AMMTO & IEDO JOINT PEER REVIEW

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Plastics Circular Economy Analysis and Modeling | AMMTO & IEDO

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CPS **25019** | FY22 & 23

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Project Overview - Plastics Economy Circular Economy Model

- **Context**: GHG emissions from the global plastic economy are expected to increase to 15% of the global carbon budget by 2050. Integrating system dynamics into a robust plastics model that already incorporates techno-economics, circularity, and environmental impacts will enable identification of key bottlenecks between manufacturers, waste sorters, and reclaimers that currently prevent rapid decarbonization of the plastics economy.
- This model can help to understand what technologies provide the most benefit for different materials and what improvements in the plastics economy can provide the most benefits.
- **Goal:** Evaluate how to minimize the GHG emissions from the U.S. plastics economy and how can we optimize the use, reuse, and recycling of PET bottles to reduce the impact of the plastic sector as it is projected to grow. Provide an understanding of the range of different pathways to maximize keeping plastic materials in the economy and providing value to society and evaluate the benefits and impacts associated with the different pathways.
- Model informed by data from The Recycling Partnership (TRP) and from BOTTLE (BioOptimized Technologies to keep Thermoplastics out of Landfills and the Environment) Consortium analysis.
- **Project Lead:** NREL - Alberta Carpenter (PI), Taylor Uekert, Tapajyoti Ghosh, Julien Walzberg

	FY21 Costs	FY22 Costs	FY23 Costs	Total Planned Funding
DOE Funded	$156K	$140K	$133K	$429K

Overview: Analysis and its role in BOTTLE

Analysis is foundational to BOTTLE's mission

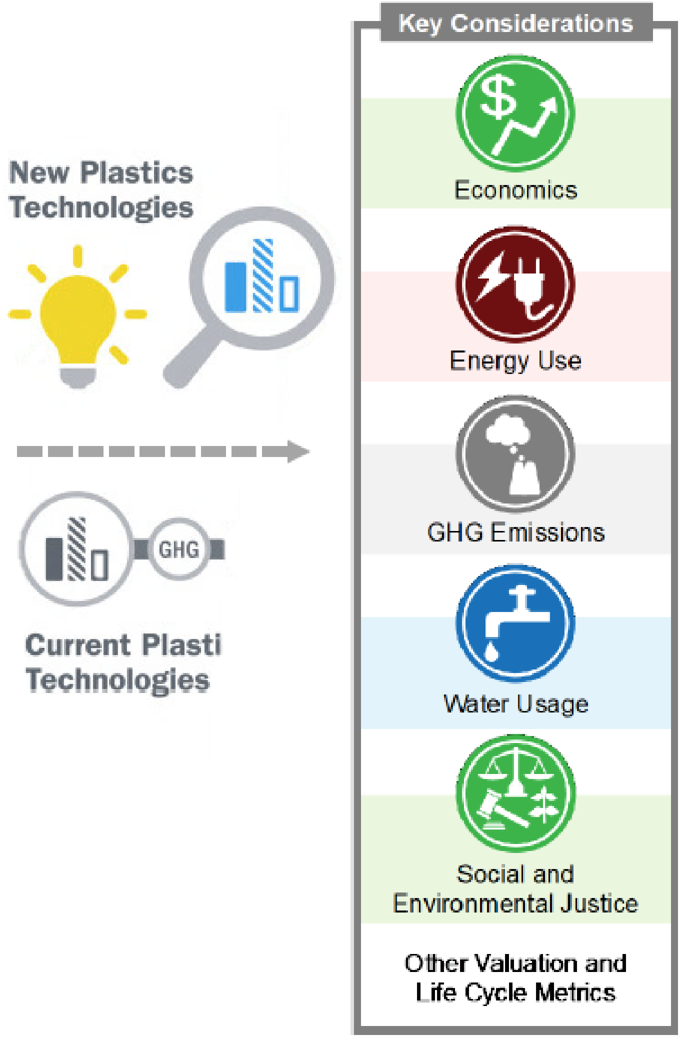
- Develop robust processes to upcycle existing waste plastics, and
- Develop new plastics and processes that are recyclable-by-design
- Analysis-guided R&D aligns with DOE's Strategy for Plastics Innovation

Economic, environmental, and comparative analysis

- Model new processes and analyze energy, carbon, cost, and GHG emissions metrics to determine their feasibility and key driving variables
- Compare these results against incumbent technologies

Framework for analysis proposed in 2022 review[1]

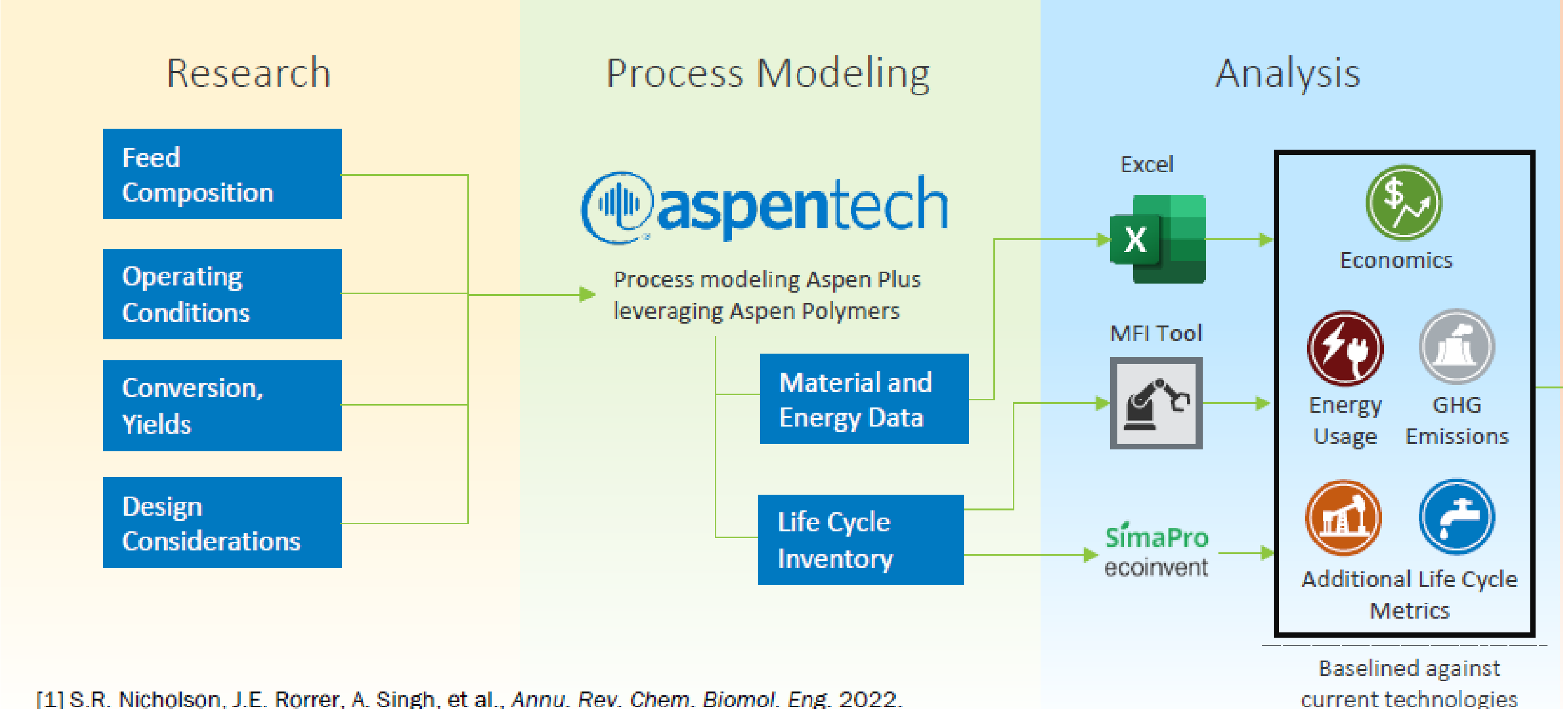
- Identify impactful areas for R&D
- Guide technologies towards a circular and sustainable plastics economy



[1] S.R. Nicholson, J.E. Rorrer, A. Singh, et al., *Annu. Rev. Chem. Biomol. Eng.* 2022. Image sourced from reference at left and S.R. Nicholson, N.A. Rorrer et al., *Joule* 2021.

Analysis Approach

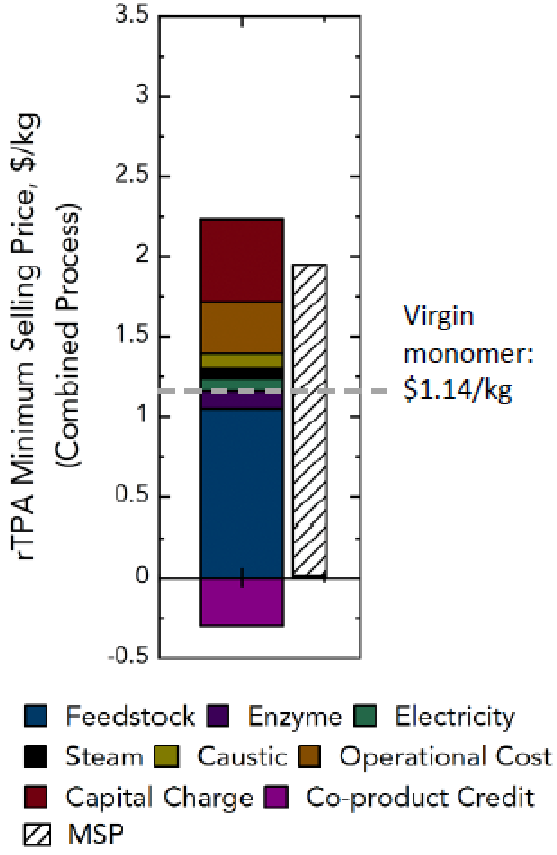
- Techno-economic analysis (TEA) and life-cycle assessment (LCA) conducted across multiple scopes
- Economics and sustainability assumptions follow transparent / open-source practices in EERE-funded R&D; framework published in recent review[1]
- Analysis is an iterative process that occurs in parallel to laboratory R&D
- Communication with each task through fortnightly team meetings and internal task meetings
- Select risks include data availability and ability to incorporate feedstock variability and quality into models



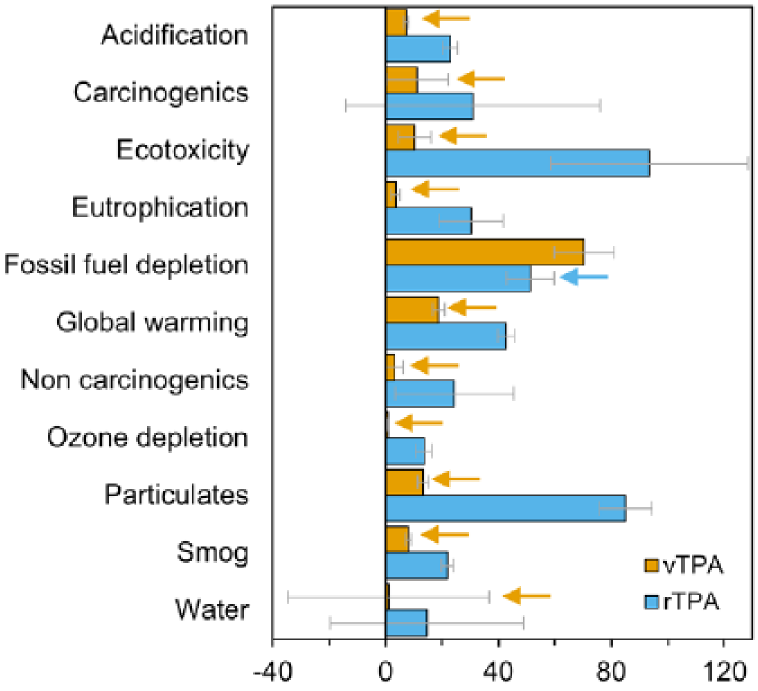
[1] S.R. Nicholson, J.E. Rorrer, A. Singh, et al., *Annu. Rev. Chem. Biomol. Eng.* 2022.

Case study I: PET enzymatic hydrolysis

Economic feasibility[1]



Environmental impact[2]

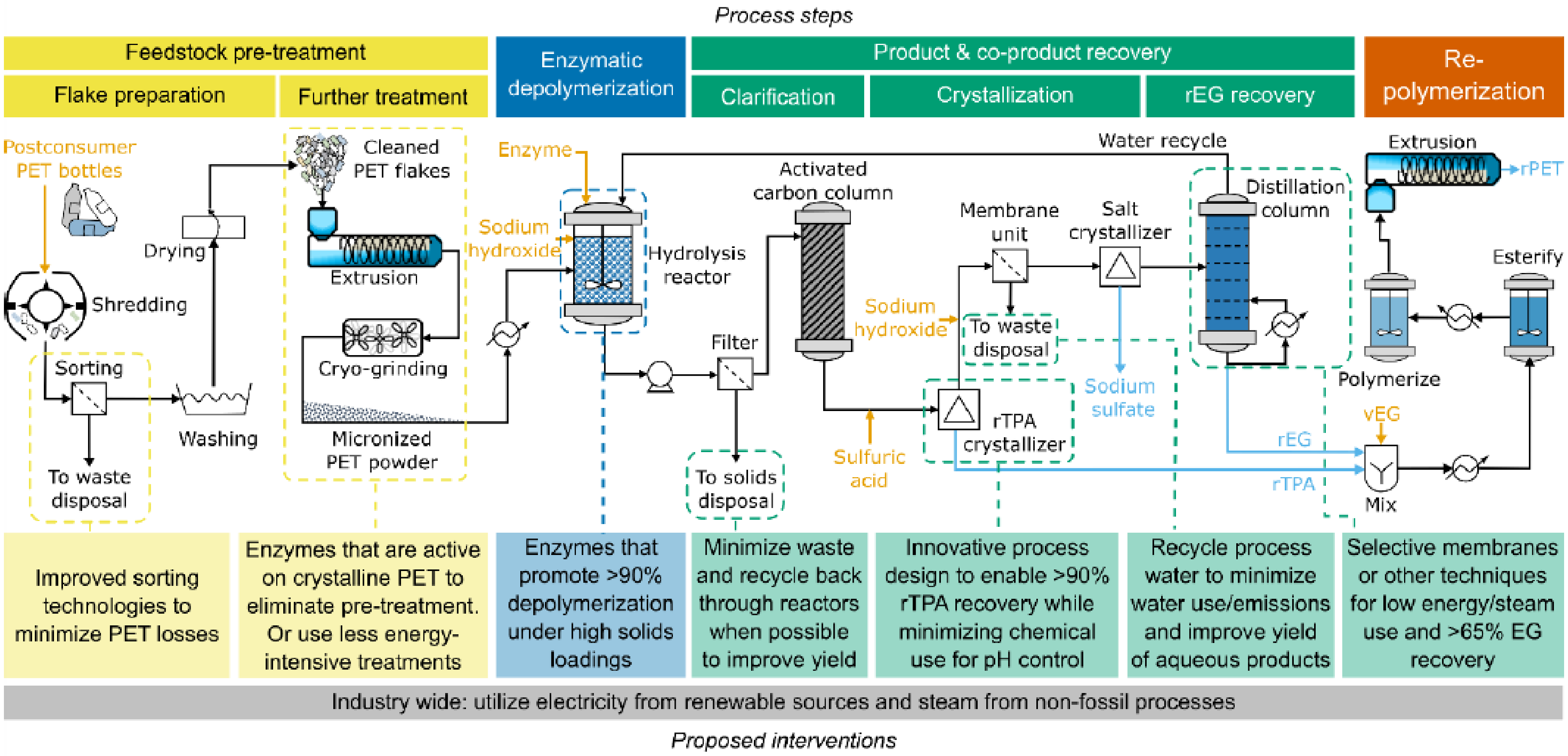


Goal: benchmark PET enzymatic recycling versus virgin PET manufacturing and identify areas for innovation

- Cost: Recycled terephthalic acid (rTPA) monomer is 1.7× more expensive than virgin vTPA
- Opportunity: Cheaper feedstock enables cost parity
- Environmental impact: rTPA has 3-17× higher impacts than vTPA (except fossil fuel depletion)
- Opportunity: New process designs reduce electricity and chemical use, enabling environmental parity

[1] A. Singh *et al. Joule* 2021 [2] T. Uekert *et al. Green Chem.* 2022

BOTTLE Research Insights



Improvements across many of these process areas will likely be necessary for scale-up of enzymatic recycling

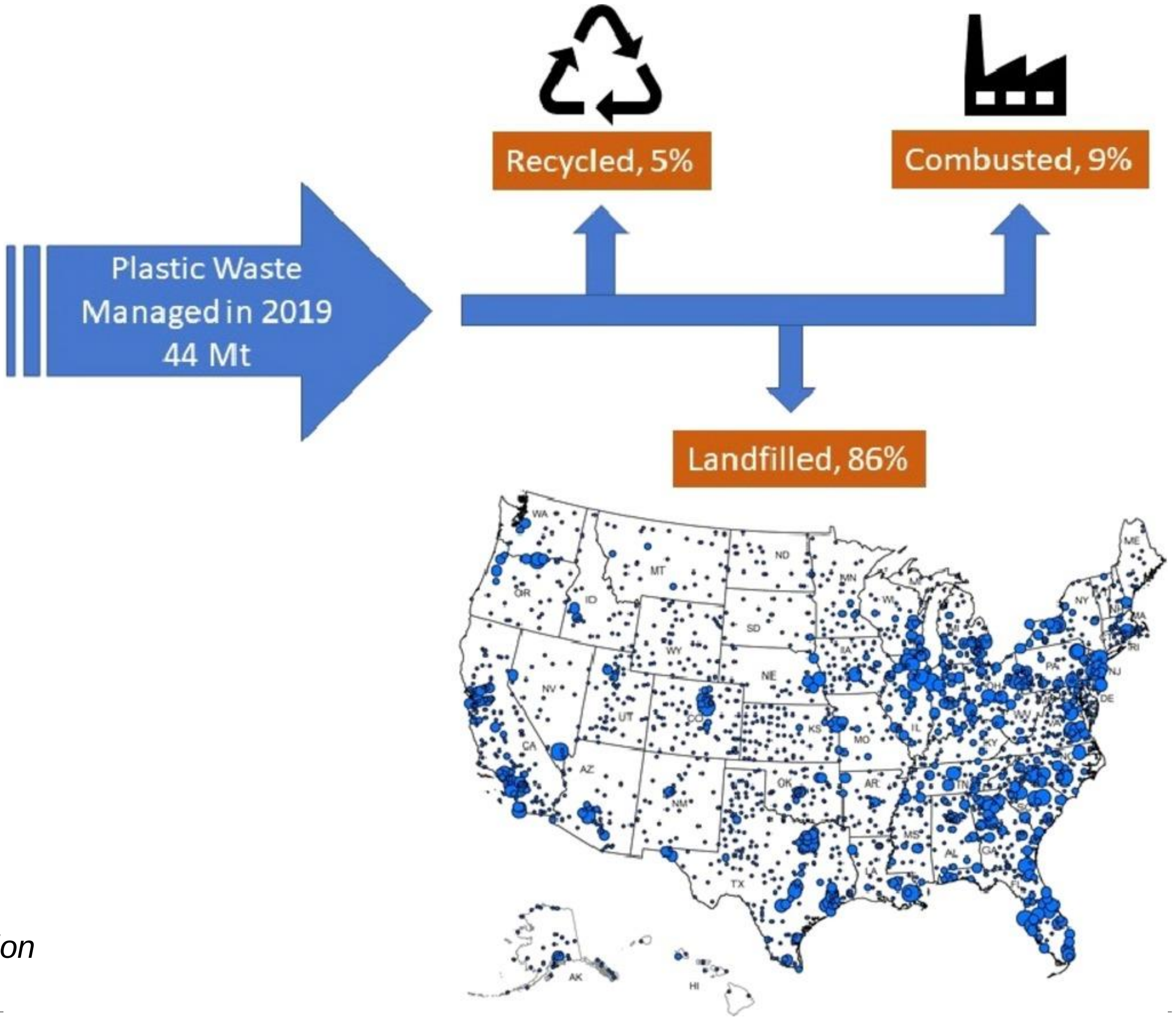
Tradeoffs: many inexpensive components (water, steam, waste, etc.) are costly from an environmental perspective

T. Uekert *et al. Green Chem.* 2022.

Quantification and evaluation of plastic waste in the United States

This work indicates that we need to understand
- how to increase how much plastics are going to recycling and
- how to reduce how much plastic is going to landfills

To answer this, we use a systems approach
- layering in systems dynamic and agent-based modeling
- to understand better where the losses are occurring and
- what are the technical, economic and social drivers

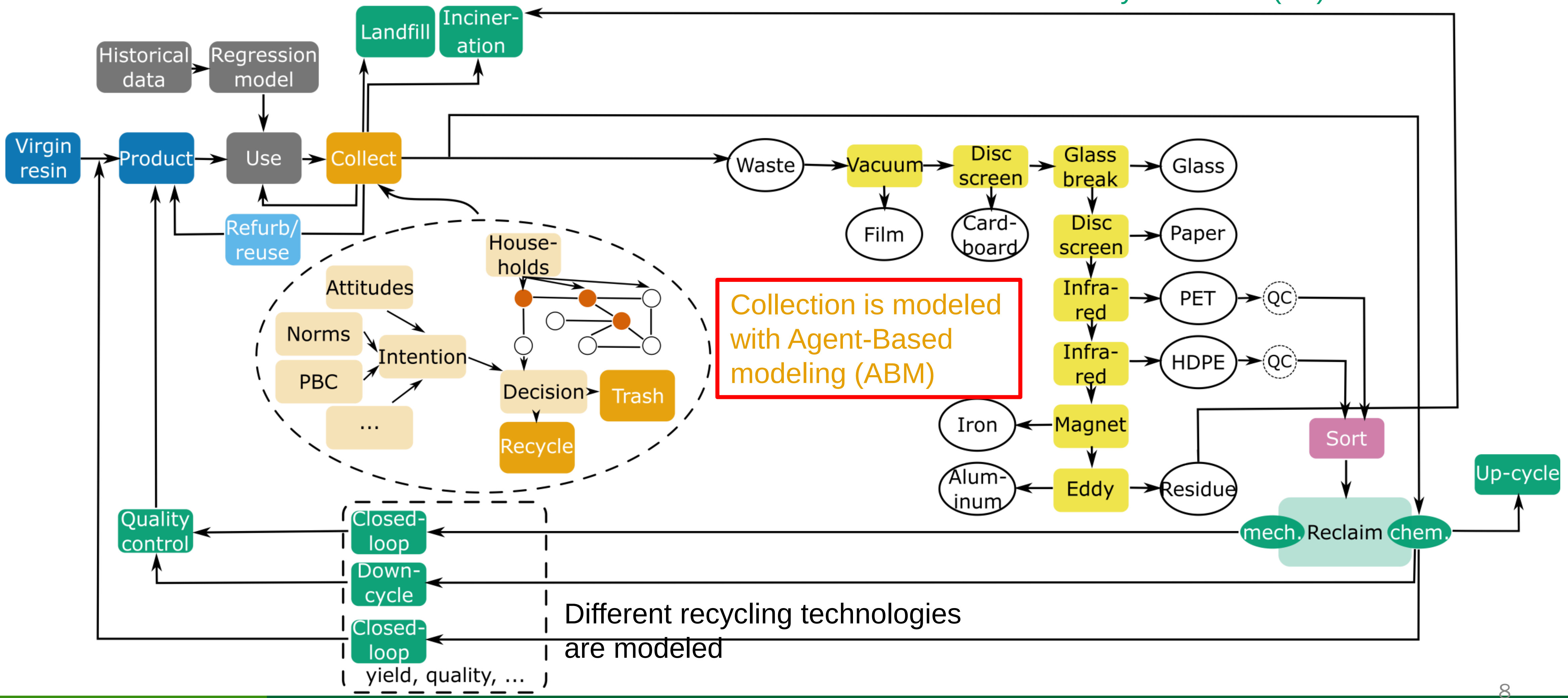


Milbrandt et al, *Resources, Conservation and Recycling*, 2022,

Overarching framework summary

Framework currently focuses on PET bottles but could be applied to any material

End-of-life pathways are compared with the Plastic Parallel Pathways Platform (4P)

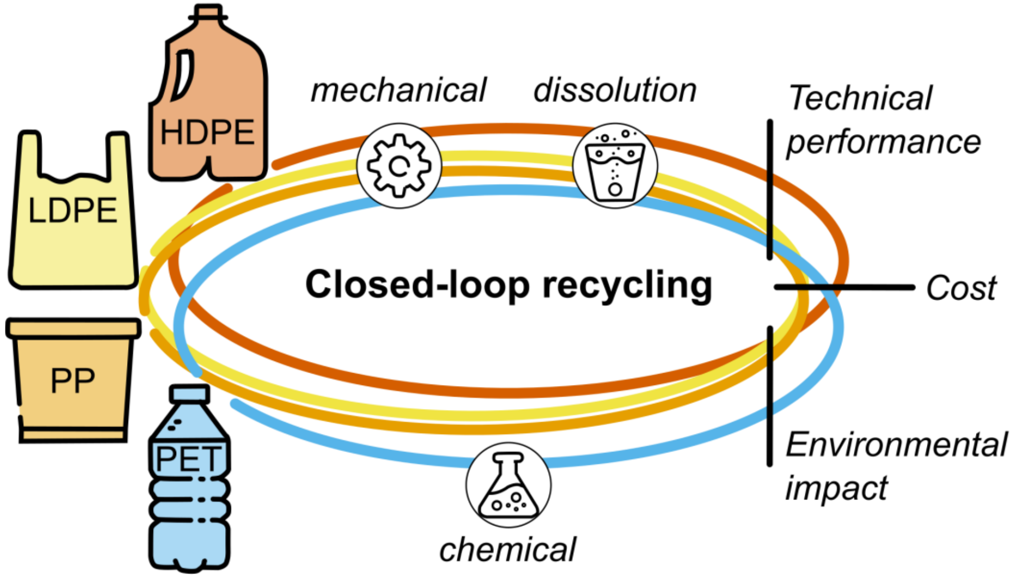


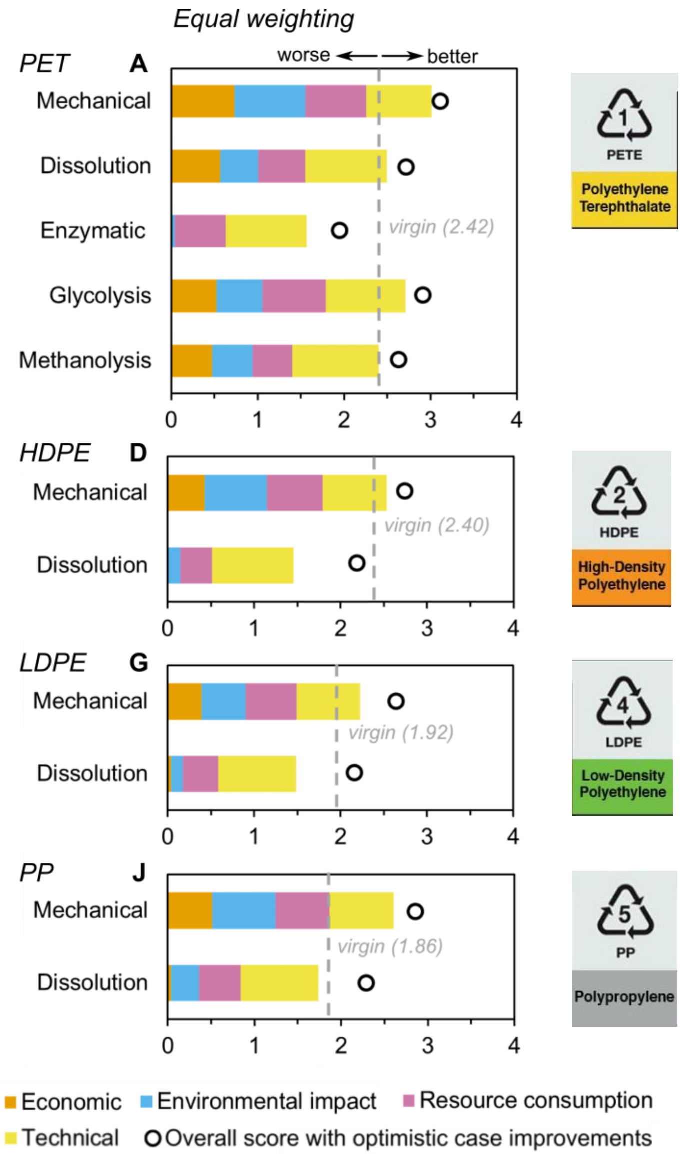
Collection is modeled with Agent-Based modeling (ABM)

Different recycling technologies are modeled

Comparing closed-loop recycling options

- Compared plastic-to-plastic technologies for PET, HDPE, LDPE, and PP across cost, environment impact, and technical capabilities
    - Mechanical recycling → lowest cost & impact, worst contamination tolerance & material yield/quality
    - Glycolysis → best chemical recycling option for PET
    - Polyolefins have limited closed-loop options

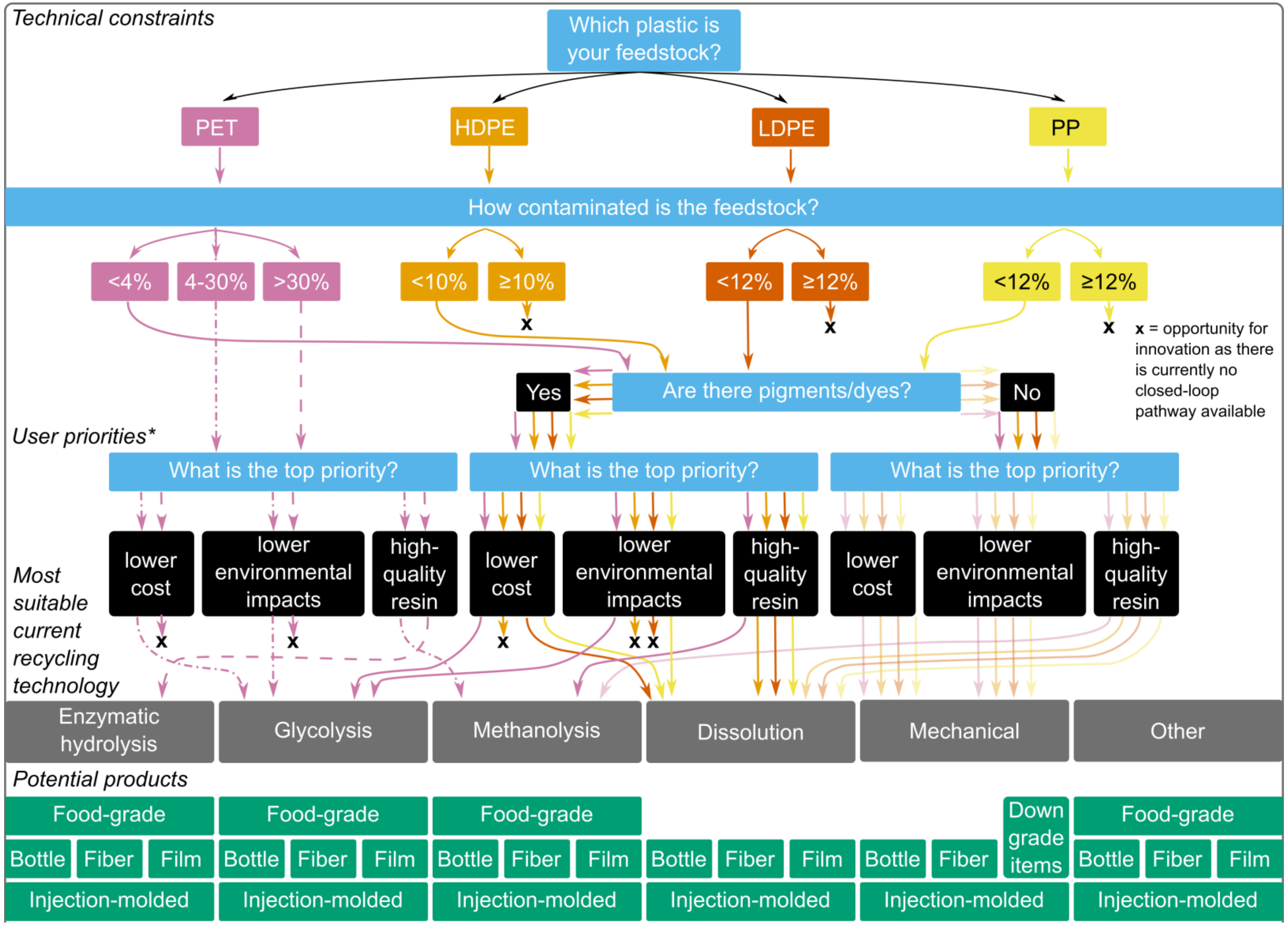




T. Uekert et al., *ACS Sustainable Chem. Eng*. **2023**, *11*, 965-978.

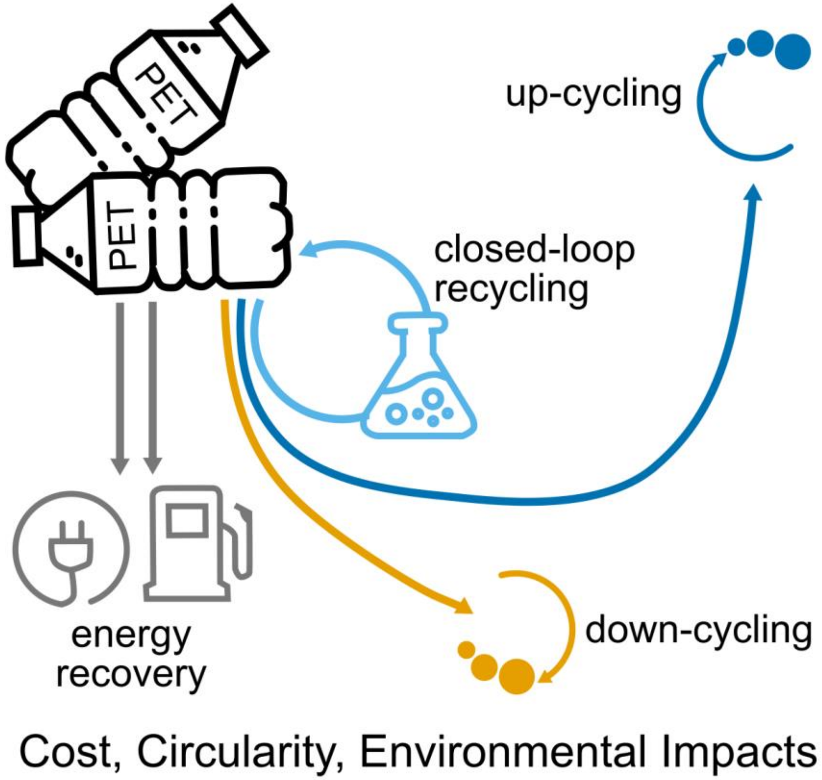
Leveraging a suite of solutions

- No single technology will be able to handle all plastic feedstocks while simultaneously reducing cost and environmental impacts
- So how can we pick the best *combination* of options?

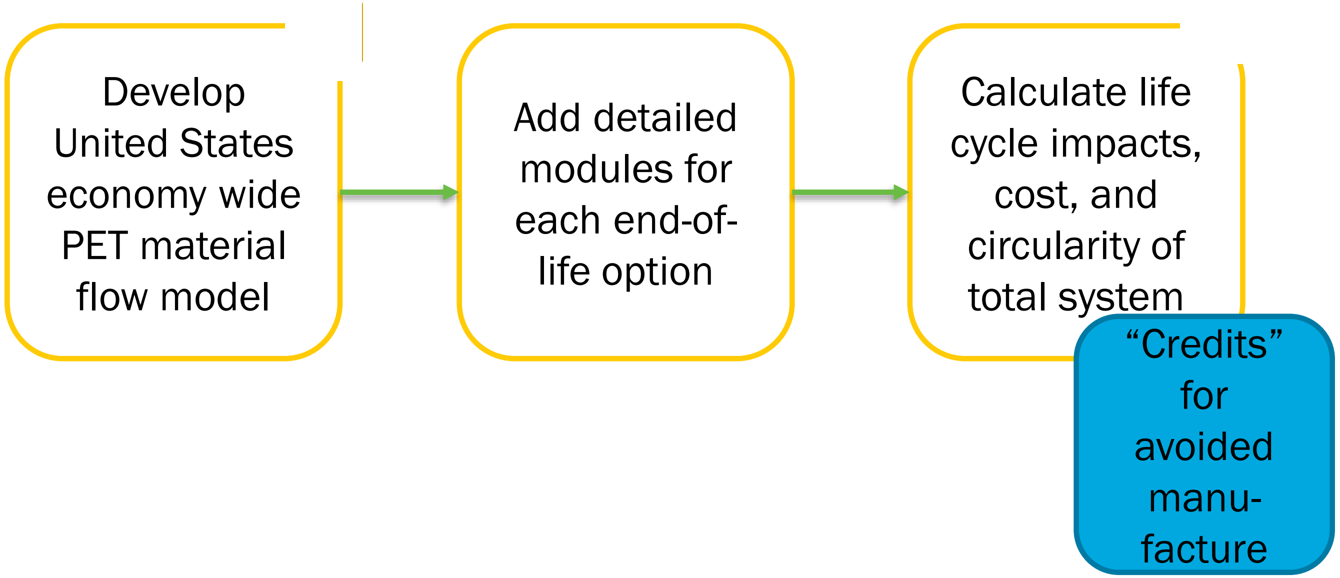


T. Uekert et al., *ACS Sustainable Chem. Eng*. **2023**, *11*, 965-978.

Expanding to open-loop recycling options



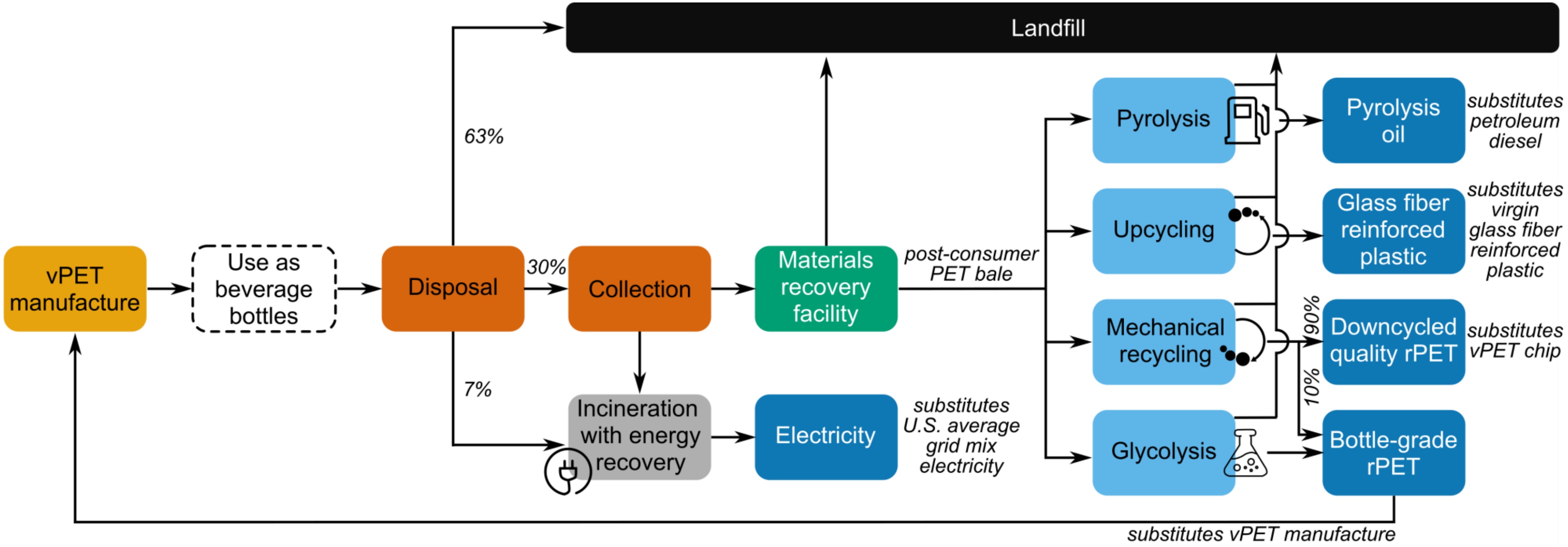
- Closed-loop recycling technologies are just one piece of the plastic landscape. How can we compare plastic-to-x options?
- Methodology:



T. Ghosh et al., *J. Clean. Prod.* **2023**, *383*, 135208.
T. Ghosh et al., in peer review, **2023**.

Assessed technologies

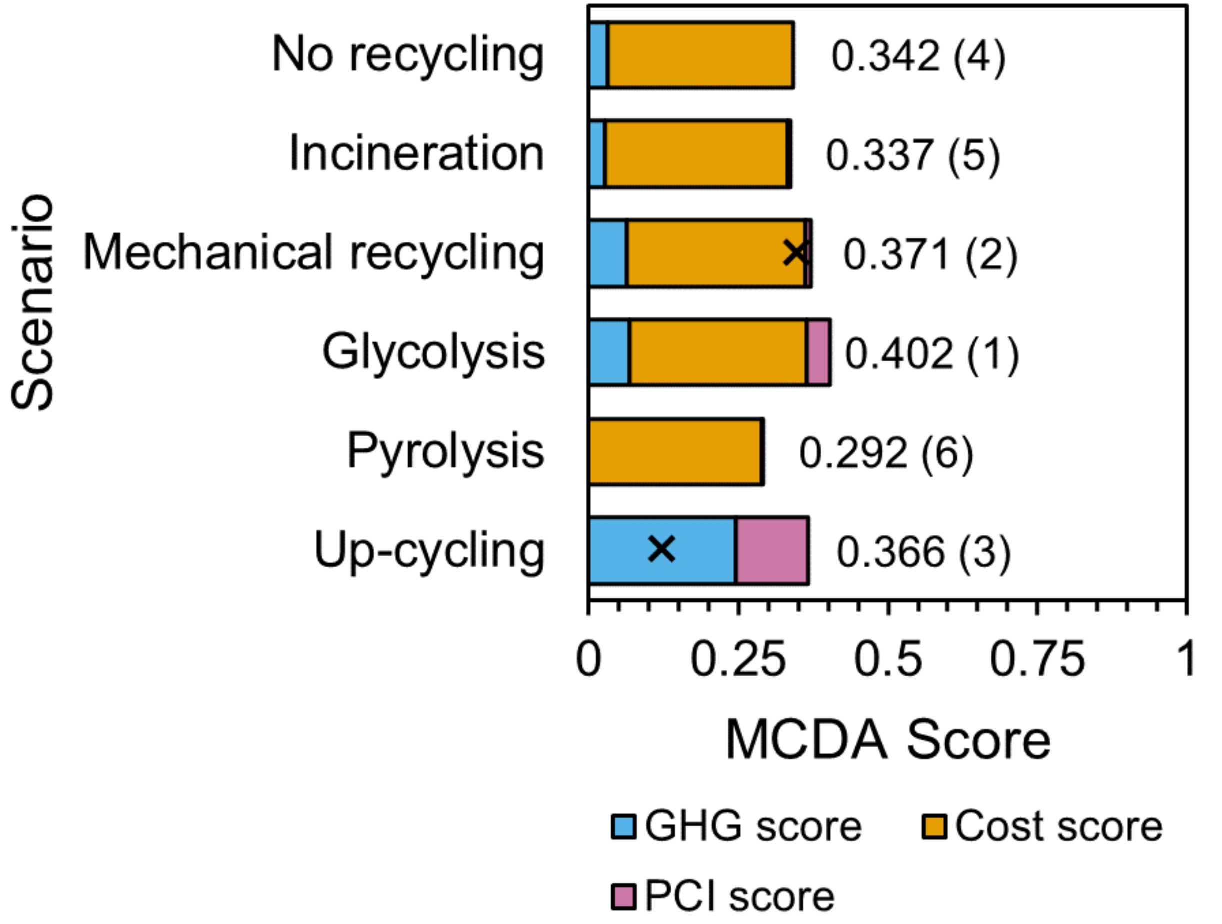
- Closed-loop recycling: glycolysis (best chemical recycling performance from previous work)
- Down-cycling: mechanical recycling to lower quality PET chip
- Up-cycling: chemical process + bio-based chemicals to make glass fiber reinforced plastic (GFRP)
- Energy recovery: incineration (electricity) or pyrolysis (fuel)



T. Ghosh et al., in peer review, **2023**.

Comparing open-loop recycling options

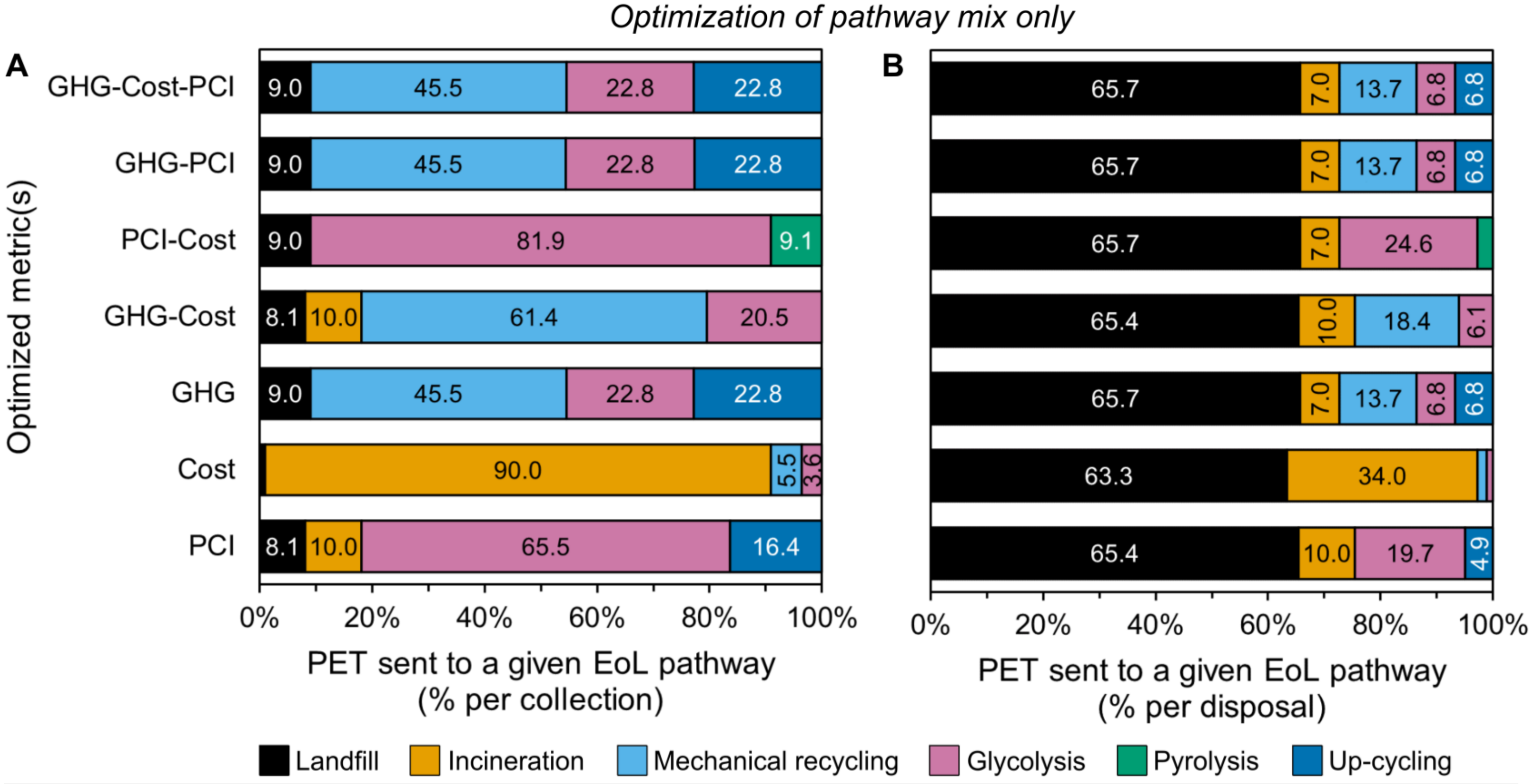
- Glycolysis offers most benefits overall, closely followed by mechanical recycling
- Upcycling to GFRP has lowest greenhouse gas (GHG) emissions & highest circularity, but highest cost
- No recycling (landfill) has lowest cost



T. Ghosh et al., in peer review, **2023**.

Optimal recycling combinations

- Brute force algorithm varies end-of-life pathway mix 1,000× to find local optimum that minimizes GHG emissions and cost and maximizes circularity.
- Mechanical recycling + glycolysis + up-cycling → reduce GHG emissions by 23%, increase costs by 52%, and increase circularity from 0 to 0.13 relative to landfilling.



T. Ghosh et al., in peer review, **2023**.

Summary

- Provided baseline costs, environmental impacts, and technical capabilities of closed-loop plastic recycling technologies
- Developed flexible framework for consistently comparing open-loop plastic technologies
- Showed a combination of mechanical recycling, glycolysis, and upcycling can reduce impacts (at the tradeoff of cost)

FOOD FOR THOUGHT

There is no “silver bullet” – we need combinations of technologies

Scale is important – how much recycled product do we actually need?

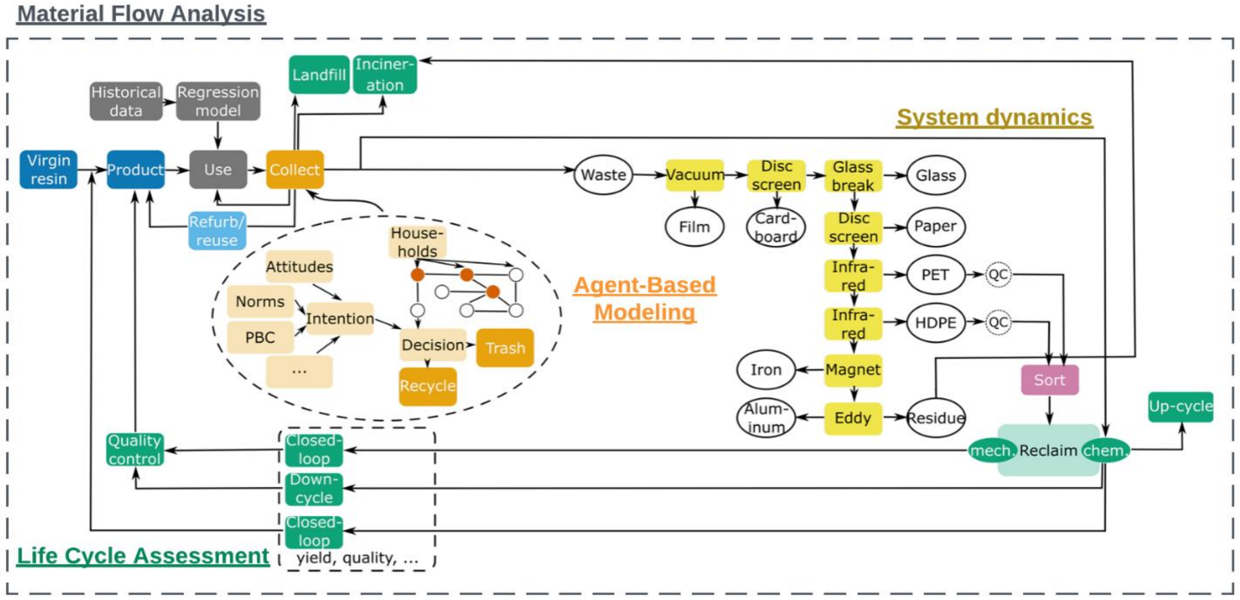
FUTURE WORK

Add more plastic types and other recyclabe materials to open-loop analysis.

Add composting pathway
Add reuse pathway
Add effects of plastic policies/targets.

Avoided impacts from higher PET waste collection

A



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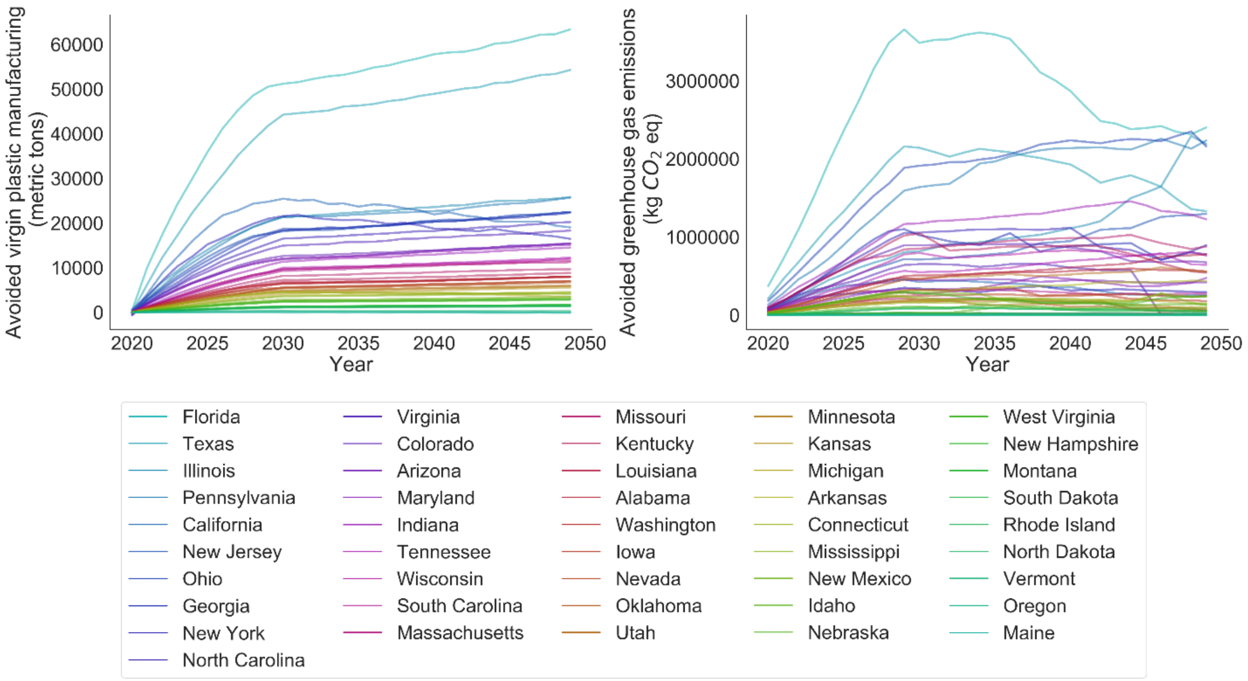

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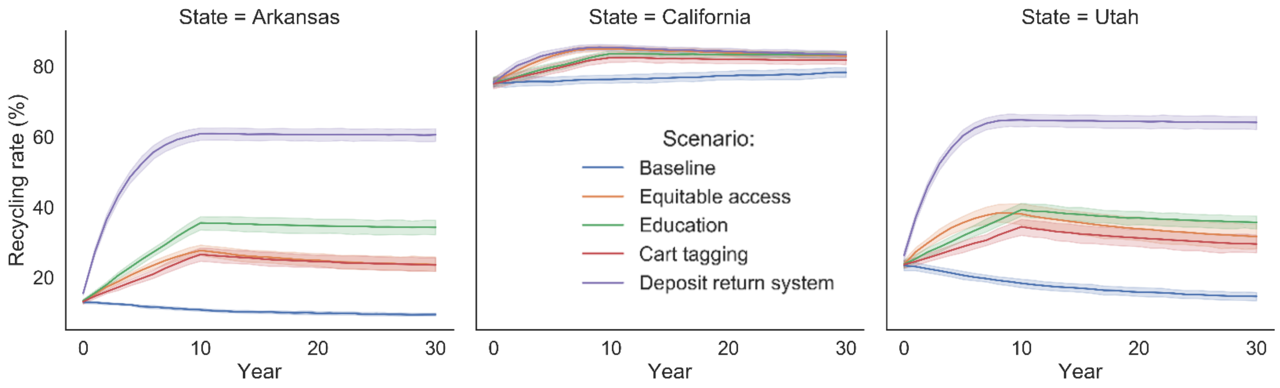

Walzberg, J., Sethuraman, S., Ghosh, T., Uekert, T., & Carpenter, A. (In review, Energy Research & Social Science).

A. Plastic Circular Economy Model (PCEM) combines MFA, SD, LCA, and ABM to model the plastic recycling system
B. Different behavioral interventions have different effects depending on the targeted population
C. The sooner the better: increased access to recycling programs avoids virgin plastic manufacturing and GHG emissions but as electricity decarbonizes, benefits lower

Summary

- Recycling behaviors are highly contextual making "one-size-fits-all" solutions sub-optimal
  - ABM is calibrated using Census Bureau and other data to fit reported PTE bottle state-specific recycling rates
  - Results show that known interventions affect populations differently depending on their characteristics
  - Results agree with the literature (the recycling partnership, resource recycling, OECD)

- Limitations:
  - Data had different geographical resolutions, some defined at the block group level, others at the state level, and some at the national scale
  - Behavioral interventions may affect households differently than what we assumed
  - Focusing on disposal behavior may miss how series of behaviors form intricate patterns: decisions and actions throughout the day may affect disposal behaviors

- Possible next steps:
  - Further investigate which interventions are the most effective (e.g., % additional recycling / $) in each state
  - Apply the model to a case study with a finer resolution (e.g., a single state at the county or census track level)
  - Apply the model to other containers and packaging materials
  - Collaborate with the recycling partnership on a case study (they provide data, we provide modeling capabilities)

17

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Questions?

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