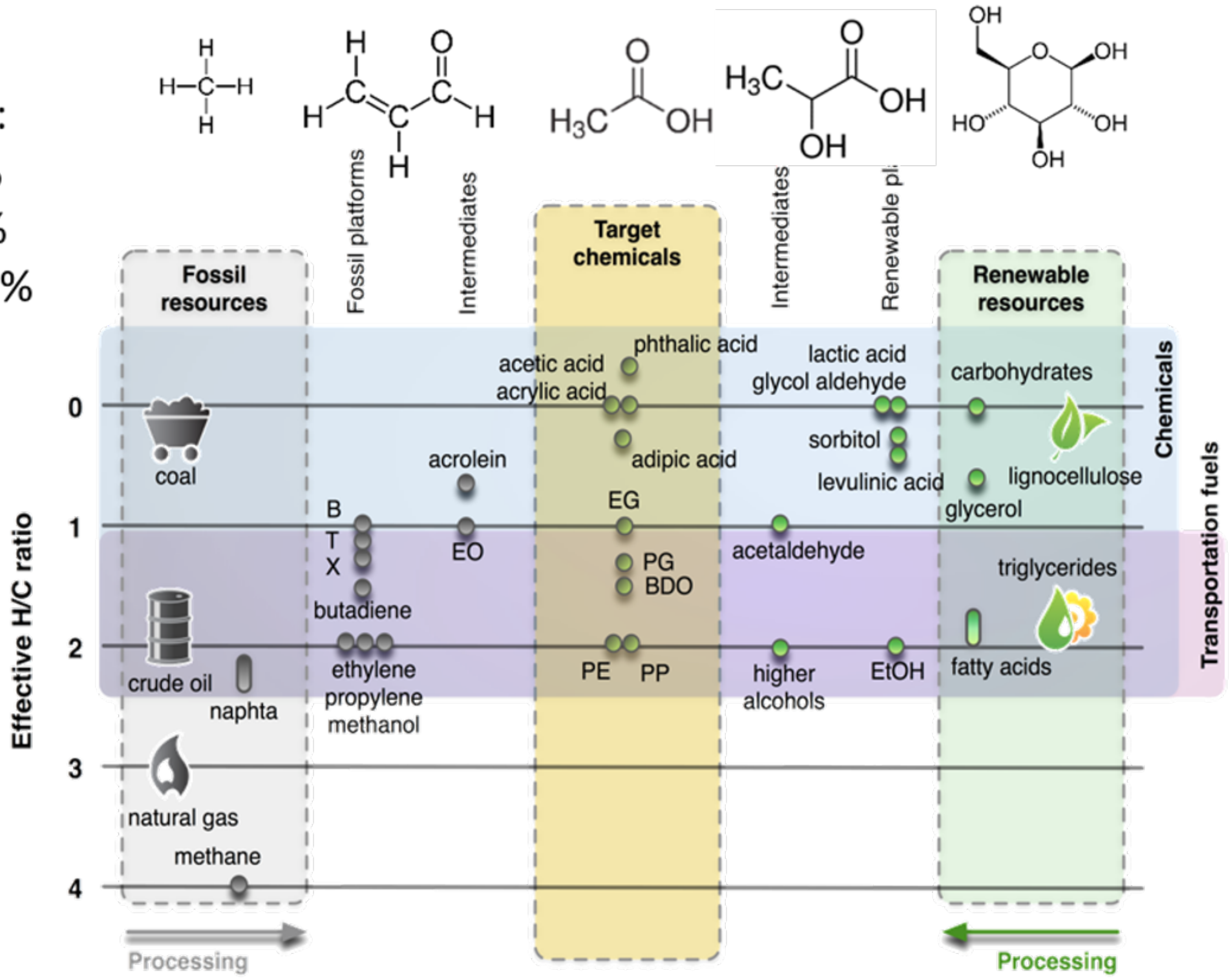
Environ. Sci. Technol. 2014, DOI: 10.1021/es504038a

https://cen.acs.org/environment/sustainability/Plastics-recycling-microbes-worms-further/96/i25

Biomass provides functionalized chemistry to support new material design

Crude oil

Avg. wt%:
C 83-87%
H 10-14%
O 0.1-1.5%



Biomass

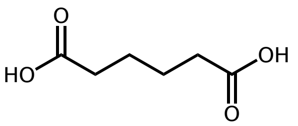
Avg. wt%:
C 36-53%,
H 5-7%,
O 31-48%

Consider the oxidation state of chemicals – retain what nature provides

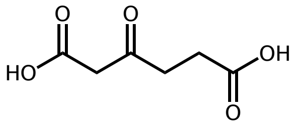
Vennestrøm, P.N. R. *et al Angew. Chem. Int. Ed.* **2011**, *50*, 10502-10509
Shen, J. *et al Energy Conversion and Management* **2010**, *51*, 983–987

Design Opportunity: performance advantaged bioproducts and recyclable-by-design PE

ß-ketoadipic acid as a substitute for adipic acid improves properties of nylon



Adipic Acid

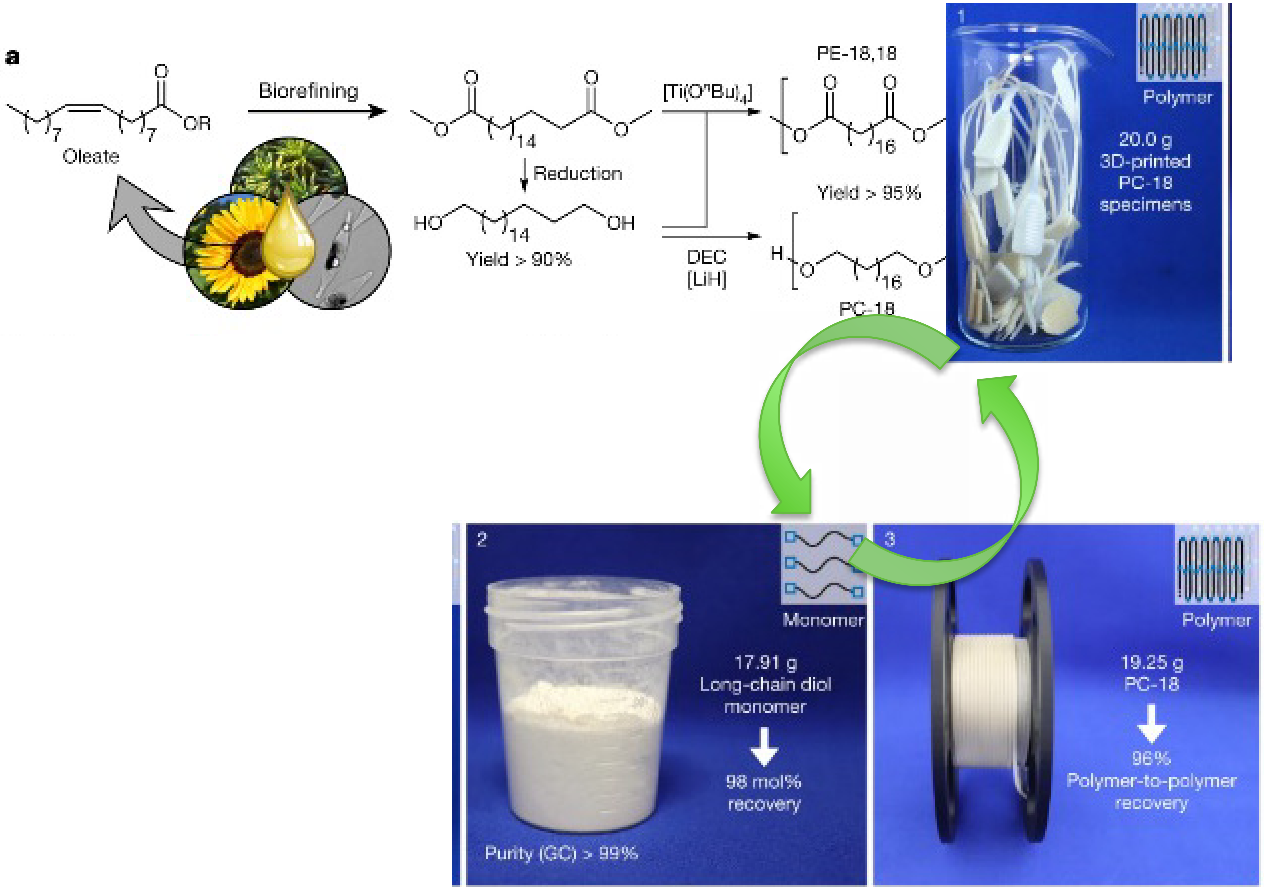


β-ketoadipic Acid

Starting Diacid/Diester	*Glass Transition Temperature*	*Melting Temperature*	*Water Permeability* g*mm/m²*day
Beta-keto Adipate	130	400*	8.0
Adipic Acid	60	260	10.1

Replacing adipic acid with ß-ketoadipic acid (derivable from sugars or aromatics) increases thermal properties, molecular weights, and lowers water permeability

Johnson et. al. Joule 2019



Bio-based polyethylene (PE) can be designed for efficient chemical recycling

M Häußler, et al. 2021. Nature

Beckham et al.

DOE investments are coordinated to develop solutions to plastic waste

Opportunity Type	Office	Name and FY	TRL	Topic
Funding Opportunity Announcements	BES	FY2020: Energy Frontier Research Centers (EFRCs)	1-2	Center for Plastics Innovation; Institute for Cooperative Upcycling of Plastics
	BES	FY2021: Chemical Upcycling of Polymers	1-2	Chemical Upcycling
	BER	FY2021: Systems Biology of Bioenergy-Relevant Microbes To Enable Production of Next-Generation Biofuels And Bioproducts	1-2	Subtopic: biological plastic upcycling organism design
	BETO/AMO	FY2020: Bio-Optimized Technologies to Keep Thermoplastics out of Landfills and the Environment (BOTTLE) FOA	2-4	Polymer redesign for recyclability and biodegradability; Chemical, biological, thermal and mechanical deconstruction and upcycling
	ARPA-E	FY2020: Recycle Underutilized Solids to Energy (REUSE)	2-4	Convert unrecyclable plastic and paper into liquid intermediates upgradable into fuels or chemicals
	BETO	FY2020: Bioenergy Technologies Office FY2020 Multi-Topic FOA	2-4	Subtopic: Technologies to transform urban and suburban wastes including plastic into products
	FE	FY20 Gasification FOA	3-5	Gasification of mixed carbonaceous materials
	FE	FY21 FE H2 FOA		Subtopic: Gasification
Small Business Innovation Research Solicitations (SBIR)	BETO/AMO	FY2020: Phase 1 Novel Utilization Strategies for Ocean Plastic Waste	2-4	Utilization of ocean plastic waste
	EERE	FY2021: Phase 1 compatibilizers of existing plastics	2-4	Novel compatibilizer strategies to enable more efficient recycling of mixed plastics
	EERE	FY2020: Phase 2 Reshaping Plastic Design and Degradation for the Bioeconomy	2-4	Novel methods for plastic redesign and upcycling
National Laboratory Calls	EERE	FY2020-FY2021: BOTTLE Consortium	2-4	Recyclable-by-design polymers; chemical and biological deconstruction and upcycling; techno-economic and life cycle analysis
Institute Project Calls	EERE	FY2021: Reducing EMbodied-energy And Decreasing Emissions (REMADE), a Manufacturing USA Institute Project Call	3-7	Enable U.S. manufacturers to increase the recovery, recycling, reuse, and remanufacturing of plastics, metals, electronic waste, and fibers.

Deconstruction Opportunity: mixed plastics

Materials: C-C Plastics

Materials: Polyesters

- PET
- Blends

Materials: Textiles & Foam

- Nylons, lactams, polyamides, polyurethanes

Challenges:

- Selective C-C chemistry
- Crystallinity
- Contamination
- Breakdown rate

Challenges:

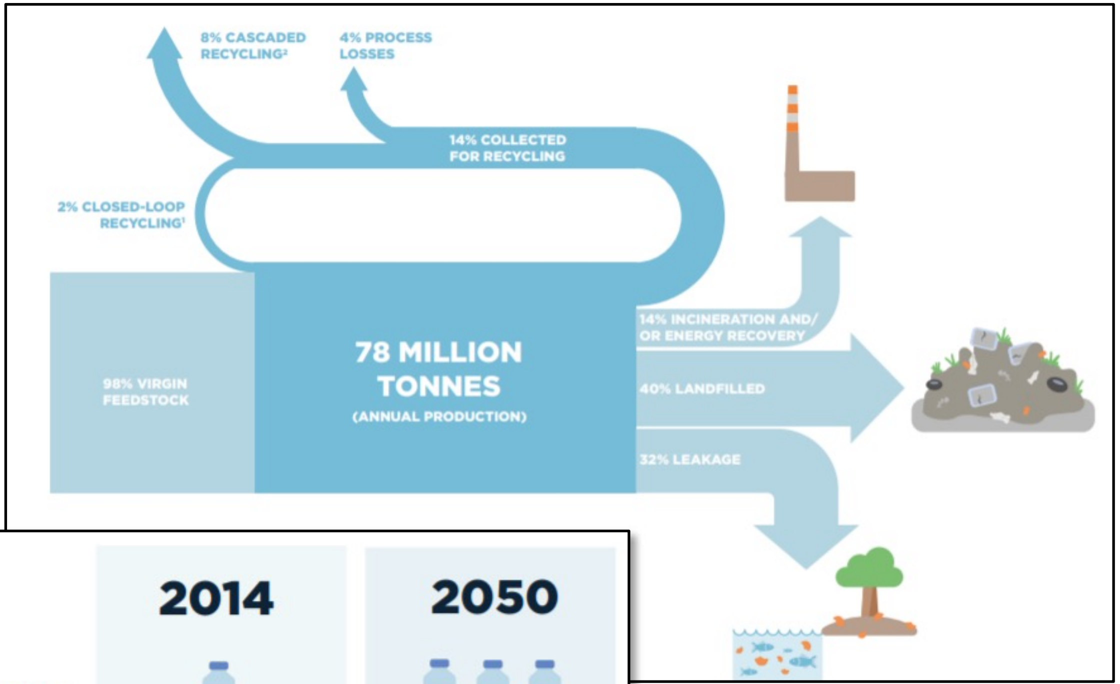
- Selective C-O chemistry
- Contamination/ mixed streams
- Breakdown rate/ extent
- Crystallinity

Challenges:

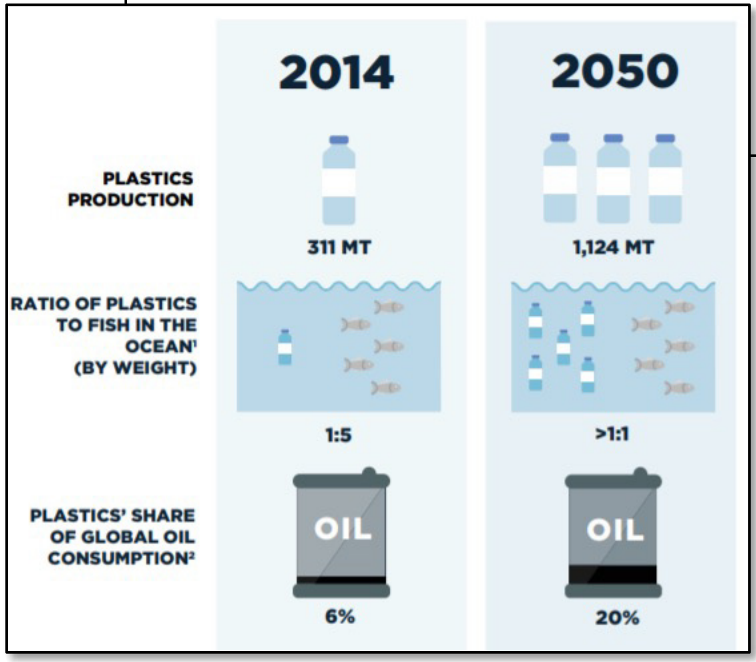
- Selective C-O, C-N chemistry
- Contamination/ mixed streams
- Breakdown rate/ extent

Plastic Waste is an Energy and Environmental Problem

- Plastic is made from non-renewable feedstocks, and is rarely recovered
- Plastic waste is increasingly accumulating[1]
- Most of that plastic waste ends up in landfills and the environment[2]
- Plastic production currently consumes 6% of global oil and is anticipated to increase to 20% of global oil by 2050[3]



Cumulative Global Plastic Waste



[1]Geyer et al. Science Advances 2017
[2]Zheng and Suh. Nature Climate Change 2019
[3]Jambeck et al. Science 2015; Ellen MacArthur Foundation

Improving our approach to plastic is critical to Biden Priorities

Climate

- Plastics contribute ~3% of global GHG emissions[1]
  - Improving the footprint of plastics is essential to decarbonize the industrial sector
- Recycling and making renewable plastics can reduce GHG emissions significantly[2]

Economy

- 95% of plastic waste is discarded, and the value of the material is lost[3]
- The ban of plastic imports to China and other SE Asian countries provides an opportunity for domestic processing and up to 1.6 million jobs[4]

Environmental Justice

- Plastic-related GHG →climate change[1]
- The US generates the most plastic waste of any country, and is one of the biggest coastal polluters[5]
- Net plastic exports go to poor countries[6]
- Irreversible environmental damage from plastic waste in the ocean is estimated to cost $2.5 trillion a year[7]

Solutions

- Recycling plastics saves >50% of GHG emissions.[8]
- Making recyclable-by-design or biodegradable plastics from renewables saves GHG and energy from production to end of life[1]
- These new industries require domestic labor, providing new jobs

1. Zheng and Suh. 2019. Nature Climate Change
2. Rorrer et al. 2019. *Joule*
3. *The New Plastics Economy*, **2016.** World Economic Forum
4. *More Jobs, Less Pollution*, **2011.** Tellus Research Institute
5 Lavendar Law et al. 2020. Science Advances
6. UN Comtrade Program
7. Beaumont et al. 2019. Marine Pollution Bulletin