Evaluating the Circular Economy

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University of Washington
Clean Energy Institute Seminar
March 2, 2023

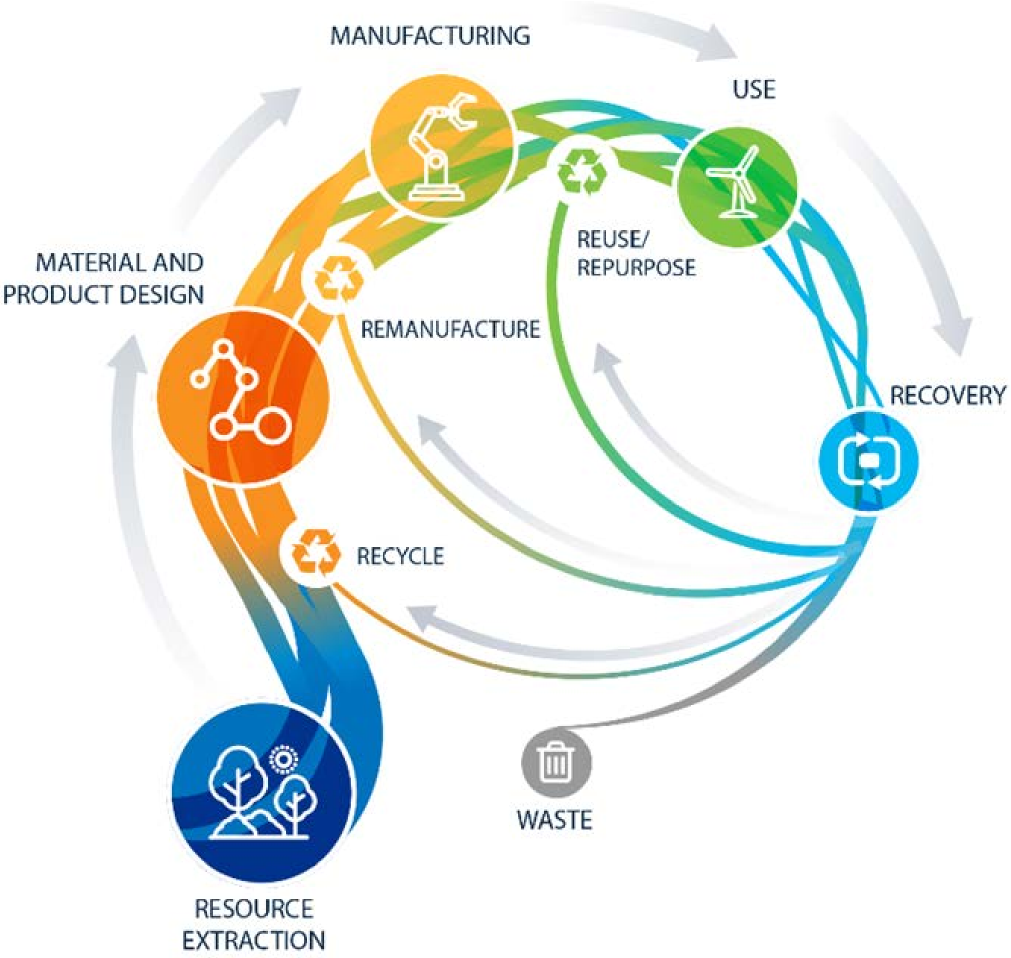

Illustration by Joelynn Schroeder, NREL

Outline

- What is the circular economy?
- How do we implement it?
- Why do we care? What are the benefits?
- What are the challenges and research questions?
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WHAT - In it’s simplest and most ideal form

CE definitions

An industrial system that is **restorative or regenerative** by intention and design, replacing the end-of-life (EOL) concept with restoration, shifting to renewable energy, and eliminating toxic chemicals, which impair reuse. It aims to **eliminate waste** through the superior design of materials, products, systems, and related business models.
Kirchherr, Reike, and Hekkert (2017)

DRAFT ISO Standard: economic system that uses a systemic approach to maintain a **circular flow of resources**, by **regenerating, retaining or adding to their value**, while contributing to **sustainable** development

NREL definitions

NREL Strategy: Holistic approach to energy technologies that not only examines the near-term benefits of producing energy through renewable resources, but it also considers the **sustainability of the infrastructure** required for energy production with an emphasis on **responsible and effective use of natural resources (e.g., materials, land, water**).

Analysis perspective: Enable a clean energy transition by ensuring **resource sustainability** for a **decarbonized** and **resilient** U.S. energy economy. Developing clean energy technologies to be reliable, durable, and **equitable in their impacts** is critical.

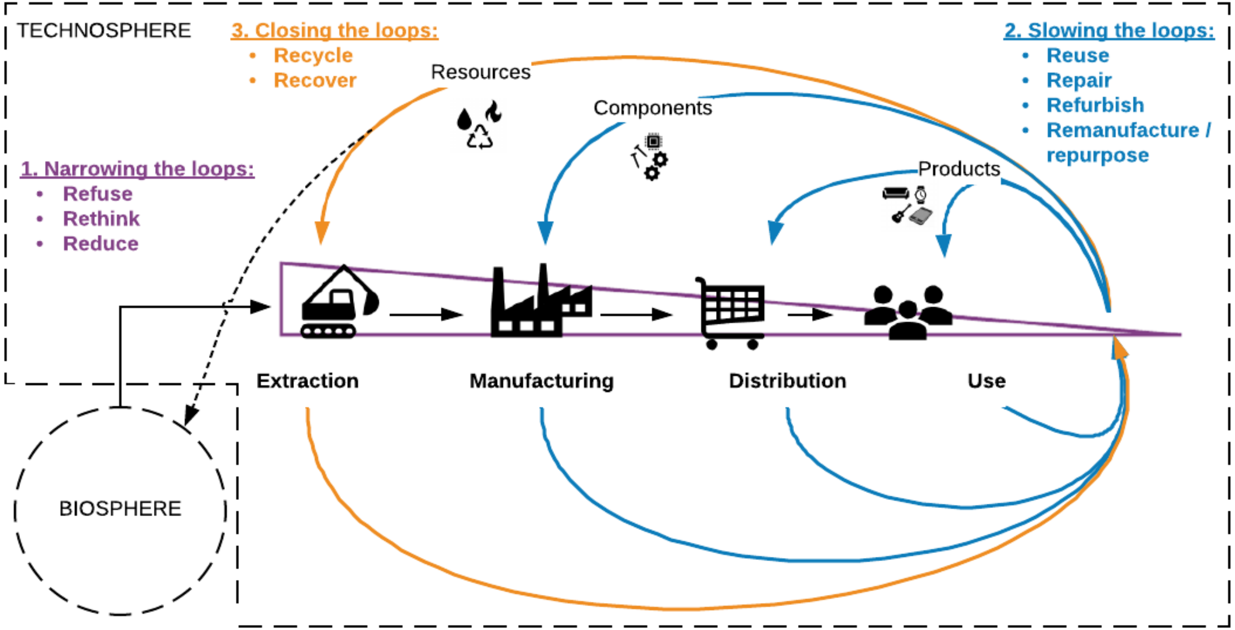
Background

- Goal of CE
  - Keeping products, components and materials at their highest utility and value, at all times
  - Eliminating the concept of waste, with materials ultimately re-entering the economy at end of use in a valuable form
  - Contributing to sustainability
- Builds on some different schools of thought
  - Cradle to Cradle
  - Biomimicry
  - Performance Economy
  - Natural Capitalism
  - Industrial Ecology

Background

- **Problem:** In the next decades demand for raw materials is expected to increase
  - 100 billion metric tonnes of materials consumed each year, 177 billion by 2050 (Circle Economy, 2021)
  - Increases the risk posed by sudden supply restrictions (*Schrijvers et al., 2020*)
  - Contributes to global GHG emissions due to their embodied energy (*Circle Economy, 2021*): cradle-to-gate materials are responsible of 18% of global GHG emissions (*Hertwich, 2019*)

- **Can the circular economy (CE) help to mitigate some of the problems?** The circular economy (CE) spurs material efficiency e.g., through reusing/recycling products and transforms waste to wealth by:
  - Narrowing flows (use less): refuse, rethink, reduce
  - Slowing flows (use longer): reuse, repair, refurbish, remanufacture /repurpose
  - Cycling flows (use again): recycle, recover



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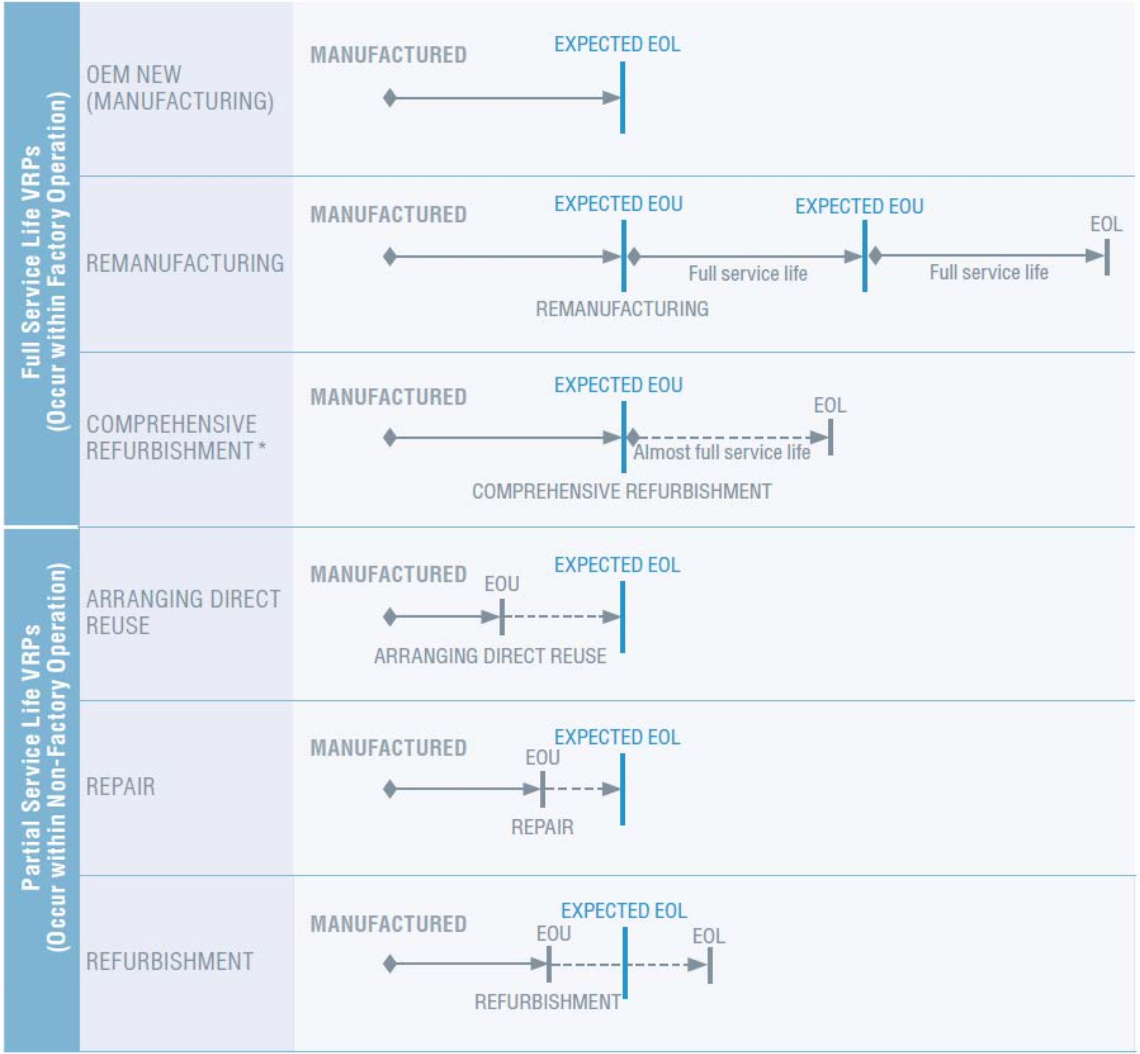
Circular Economy Strategies (Rx)

Circular Economy ↑ Increasing Circularity — Linear Economy

	Strategy	Description
Smarter product use and manufacture	**R0** - Refuse	Making products redundant by abandoning its function or by offering the same function with a radically different product
	R1 - Rethink	Make product use more intensive
	R2 - Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of products and its parts	**R3** - Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfills its original function
	R4 - Repair	Repair and maintenance of defective product so it can be used for its original function
	R5 - Refurbish	Restore an old product and bring it up to date
	R6 - Remanufacture	Use parts of discarded products in a new product with the same function
	R7 - Repurpose	Use discarded products or its parts in a new product with a different function
Useful application of materials	**R8** - Recycle	Process materials to a commodity level with same or lower quality
	R9 - Recover	Incineration of materials with energy recovery

Reproduced based on *J. Potting, M. P. Hekkert, E. Worrell, A. Hanemaaijer, Circular economy: measuring innovation in the product chain (PBL Publishers, 2017), vol. No. 2544.*

Value is retained through increased usage and longevity



IRP (2018). Re-defining Value – The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy. Nabil Nasr, Jennifer Russell, Stefan Bringezu, Stefanie Hellweg, Brian Hilton, Cory Kreiss, and Nadia von Gries. A Report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya.

ReSOLVE Framework

THE RESOLVE FRAMEWORK

	Examples
REGENERATE	• Shift to renewable energy and materials • Reclaim, retain, and restore health of ecosystems • Return recovered biological resources to the biosphere
SHARE	• Share assets (e.g. cars, rooms, appliances) • Reuse/secondhand • Prolong life through maintenance, design for durability, upgradability, etc.
OPTIMISE	• Increase performance/efficiency of product • Remove waste in production and supply chain • Leverage big data, automation, remote sensing and steering
LOOP	• Remanufacture products or components • Recycle materials • Digest anaerobic • Extract biochemicals from organic waste
VIRTUALISE	• Dematerialise directly, e.g., books, CDs, DVDs, travel • Dematerialise indirectly, e.g., online shopping, autonomous vehicles
EXPLORE	• Replace old with advanced non-renewable materials • Apply new technologies (e.g. 3D printing) • Choose new product/service (e.g. multimodal transport)

EMF, Sun and McKinsey, 2015. Exhibit 10 from "Growth within: A circular economy vision for a competitive Europe", June 2015, McKinsey & Company, www.mckinsey.com.

We need to apply out of the box thinking…..

……………………..

but remember that the solution might need an out of the box ecosystem to be successful

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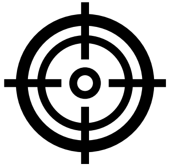
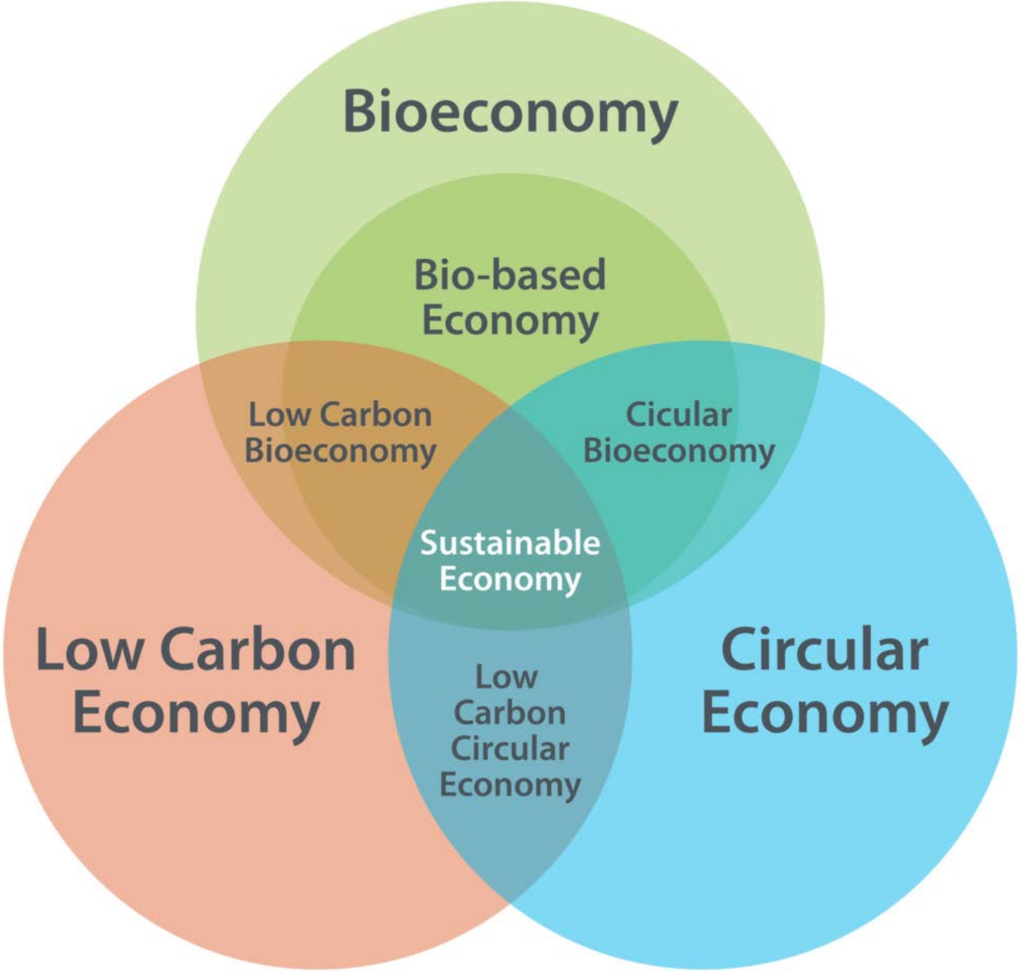
Why CE?

Is circularity the goal? 

Or a tool? 

DRAFT ISO Standard: economic system that uses a systemic approach to maintain a **circular flow of resources**, by **regenerating, retaining or adding to their value**, while contributing to **sustainable** development



adapted from Kardung and Wesseler 2019

The Seven Pillars of the Circular Economy

- Materials are cycled at continuous high **value**
- All **energy** is based on renewable sources.
- **Biodiversity** is supported and enhanced through human activity.
- Human **society and culture are preserved**.
- The **health and wellbeing** of humans and other species are structurally supported
- Human activities maximize generation of societal value
- **Water resources** are extracted and cycled sustainably.

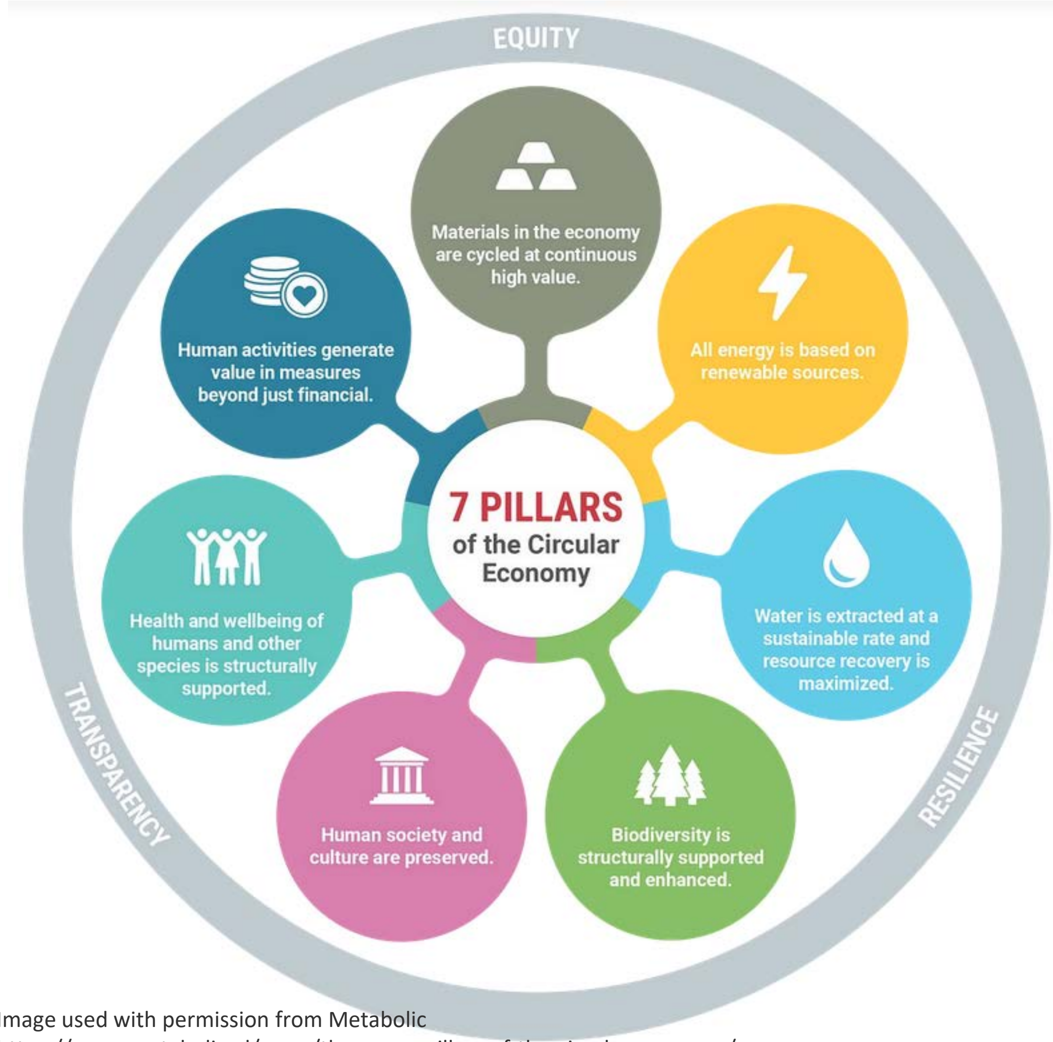


Image used with permission from Metabolic
https://www.metabolic.nl/news/the-seven-pillars-of-the-circular-economy/

CE & UN Sustainable Development Goals (SDGs)

- CE could directly contribute to SDGs around water, energy, economic growth, responsible consumption & production, and life on land respectively
- CE could also support other SDGs (no poverty, zero hunger, sustainable cities & communities, and life below water)
- Some SDGs can also contribute to CE

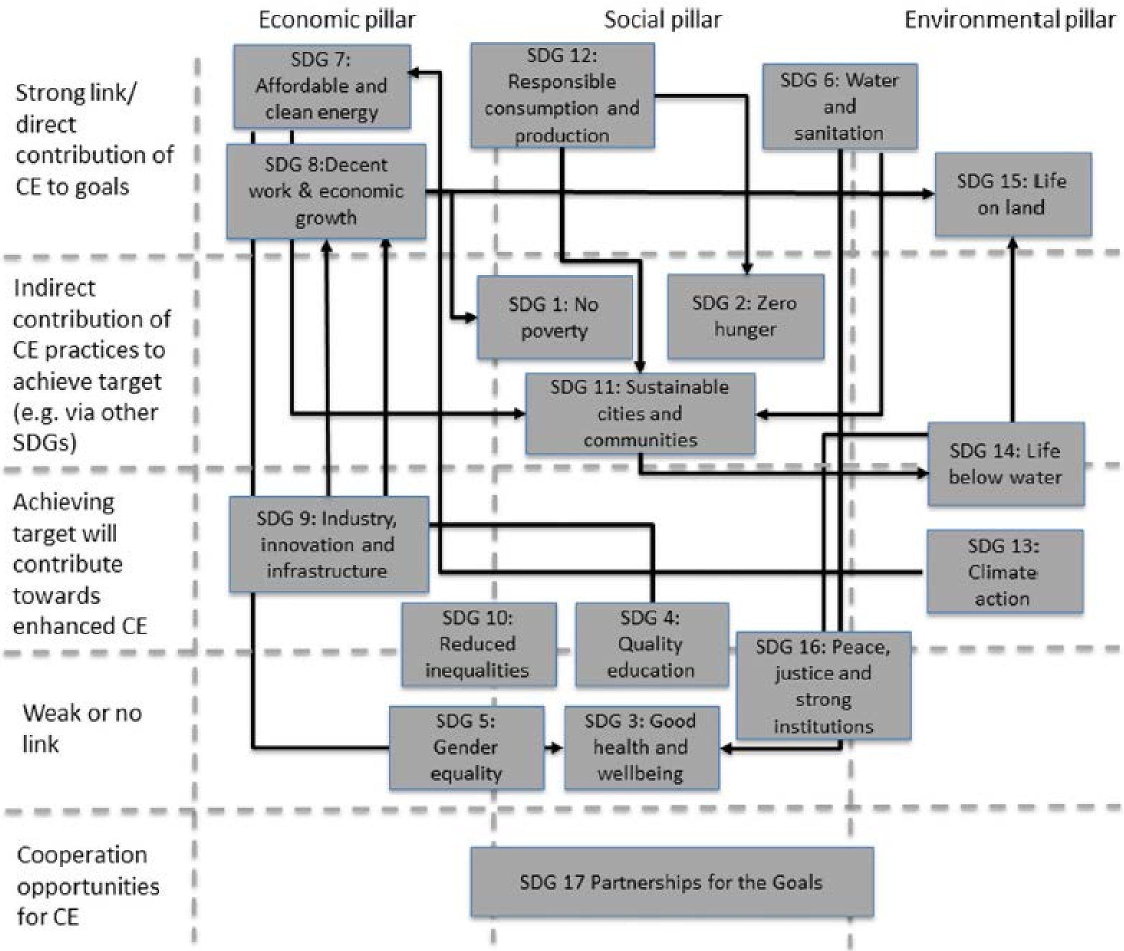
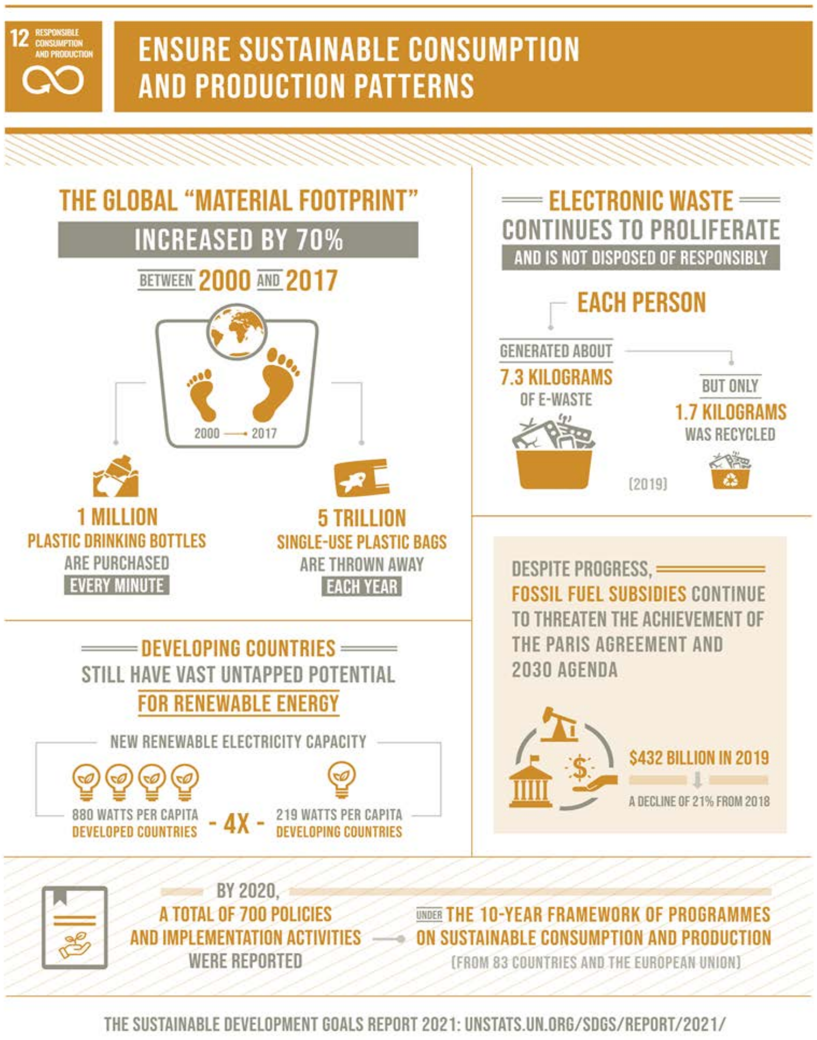


Image source: *Schroeder, P., Anggraeni, K., & Weber, U. (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology, 23(1), 77-95. doi:https://doi.org/10.1111/jiec.12732*

UN SDG #12

- UN Sustainable Development Goal #12 – Ensure sustainable consumption and production patterns. Example of contributions to SDG 12:
  - 12.2 achieve sustainable management and efficient use of natural resources
  - 12.3 halve per capita global food waste
  - 12.5: reduce waste generation through prevention, reduction, recycling and reuse



Why do we care?

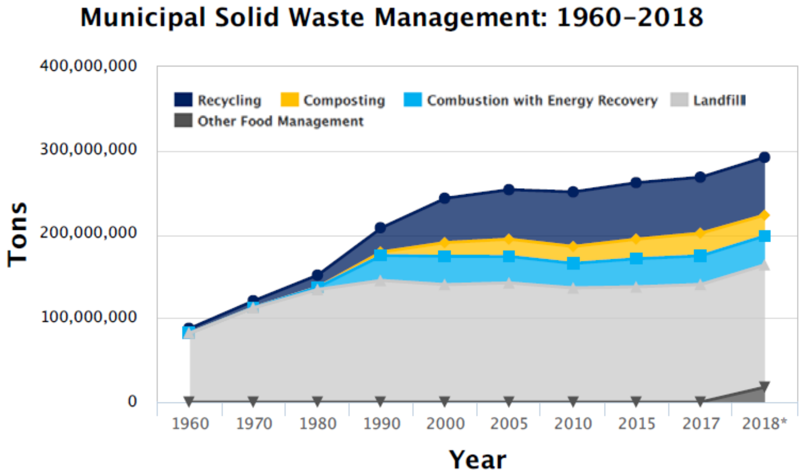
- From Department of Energy perspective, CE provides strategic opportunity to:
  - Support robust and secure supply chains
  - **Enhance domestic manufacturing** and industry
  - Maximize product and material value
  - Support the **growth of the material recovery industry**
  - Lead in the development and commercialization of end-of-life processing technologies
  - Minimize **life cycle impacts of U.S. manufacturing products.**

Why do/should society and communities care?

Short term: better value for our products, better control of materials at end of life (less littering of lands and oceans), and jobs that facilitate that.

Long term: contributing to sustainable development where we are **meeting the needs of the present without compromising the well-being of future generations** (UN General Assembly 1987) and creating and maintaining conditions under which **humans and nature can exist in productive harmony**, and **fulfilling the social, economic and other requirements of present and future generations**" (NEPA 1969).

How are we doing?



U.S. Recycling, Composting, Combustion with Energy Recovery and Landfilling of Materials in Municipal Solid Waste (MSW) in million short tons, 1960-2018. US EPA. https://www.epa.gov/facts-and-figures-about-materials-waste-and-recycling/national-overview-facts-and-figures-materials

Of the 32 MMT of plastic waste present in U.S. MSW in 2017, an estimated 74% was sent to landfill, with the balance being either combusted for energy recovery (16%) or recycled (8%) (U.S. EPA 2019)

World Economic Forum:

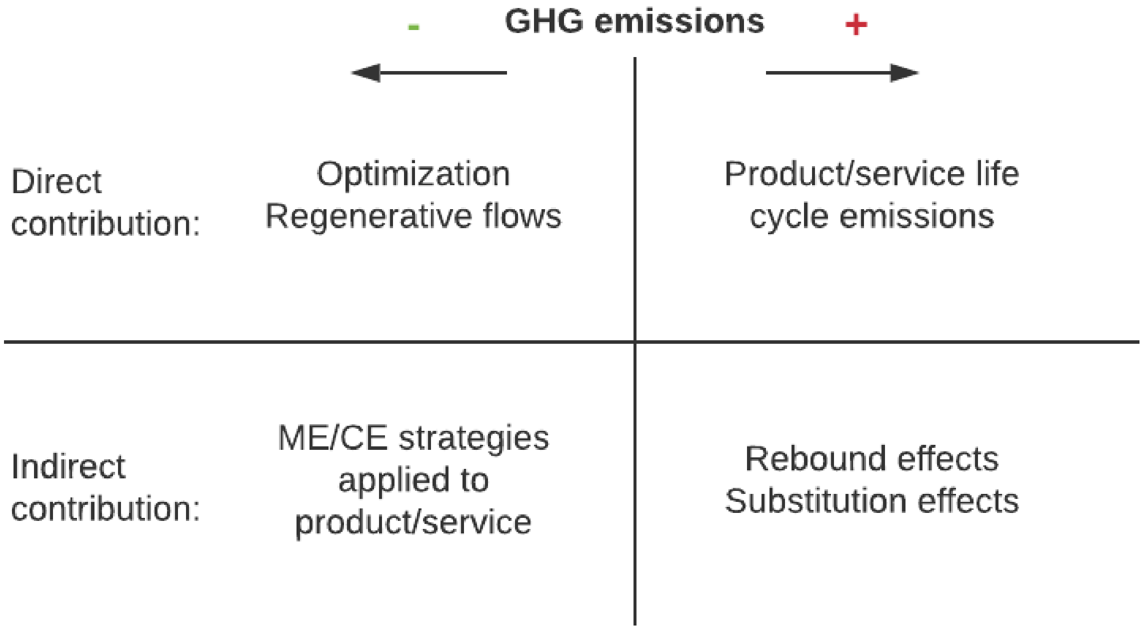
- The plastic recycling rate is falling in the United States, but plastic waste generation is soaring.
- The recycling rate fell from 8.7% in 2018 to 5-6% in 2021, according to the Environmental Protection Agency.
- This is because of a sharp drop in plastic waste exports, with China and Turkey banning such imports.
- The U.S. petrochemical and plastic industry has called for improved recycling but faces pressure to stop its own production of plastic.

CE & Decarbonization

Doubling global circularity (currently at 8.6%) could contribute up to **85% of the greenhouse gas (GHG) emission reductions** needed to limit global warming below 2°C (*Circle Economy 2021*)
→ however, the gap is growing (9.1% circular in 2018 to 8.6% in 2020)!

Examples of contribution of CE to decarbonization:

- Extending a building's lifetime by 50 years could save 400 Mt of CO_2eq/year (*Cai et al., 2012*)
- Energy sector (*Cantzler et al., 2020*): Repurposed electric vehicle batteries in houses ↓ GHG emission by 58%



CE & Decarbonization – *research needs*

- There are possible trade-off between material efficiency (ME) and operational energy for instance:
  - Use of timber structures ↓ buildings' material-related GHG emissions but ↑ GHG emissions during operation due to lower thermal performances
  - Prolonging lifetimes of material stocks versus improving their energy efficiency (*Haas et al., 2020*):
    - For instance, in the transportation sector fuel-efficiency increases by 1.8-3% per year
  - Vehicle electrification ↓ operation GHG emissions but ↑ material-related GHG emissions

→ Research is needed to investigate trade-offs

BUT: Existing policy instruments such as landfill bans or dedicated parking space for car sharing can already be leveraged to increase circularity and contribute to decarbonization!

		Material-related GHG emissions		
		Decreasing	**Neutral**	**Increasing**
Operation-related GHG emissions	**Increasing**	**-Buildings:** lifetime extension, wood structures, cement recycling **-Vehicles:** lifetime extension	**-Buildings:** higher indoor temperature	**-Buildings:** larger **-Vehicles:** larger
	Neutral	**-Buildings:** steel recycling **-Vehicles:** more intensive use (e.g., sharing), recycling		
	Decreasing	**-Buildings:** smaller, more intensive use **-Vehicles:** smaller light-weighting	**-Buildings:** better indoor temperature management **-Vehicles:** driving style, improved engine control	**-Buildings:** extra insulation, stock renewal, heat storage design **-Vehicles:** electrification

Trade-offs of ME strategies in buildings and vehicles (adapted from Hertwich et al. (2019))

Other impacts?

- What about the other environmental and social challenges of our time?
  - Biodiversity
  - Equity & Justice
  - Water scarcity
  - ….

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Guiding CE Research Questions at NREL

Circular

- How circular are current clean energy technologies now?
- How might clean energy technologies become more circular?
- How might the costs of clean energy technology change as the supply chains for clean energy supply chains become more circular?
- How might policy and regulation drive a circular economy for energy materials?

Sustainable

- **What are the externalities** associated with the current clean energy economy and how sustainable are current decarbonization pathways?
- How might those externalities change with circular economy transitions?
- **Where are these impacts distributed?** How might the spatial distribution of impacts change as supply chains become more circular?

Resilient - Robust to Supply Chain Disruptions

- How can a circular economy **mitigate potential supply chain disruptions** in the clean energy economy?
- Which types of circular economy pathways present the greatest **opportunities for reducing our dependence on international supply chains f**or clean energy technologies (e.g., for critical materials such as Dysprosium)?
- How might circularity transitions influence the type and quantity of materials that are required for clean energy technologies, including our dependence on non-domestic sources of these materials?

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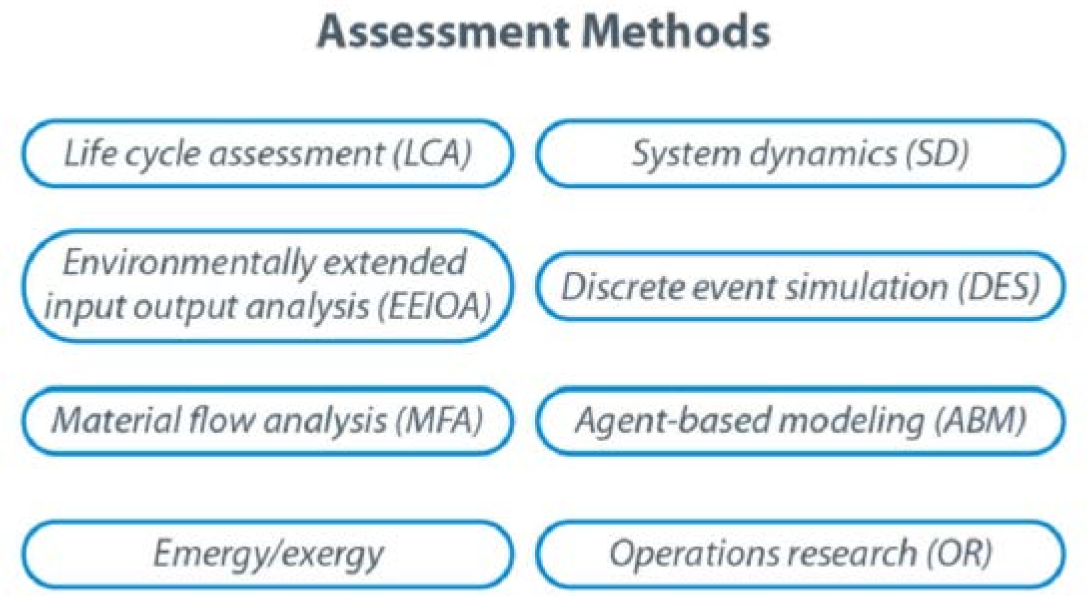
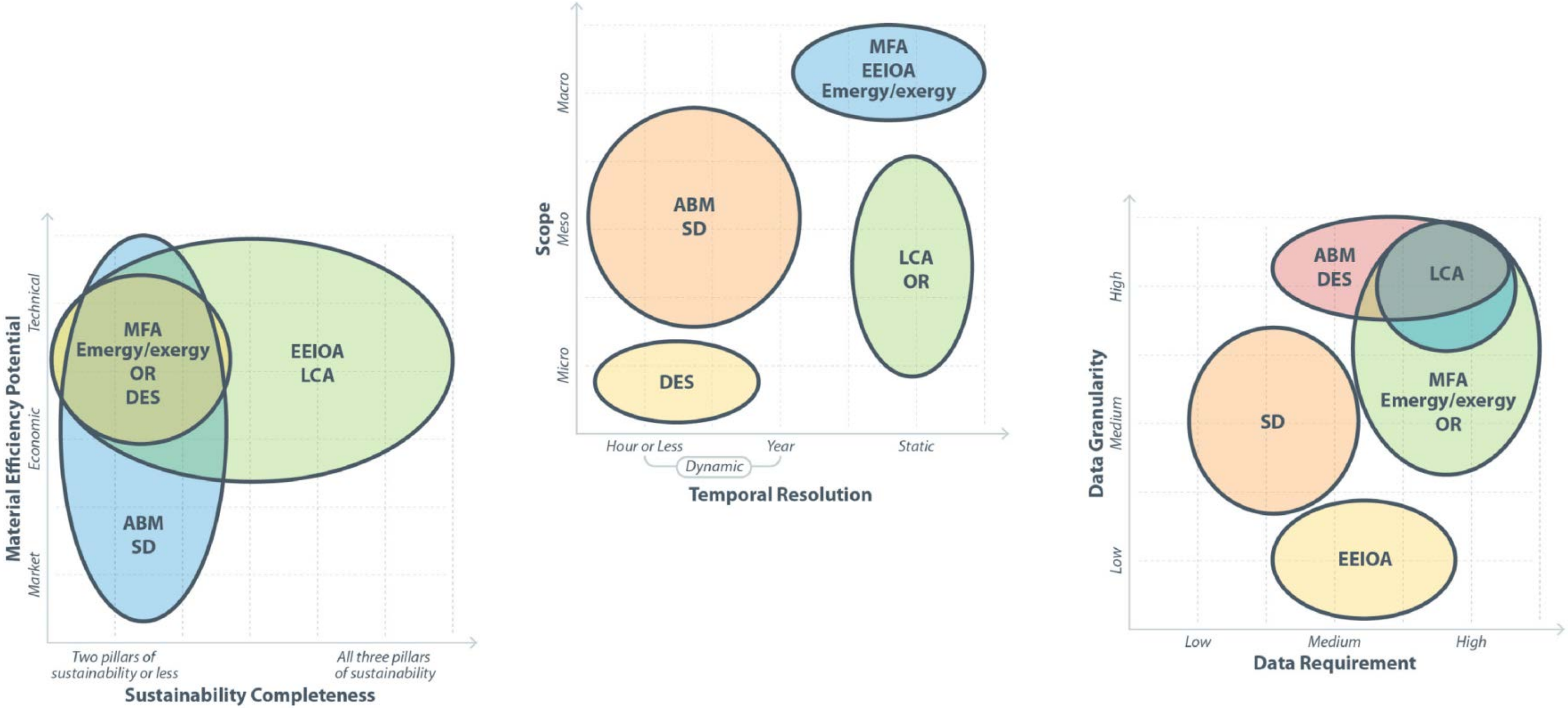
How do we evaluate CE?

This depends on the research question



Walzberg et al, *Frontiers in Sustainability* 1:620047 (2020). https://doi.org/10.3389/frsus.2020.620047

How do we evaluate CE?



Walzberg et al, Frontiers in Sustainability 1:620047 (2020). https://doi.org/10.3389/frsus.2020.620047

Some of the approaches being used at NREL

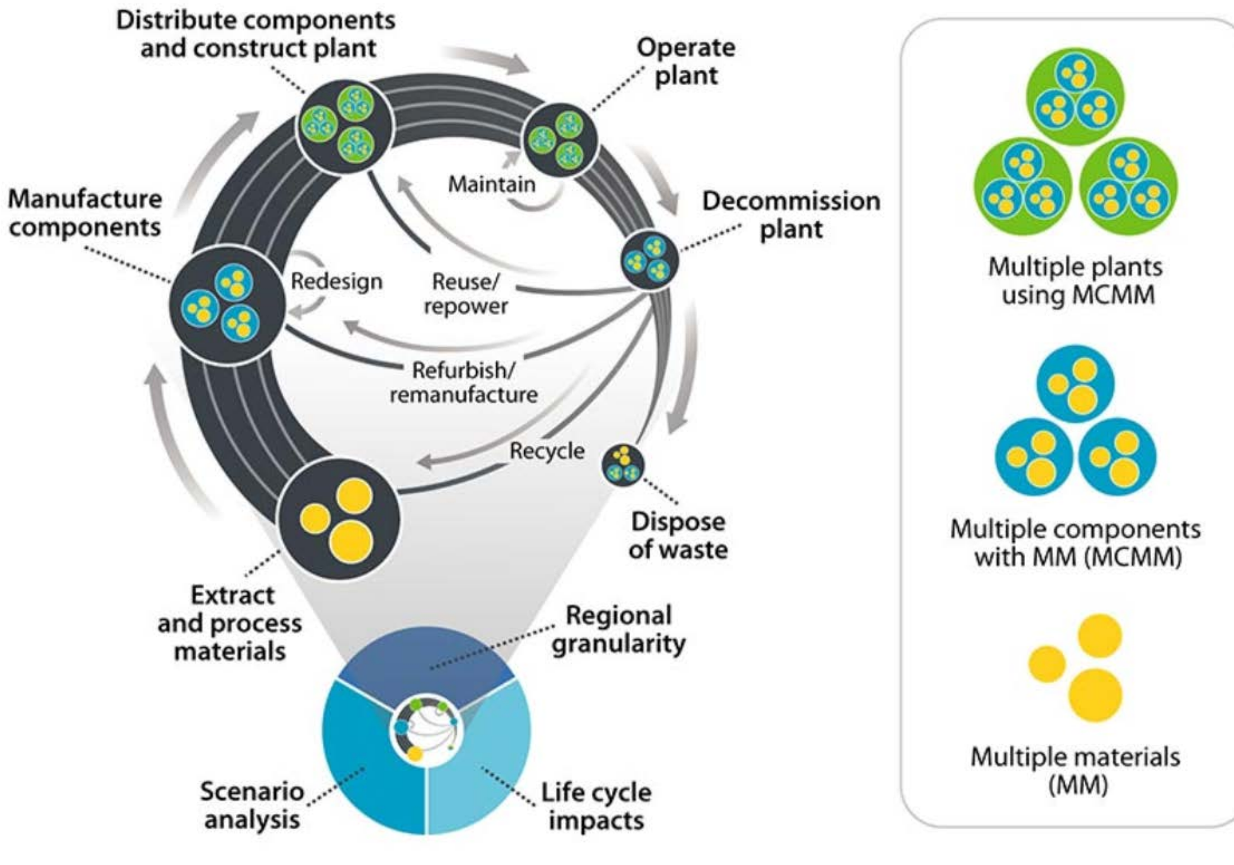
- Circular Economy Life cycle Assessment and VIsualization (CELAVI) framework
- Lithium-Ion Battery Resource Assessment (LIBRA) Model
- Agent based modeling for the circular economy
- PV in the Circular Economy (PVICE)
- Systems level approach for plastics recycling
- Plastics Parallel Pathways Platform (4P)
- BOTTLE Consortium analysis guided research

CELAVI framework

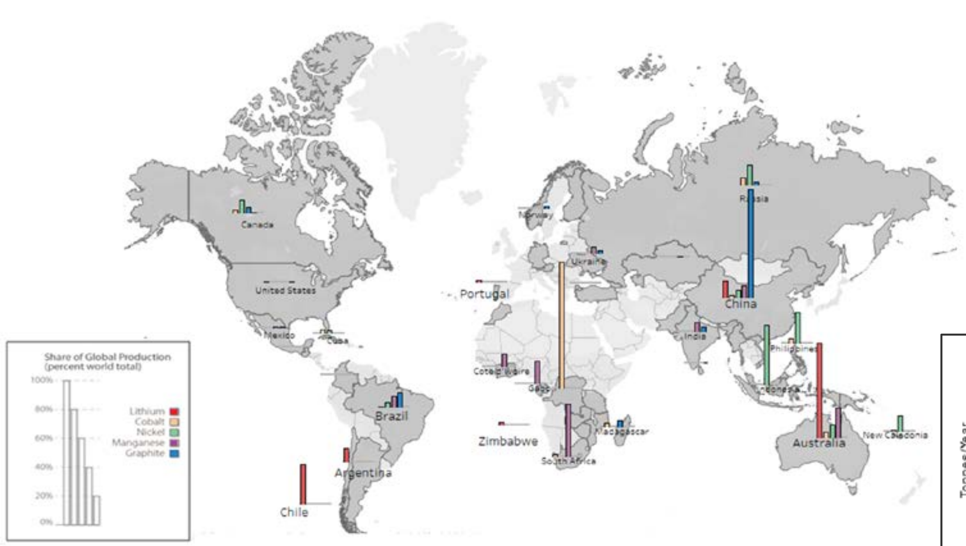
The Circular Economy Lifecycle Assessment and Visualization (CELAVI) framework is a dynamic and flexible tool that models the impacts of clean energy supply chains during the transition from a linear to a circular economy. .

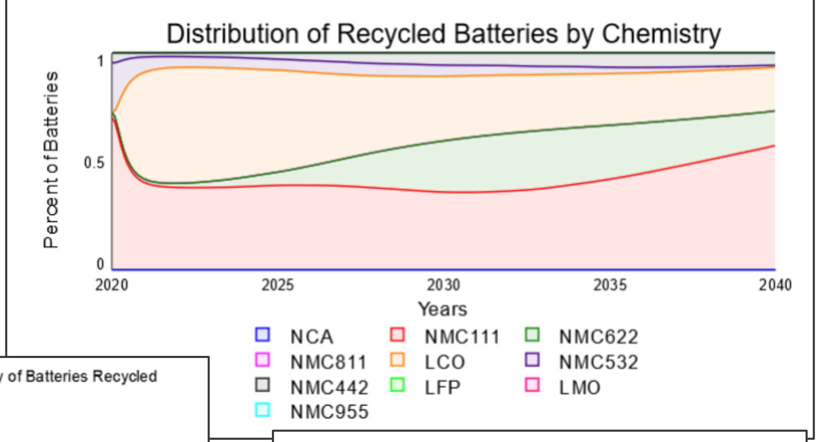
https://www.nrel.gov/analysis/celavi.html

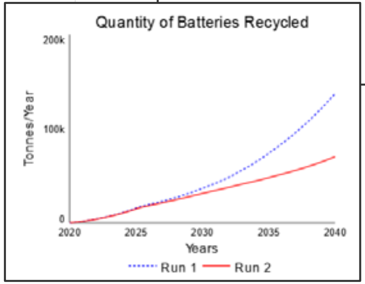
Hanes et al. 2021.

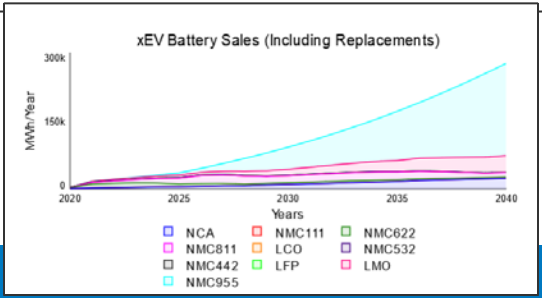


CELAVI users can explore circular and linear supply chains, as well as supply chains with varying degrees and types of circularities, to understand current and future technology demand, the state of technologies that enable circularity, and implementation over time.









LIBRA – Lithium-Ion Battery Resource Assessment Model

LIBRA is a system-dynamics model that evaluates the economic viability of the battery manufacturing, reuse, and recycling industries across the global supply chain under differing *dynamic* conditions

https://www.nrel.gov/transportation/libra.html

Weigl et al. 2022

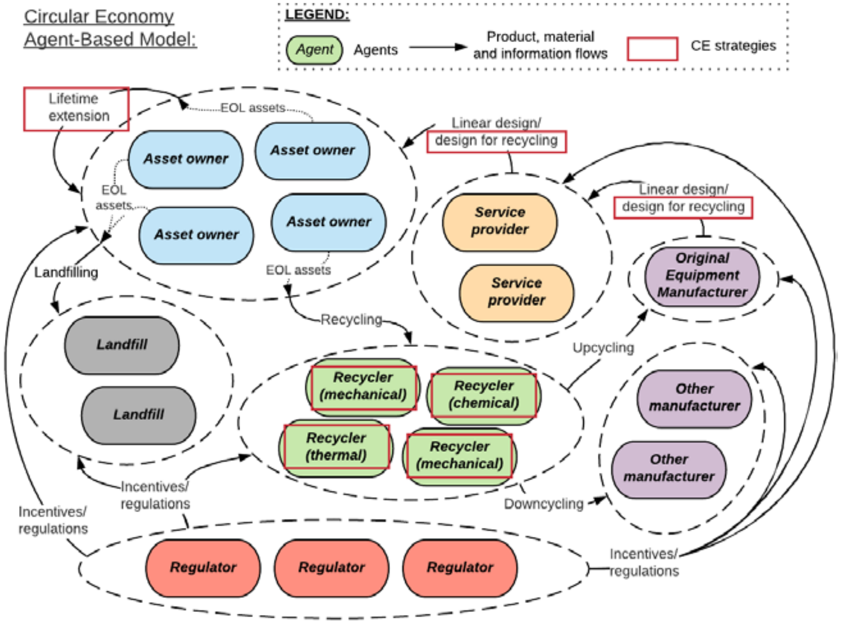
Agent-Based Modeling for the Circular Economy (CE ABM)

Team – J. Walzberg, R. Burton, A. Cooperman, A. Carpenter, G. Heath, A. Eberle

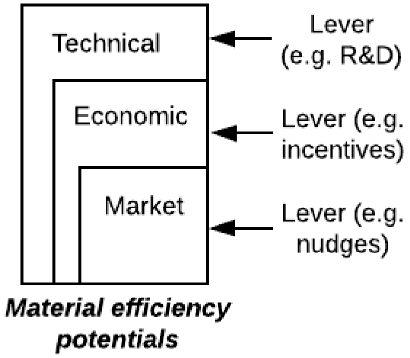
Walzberg et al 2021a; Walzberg et al 2021b; Walzberg et al 2022.

- **Research question:** What are the technical, economic, and market conditions maximizing value retention and minimizing raw material inputs when applying CE strategies to energy-generating and energy-consuming technologies?

- By providing technological and behavioral pathways for increased circularity, the project contributes to **AMO's Sustainable Manufacturing technical area** (e.g., helps in designing interventions to increase the recycling rate)



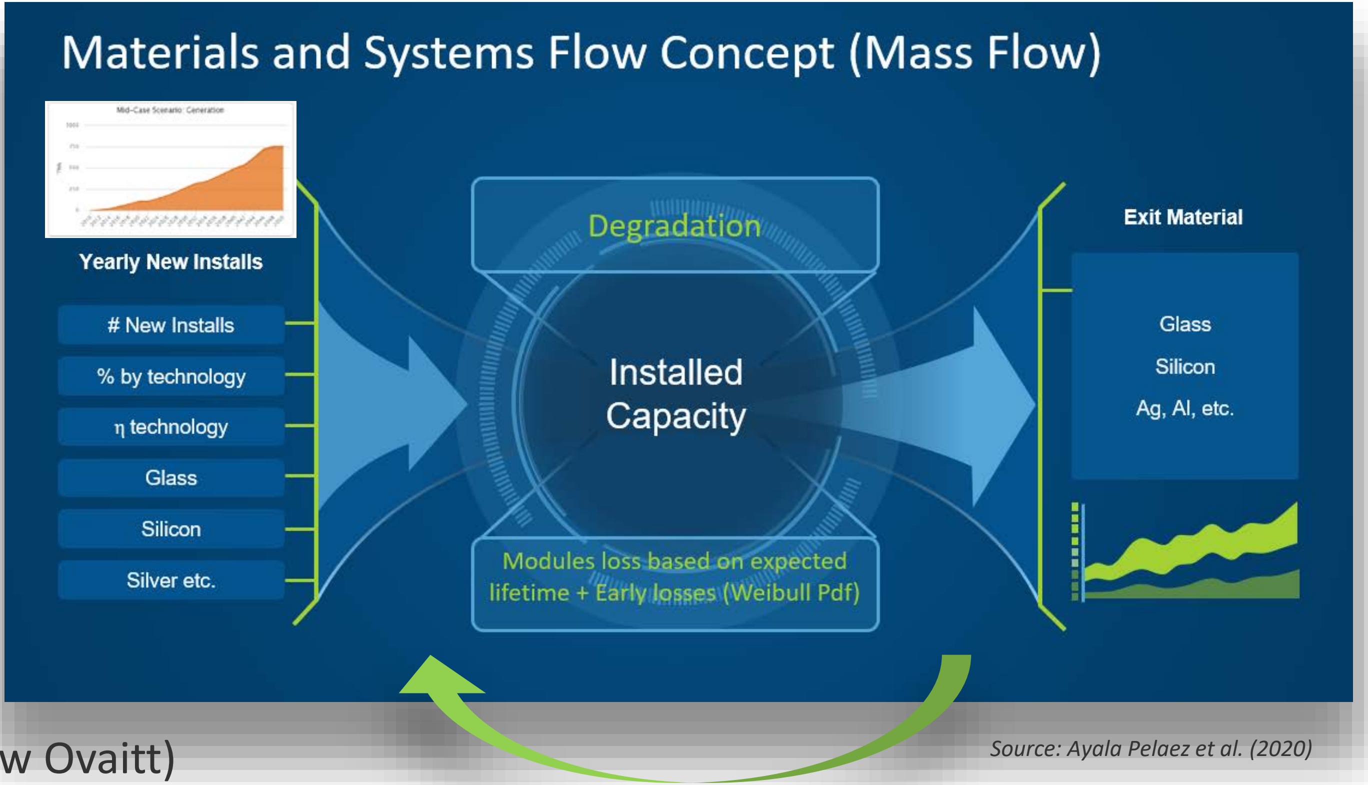
- The model accounts for 6 types of stakeholders – manufacturers, service providers, asset owners, recyclers, regulators, and landfills – and 4 R-x strategies – redesign, reuse, repair, recycle



- By modeling stakeholders' decisions, the CE ABM enables exploring regulatory, economic, and behavioral interventions targeting the technical, economic, and market potentials of a technology

PV in the Circular Economy (PV_ICE)

An open-source tool to quantify photovoltaics (PV) dynamic mass and energy flows in the circular economy, from a reliability and lifetime approach.



Source: Ayala Pelaez et al. (2020)

Includes pathways for circularity at various stages
REUSE, REPAIR, RECYCLE, REMANUFACTURING

PI: Silvana Ayala Pelaez (now Ovaitt)

(PV ICE n.d.)
(Ayala Pelaez et al. 2020)
(Ovaitt et al. 2022)

PV ICE's Integrated NREL Circular Approach

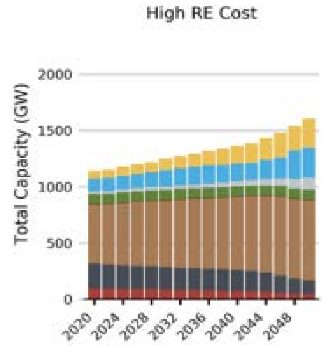
NEW INSTALLS

MANUFACTURING

INSTALLED CAPACITY AND EXTENDED USEFUL LIFE

END OF LIFE MODES

CIRCULAR PATHWAYS

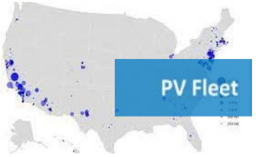


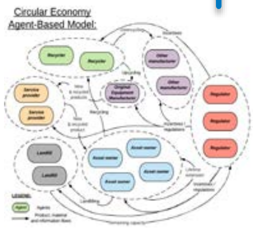
ReEDS

MFI

PV Reliability Group

DuraMAT
Durable Module Materials Consortium





Walzberg's Agent-Based Model

CELAVI Landfill Calculation Approach

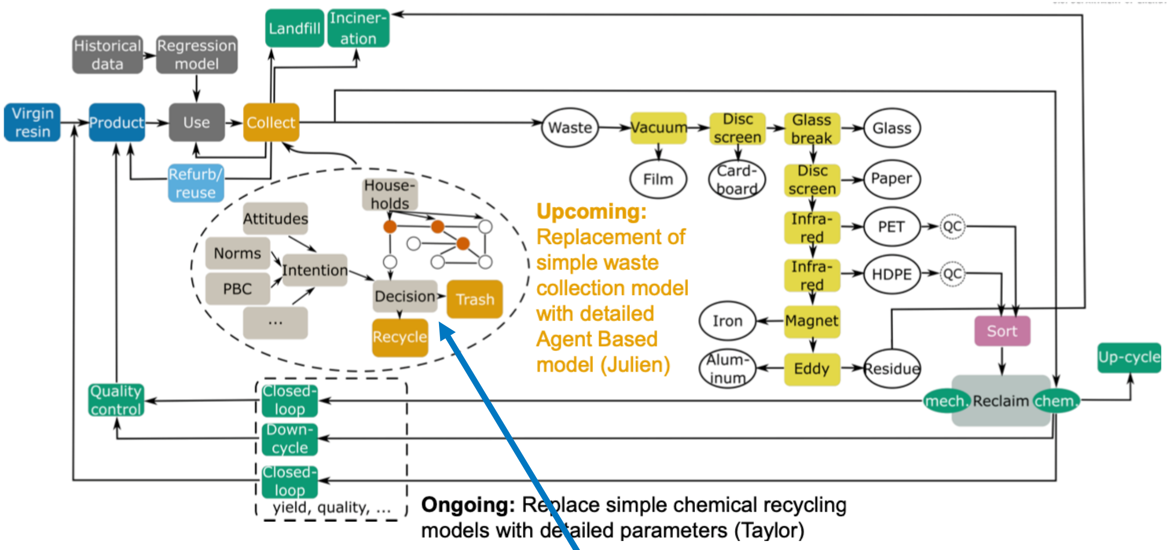
MFI – Materials Flows through Industry, https://www.nrel.gov/manufacturing/mfi-modeling-tool.html
ReEDS – Regional Energy Deployment System, https://www.nrel.gov/analysis/reeds/

System Dynamics & Agent-Based Modeling of Plastic Recycling

Team – Julien Walzberg, Tapajyoti Ghosh, Taylor Uekert

Ghosh et al 2022

- **Research question:** what are the interventions most improving households recycling behaviors in a specific population?
- Quantifying environmental and economic impacts and circularity for all scenarios



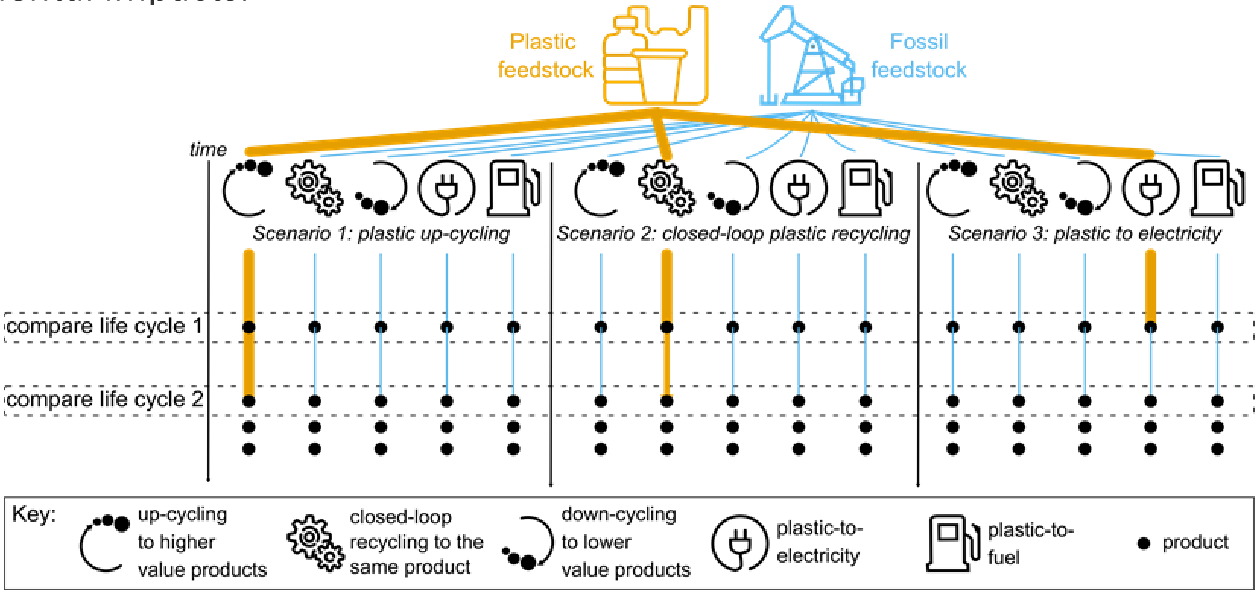
ABM model for recycling behavior

- The ABM simulates households' waste disposal behavior and forms an integral part of a system dynamics model for plastic recycling.
- Closing the linear flow of plastics ensure reduction of plastic waste in the environment as well as carbon mitigation by displacement of virgin material production.

Plastic parallel pathways platform

Team – T. Uekert, T. Ghosh, J. Walzberg, S. Nicholson

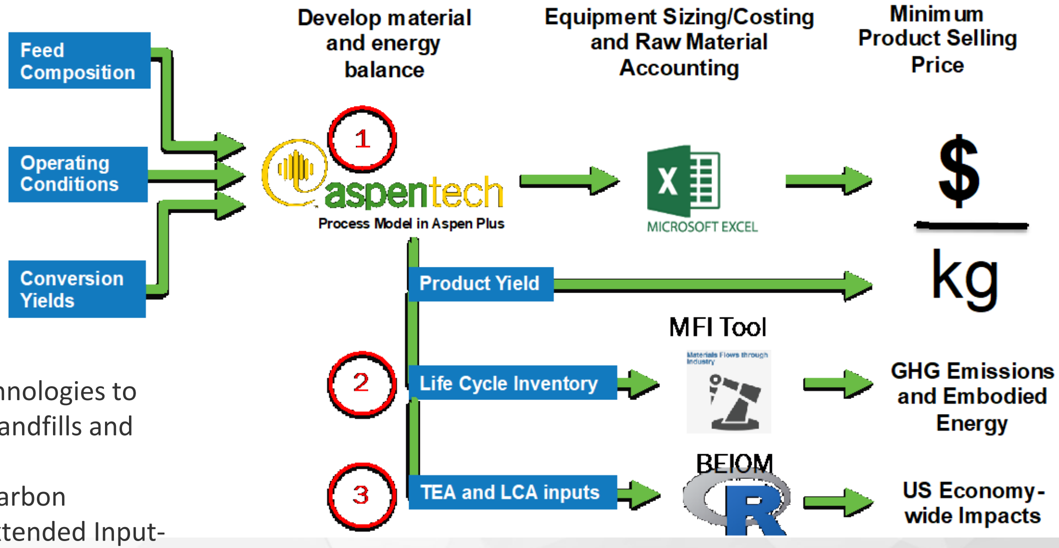
- Research question: How can we decide which plastic management strategies are "best" for a given situation/application?
- Approach: develop a Python-based framework for quantitatively comparing plastic end-of-life strategies that generate different products and evaluating cost, technical performance and life cycle environmental impacts.

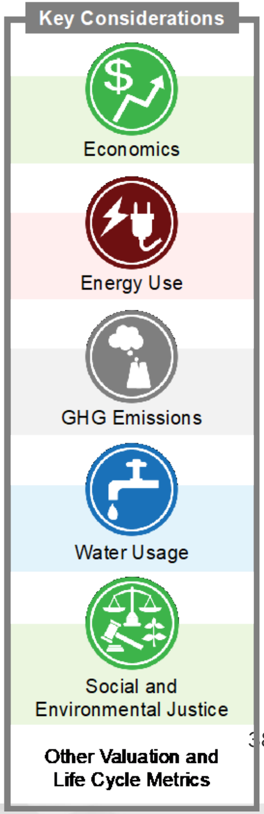


BOTTLE Analysis approach

bottle
changing the way we recycle™
U.S. DEPARTMENT OF ENERGY

- Analysis helps guides polymer and process R&D
- TEA using Aspen Plus
- Energy/greenhouse gas (GHG) assessment via Materials Flows through Industry (MFI)
- Socio-economic and environmental assessment with the environmentally extended input-output framework





BOTTLE – Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment
BEIOM – Bio-based circular carbon economy Environmentally-extended Input-Output Model

PET enzymatic hydrolysis

Goals:

- Determine **key drivers** for community to enable enzymatic PET depolymerization
- Provide **base model to compare enzyme-based approaches** for PET recycling to chemo-catalytic and thermal methods
- **Highlight areas for further impactful development** of biocatalysis-enabled plastics recycling

Methods:

- TEA, MFI, EEIO (BEIOM)
- Process data from patent and peer-reviewed literature

Published

A. Singh et al. (2021). Techno-economic, life-cycle, and socioeconomic impact analysis of enzymatic recycling of poly (ethylene terephthalate). *Joule*.

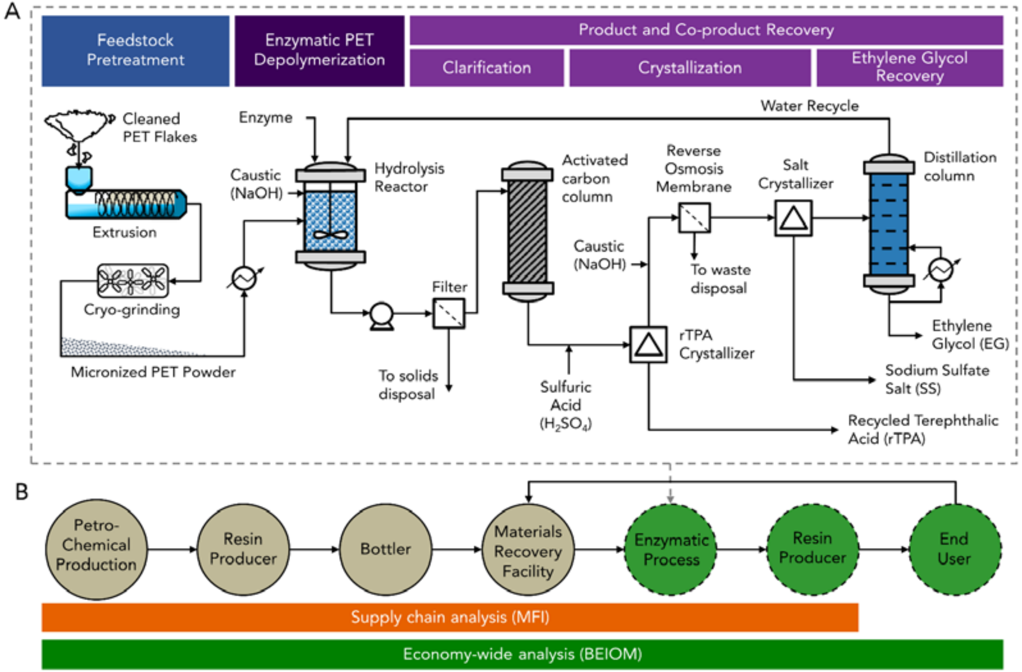
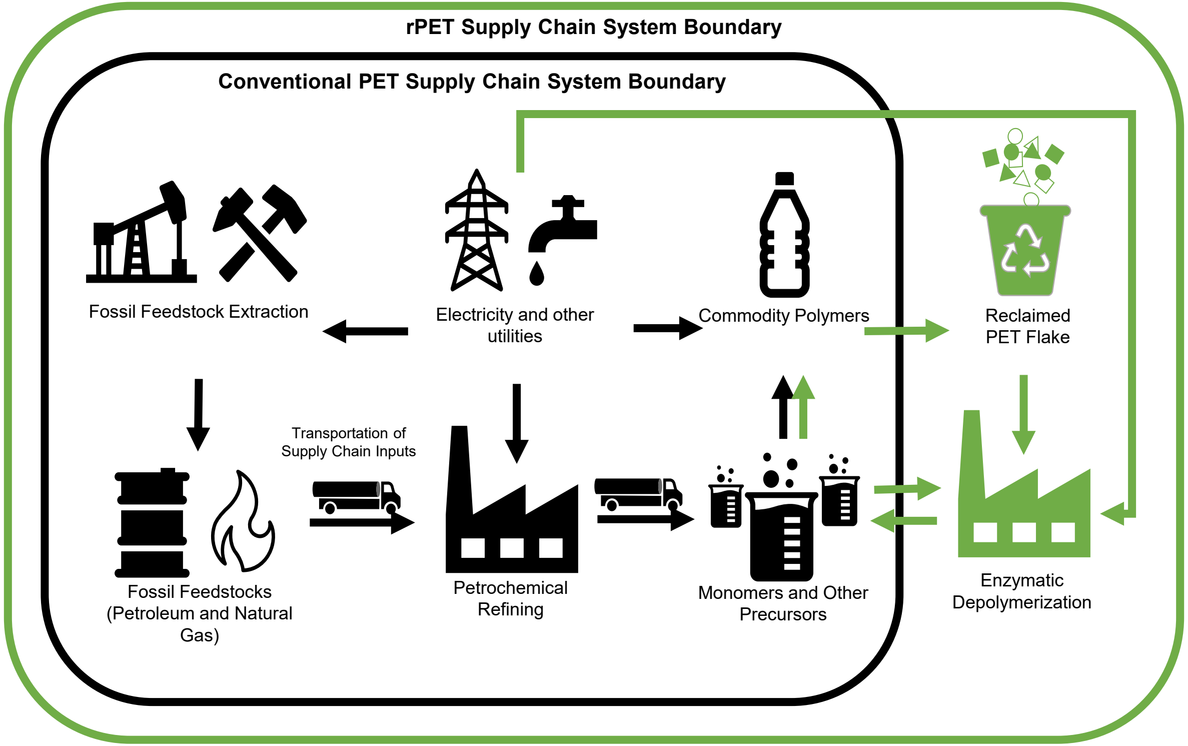
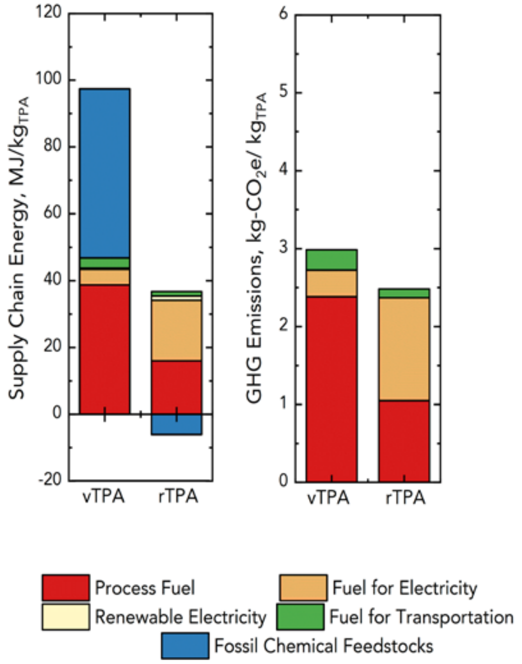


Figure: (A) Simplified process flow diagram of the PET enzymatic depolymerization process
(B) A representation of the bottom-up supply chain model (MFI tool) scope and top-down environmentally-extended input-output (BEIOM model) scope

EEIO = environmentally-extended, input-output, rTPA = recycled terephthalic acid

MFI Results: Comparison with fossil derived TPA



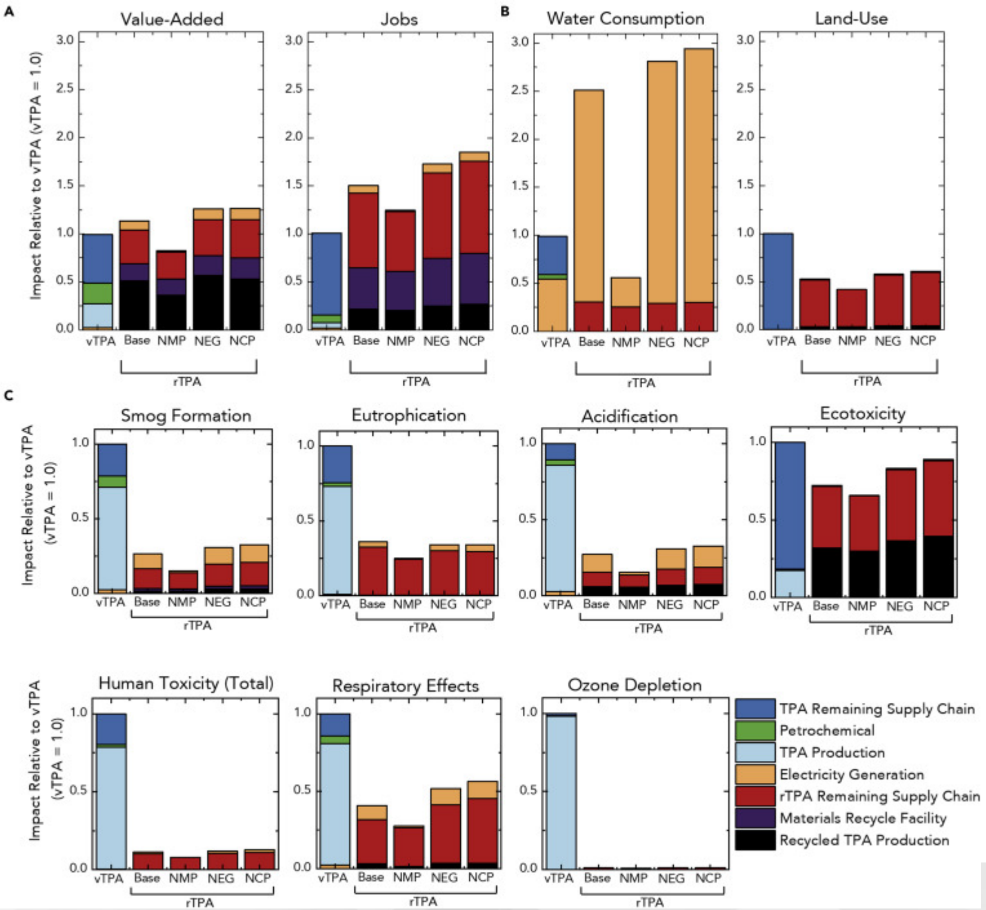


- Supply Chain Impacts (MFI), compared to virgin TPA
  - Supply-chain energy reduced by 69-83%, GHG emissions by 17-43% per kg of TPA
  - Major drivers: mechanical pretreatment and EG recovery

A. Singh et al. (2021).

BEIOM Results: Economy-wide Environmental Impacts

- Economy-wide Impacts (BEIOM), of adding enzymatic recycling PET plants
  - TPA recycling process can reduce environmental impacts by up to 95% while generating up to 45% more socioeconomic benefits, also relative to virgin TPA production.
  - Major domestic job growth concentrated in the supply chain of feedstock with these recycling plants



A. Singh et al. (2021).

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Questions?

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NREL/PR-6A20-85218

This work was authored by the National Renewable Energy Laboratory, operated by Alliance for Sustainable Energy, LLC, for the U.S. Department of Energy (DOE) under Contract No. DE-AC36-08GO28308. Funding provided by U.S. Department of Energy Office of Energy Efficiency and Renewable Energy Industrial Efficiency and Decarbonization Office and Advanced Materials and Manufacturing Technologies Office (formerly the Advanced Manufacturing Office). The views expressed in the article do not necessarily represent the views of the DOE or the U.S. Government. The U.S. Government retains and the publisher, by accepting the article for publication, acknowledges that the U.S. Government retains a nonexclusive, paid-up, irrevocable, worldwide license to publish or reproduce the published form of this work, or allow others to do so, for U.S. Government purposes.

NREL
Transforming ENERGY

	Strategy	Description
Smarter product use and manufacture	**R0** - Refuse	Making products redundant by abandoning its function or by offering the same function with a radically different product
	R1 - Rethink	Make product use more intensive
	R2 - Reduce	Increase efficiency in product manufacture or use by consuming fewer natural resources and materials
Extend lifespan of products and its parts	**R3** - Re-use	Re-use by another consumer of discarded product which is still in good condition and fulfills its original function
	R4 - Repair	Repair and maintenance of defective product so it can be used for its original function
	R5 - Refurbish	Restore an old product and bring it up to date
	R6 - Remanufacture	Use parts of discarded products in a new product with the same function
	R7 - Repurpose	Use discarded products or its parts in a new product with a different function
Useful application of materials	**R8** - Recycle	Process materials to a commodity level with same or lower quality
	R9 - Recover	Incineration of materials with energy recovery

- Define the product function and performance criteria
- Work through ways of applying each Re-X strategy
  - How would it be applied?
  - What are the limitations and challenges?

Additional exercise questions

- What kind of environmental emissions are occurring?
- Where are they occurring?
- When are they occurring?
- How can they be mitigated?
- Which are most important?
- What is the impact at end of life? What happens to those materials?

Approach

- BOTTLE™ Consortium approach: techno-economic analysis (TEA), life cycle assessment (LCA)
  - Carbon, energy, and economic targets
  - Informing the research
- Technology performance
- Systems thinking
  - Agent-based modeling to understand what factors affect decision-making and interactions of different actors in the larger system
  - Systems dynamics approach to highlight feedbacks among supply chain components to evaluate the challenges/opportunities

BOTTLE: Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment

Metrics for BOTTLE projects

The mission of BOTTLE is to:

- Develop robust processes to upcycle existing waste plastics
- Develop new plastics and processes that are recyclable-by-design

BOTTLE projects will aim to meet three key metrics:

Energy:

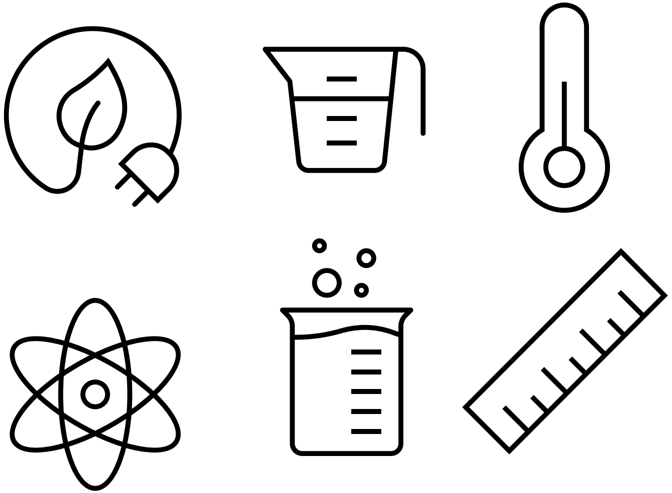
- ≥50% energy savings relative to virgin material production
- Closed-loop recycling estimated to save 40%–90% energy[1]

Carbon:

- ≥75% carbon utilization from waste plastics
- Estimated based on recycling of commodity thermoplastics

Economics:

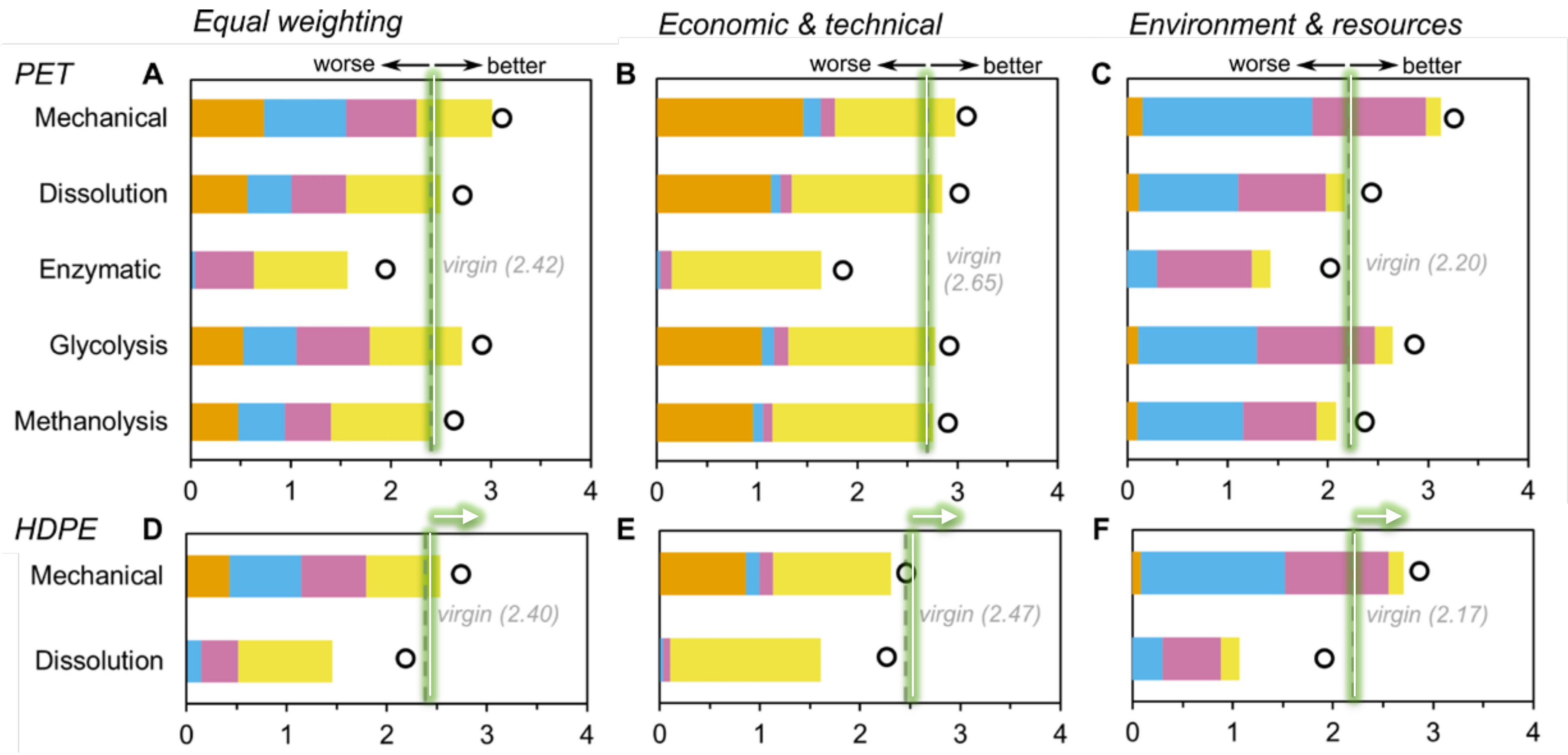
- ≥2x economic incentive over reclaimed materials



1. Rahimi and Garcia, *Nature Reviews Chemistry*, 2017

Multi-criteria decision analysis

- Multi-criteria decision analysis (MCDA) allows for the evaluation of conflicting criteria

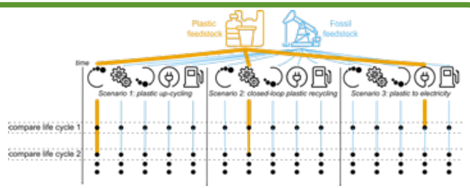


- Some recycling technologies already offer better alternatives than virgin
- Many emerging technologies perform worse under environmental weighting → need streamlining
- Does not necessarily mean technologies with low scores are "bad"

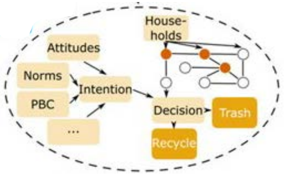
Uekert et al., 2022, in preparation

Other relevant tools

Plastics Parallel Pathways Platform (4P)
- Compare plastic end-of-life pathways that generate different products
- Assess environmental and economic impacts over multiple lifetimes
- Include circularity indicators



Agent-based model (ABM)
- Map plastic recycling, landfilling, and “wishcycling” behavior in households
- Determine social interventions that increase recycling rates



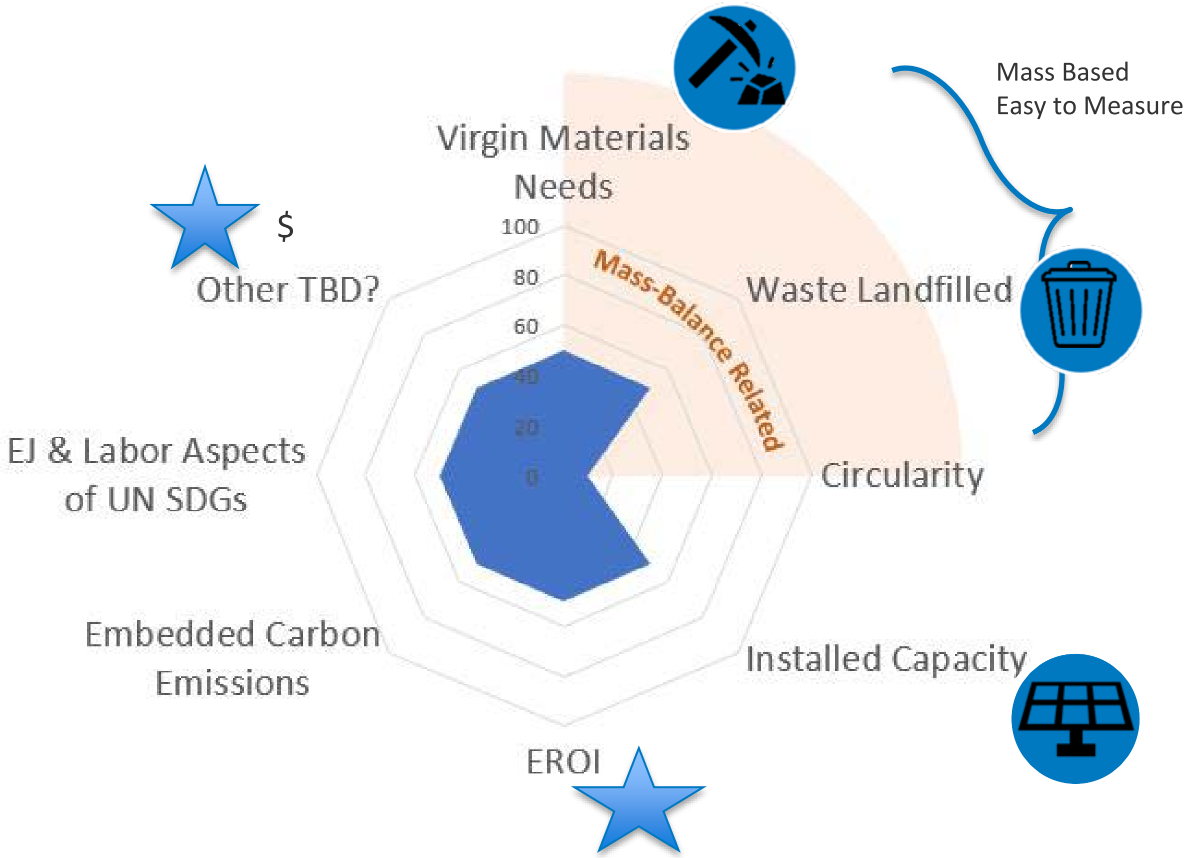
LiAISON
- Python-based, prospective LCA to preempt trade-offs and unintended consequences and inform R&D prioritization of new technologies
- https://www.nature.com/articles/s41467-022-31146-1

Risk and impact assessment for technology adoption
- De-risk technology adoption by identifying routes from technology readiness to market and from market readiness to market share

Sustainability Dimensions

PV_ICE

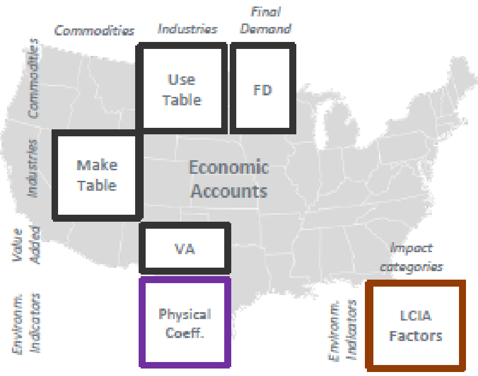
In progress



BEIOM: Bio-based circular carbon economy Environmentally-extended Input-Output Model

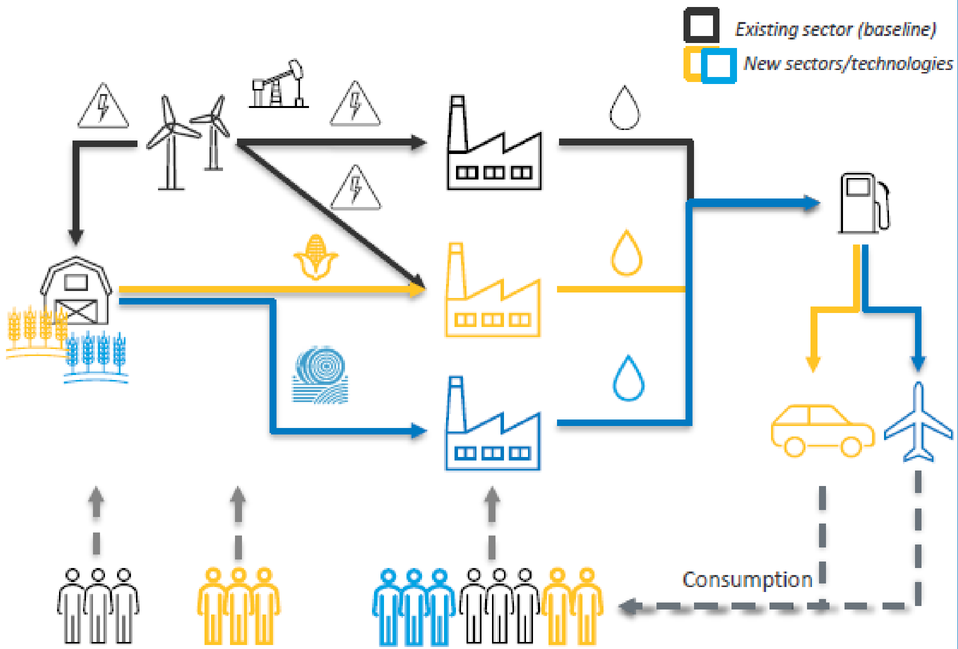
PI: Patrick Lamers, NREL | Sponsors: DOE BETO, EPA ORD

Method & Datasets



- *EEIO: established method to assess impacts of products or product portfolios (e.g., by Amazon)*
- *Uses national-level datasets from federal agencies (EPA, USDA, etc.)*
- *Traces structural changes in the US economy*
- *Analyzes sector interactions*
- *Includes feedback effects*
- *Does not apply system cut-offs within US geographical boundaries*

Defining new technologies/industries/paradigms



Using process-level techno-economic and life cycle inventory data, we can define any new technologies (or portfolios thereof) and assess their net socioeconomic and environmental effects at industrial scale in an economy-wide context.

Net effects