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Towards a Circular Economy for PET bottles in the US – 4P model

International Symposium on Sustainable Systems and Technology
June 13, 2023

Journal of Cleaner Production
Volume 383, 10 January 2023, 135208

Towards a circular economy for PET bottle resin using a system dynamics inspired material flow model

Tapajyoti Ghosh, Greg Avery, Arpit Bhatt, Taylor Uekert, Julien Walzberg, Alberta Carpenter

Energy Research & Social Science
Volume 100, June 2023, 103116

Original research article

Think before you throw! An analysis of behavioral interventions targeting PET bottle recycling in the United States

Julien Walzberg [a], Sandhya Sethuraman [a], Tapajyoti Ghosh [a], Taylor Uekert [a], Alberta Carpenter [a b]

Accepted for publication in
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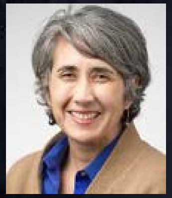
Comparing parallel plastic-to-x pathways and their role in a circular economy for PET bottles

Tapajyoti Ghosh, Taylor Uekert,* Julien Walzberg, and Alberta C. Carpenter*


Tapajyoti Ghosh


Taylor Uekert


Julien Walzberg


Alberta Carpenter

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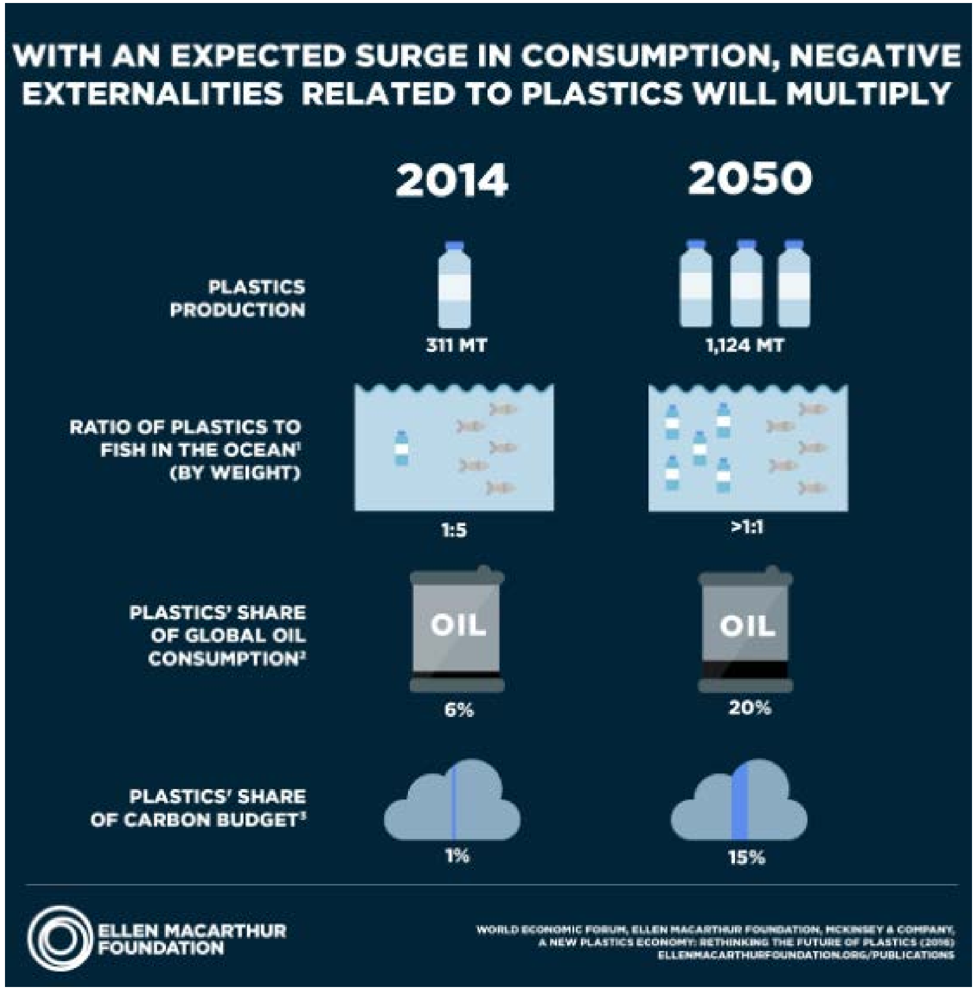
Motivation



5% of plastic waste in U.S. is recycled[1]

Data gaps:

- Technical capabilities, cost, environmental impact of recycling strategies
- Plastic waste collection – current status and how to improve
- What about other upcycling, downcycling, or even reuse strategies? How can we compare and pick the best?

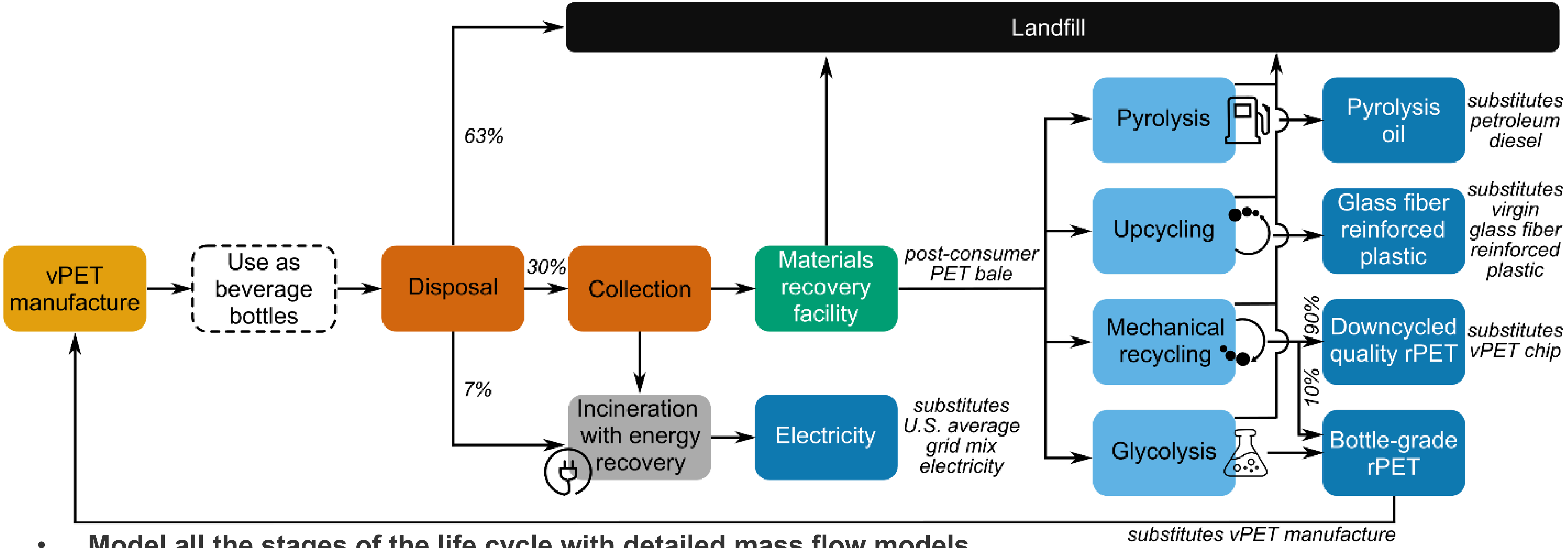
[1] Milbrandt et al., *Resour. Conserv. Recycl.*, 2022

Objectives

Develop a framework capable of quantitatively comparing the plastic end-of-life strategies that generate different products.

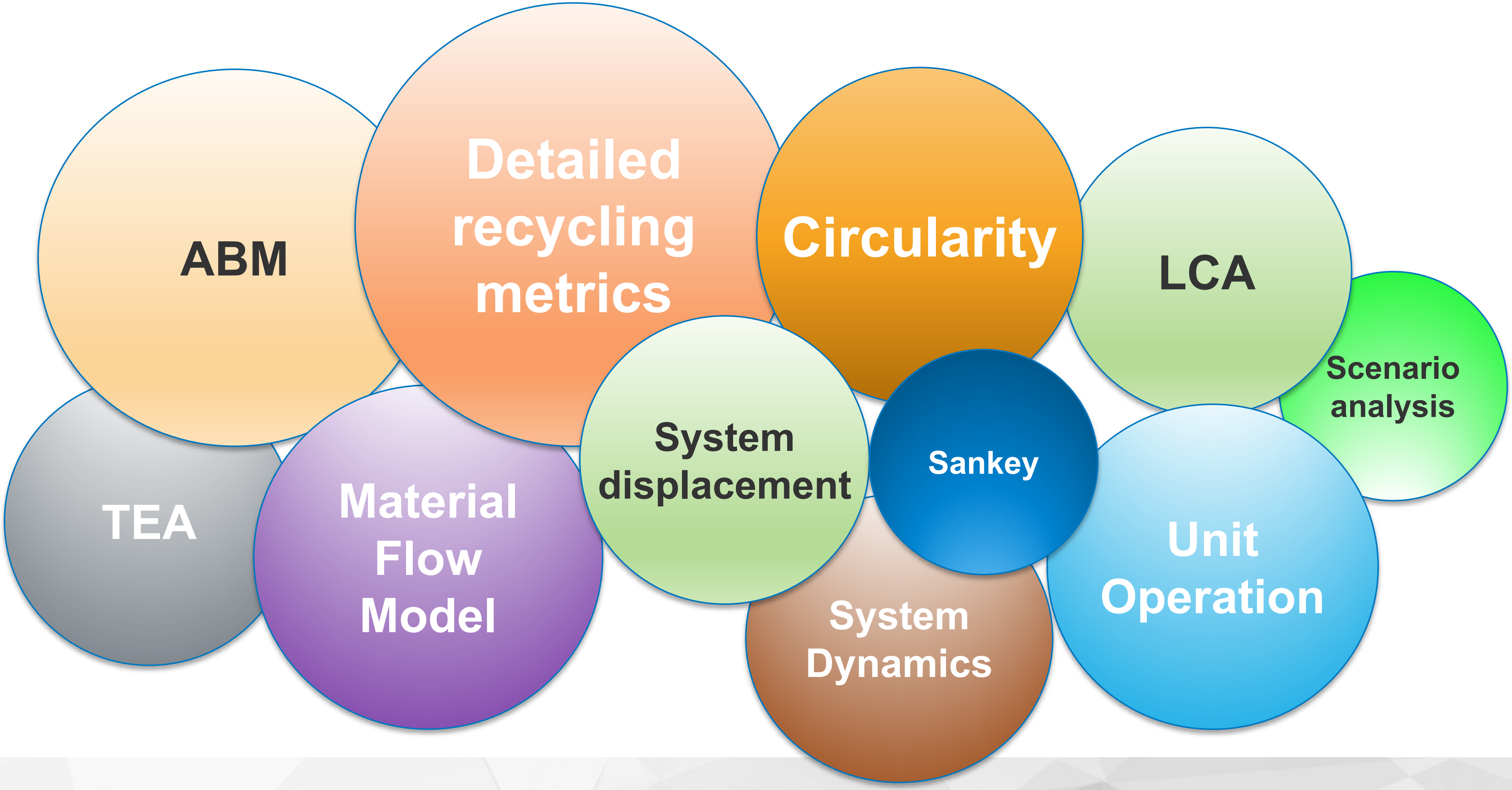
- Tracking the flow of plastics in the economy within single and multiple life cycles.
- Implementing metrics for measuring circularity for complex systems.
- Process-based life cycle assessment to compare circular solutions' environmental impacts
- Techno-economic analysis of end-of-life pathways.

Plastic Parallel Pathways Platform– 4P Model



- Model all the stages of the life cycle with detailed mass flow models.
- Model of the constraints mathematically.
- Model substitution of virgin with recycled resin, electricity from incineration, diesel fuel and reinforced polymer resin.
- Model novel recycling pathways
- Improve regional resolution
- Calculate circularity and LCA indicators

Plastic Parallel Pathways Platform – a systems analysis tool for plastics end-of-life management



Plastic Circularity Index

Linear Flow Index

The Linear Flow Index (LFI) measures the proportion of material flowing in a linear fashion, sourced from virgin materials and ending up as unrecoverable waste.

$$\text{LFI} = \frac{\text{Linear flow}}{\text{Total Flow}}$$

Utility Factor

A utility factor (*X*) is incorporated, which considers both the product lifetime (*L*) and product utility, or the extent to which a product is used to its full capacity (*U*)

$$X = \left(\frac{L}{L_{av}}\right)\left(\frac{U}{U_{av}}\right)$$

Where L_{av} is the industry average product lifetime and U_{av} is the industry average product utility.

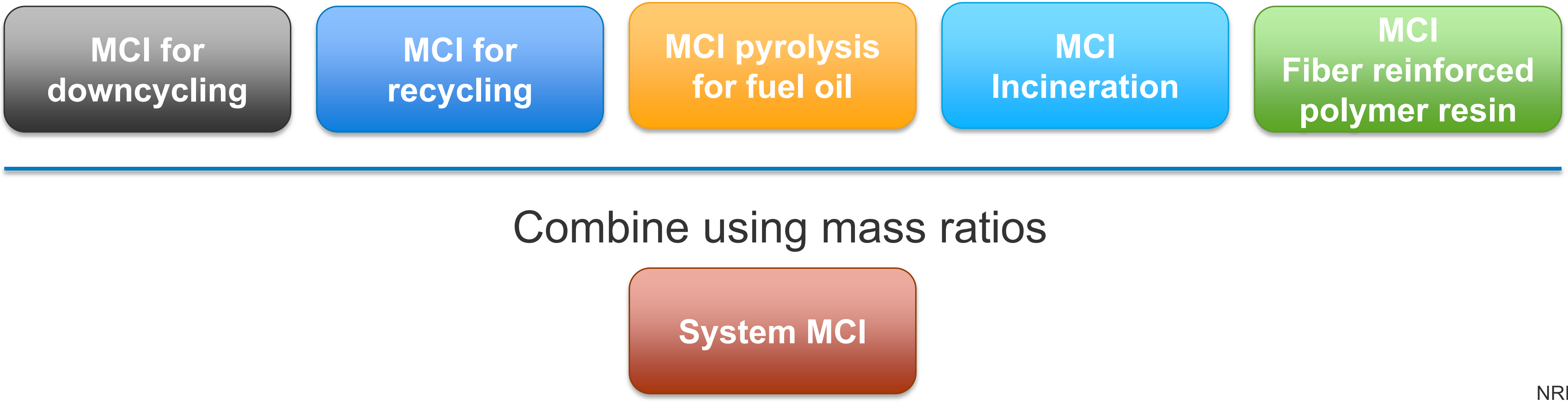
https://ellenmacarthurfoundation.org/material-circularity-indicator

Plastic Circularity Index

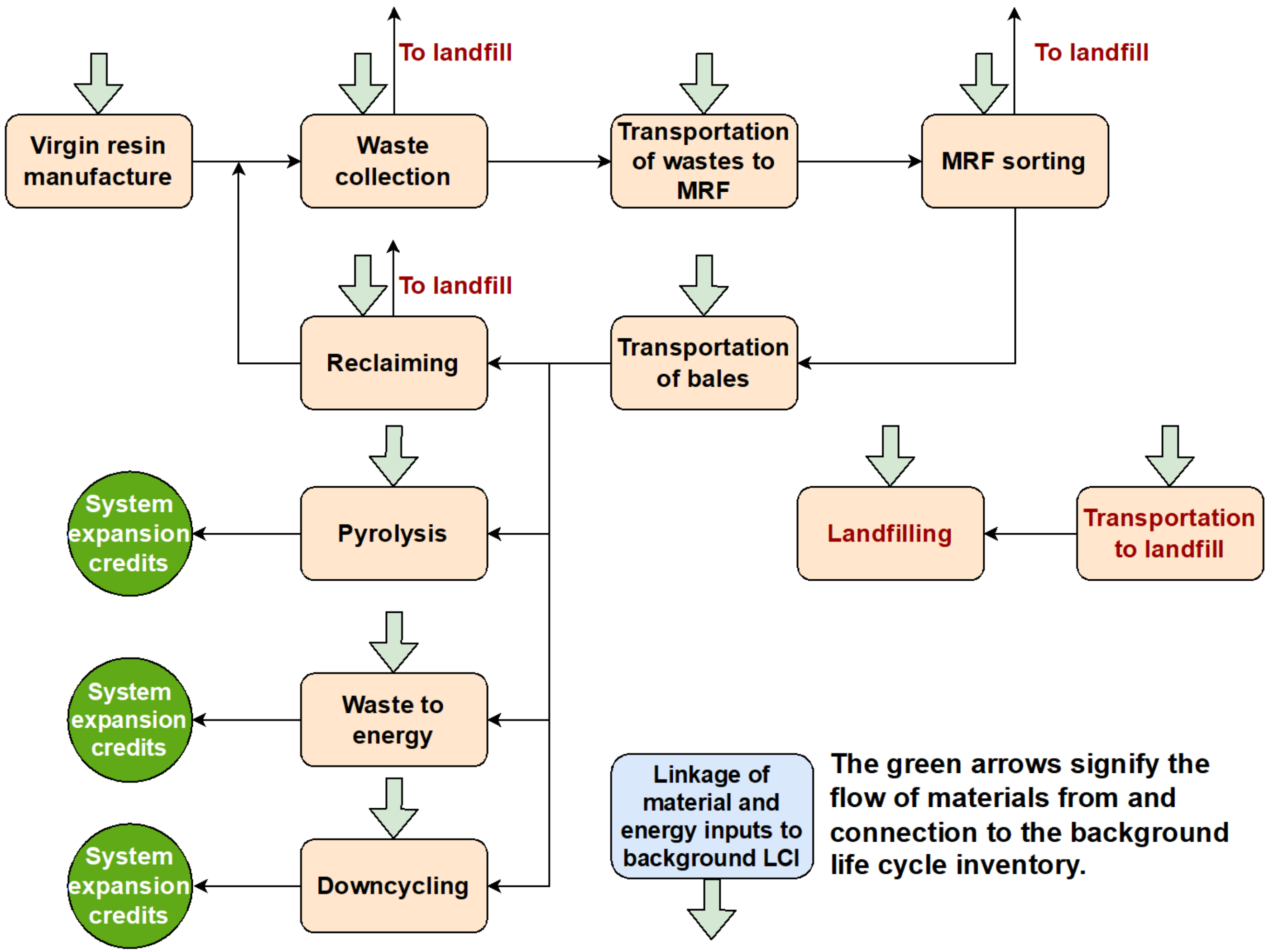
Plastic Circularity Index is defined by considering the Linear Flow Index of the product and a factor F(X), built as a function of utility X. The product's utility is captured using the X.

$$\text{PCI} = 1 - \left(LFI \times \left(\frac{0.9}{X} \right) \right)$$

PCI is calculated for the entire system for every time step in the model.



Life Cycle Assessment



- **PyLCIA* – Python based Rapid LCA (Prospective LCA performing 1000s of calculations with evolving inventory – background as well as foreground changes with time)**
- **Foreground system – Activities in the material flow model**
- **Background system – US life cycle inventory[1]**
- **Electricity provider – ReEDS[2] dynamic grid mix utilized for foreground system electricity consumption**
- **TRACI 2.1[3] LCIA methodology adopted**

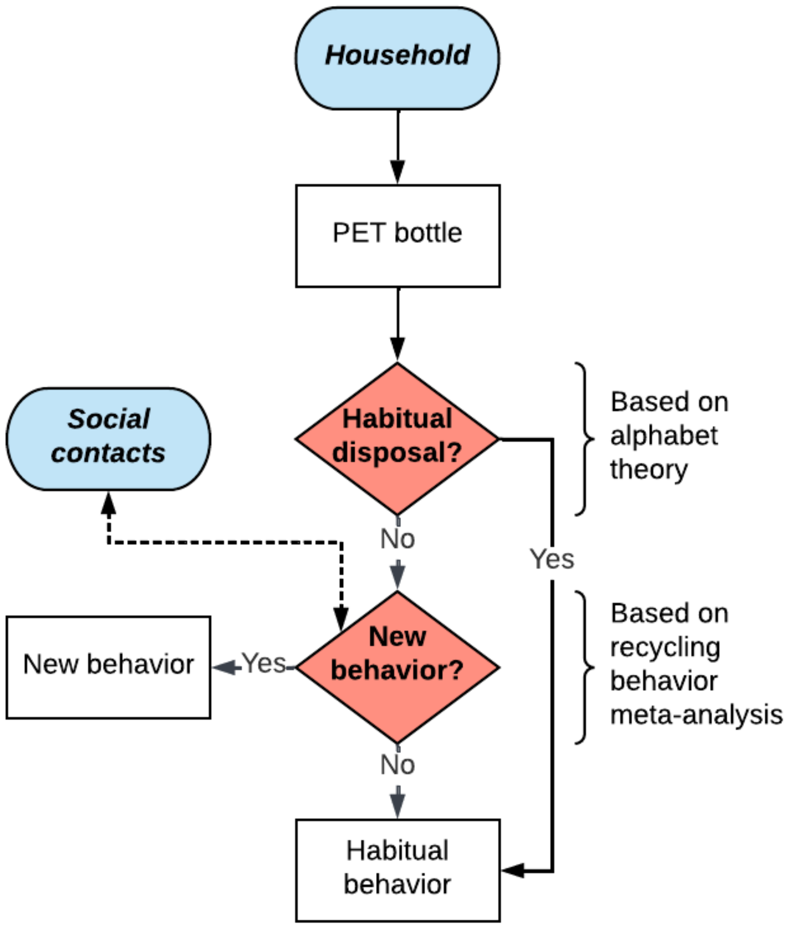
* Ghosh, Tapajyoti, et al. "Towards a circular economy for PET bottle resin using a system dynamics inspired material flow model." *Journal of Cleaner Production* 383 (2023): 135208.
1. "U.S. Life Cycle Inventory Database." (2012). National Renewable Energy Laboratory, 2012. Accessed November 19, 2012: https://www.lcacommons.gov/nrel/search
2. https://www.nrel.gov/analysis/reeds/ 3. https://www.epa.gov/chemical-research/tool-reduction-and-assessment-chemicals-and-other-environmental-impacts-traci

Waste collection stage

Agent-based modelling (ABM)

ABM models human behaviors

- **Objective:** model household recycling behaviors under different intervention scenarios (e.g., increased access to curbside recycling programs or car-tagging campaigns)
- **Scope**: trash, recycling, and "wish-cycling" of PET with up to Census Block Group geographic resolution
- **Methodology**: Model the habitual nature of disposal behaviors and agents have a chance to “ponder” their action based on factors from a meta-analysis on recycling behavior



Decision tree representing agents’ behavioral rules

Other end-of-life pathways

- Chemical recycling via glycolysis
- Pyrolysis to produce plastic pyrolysis oil
- Upcycling to produce resin for reinforced polymer
- Incineration to produce electricity

Model:
Linear models with ***parameters*** for conversion, recovery and loss

Parameters and Scenario

- Landfill diversion
- Waste incineration diversion
- Mechanical recycling diversion
- Chemical recycling diversion
- Chemical upcycling diversion
- Pyrolysis diversion
- Polyester diversion
- Recovery mechanical recycling
- Recovery chemical recycling
- Material recovery facility equipment efficiency
- Collection rate variables / ABM
- Selectivity of recycled PET

Scenarios can be created by adjusting the parameters using the data driven framework. Scenario creation is easy and once built can be saved for future use. Scenarios can be be created both by changing parameters per scenario as well as with time (yearly) for a single scenario.

Case Study– PET Bottles

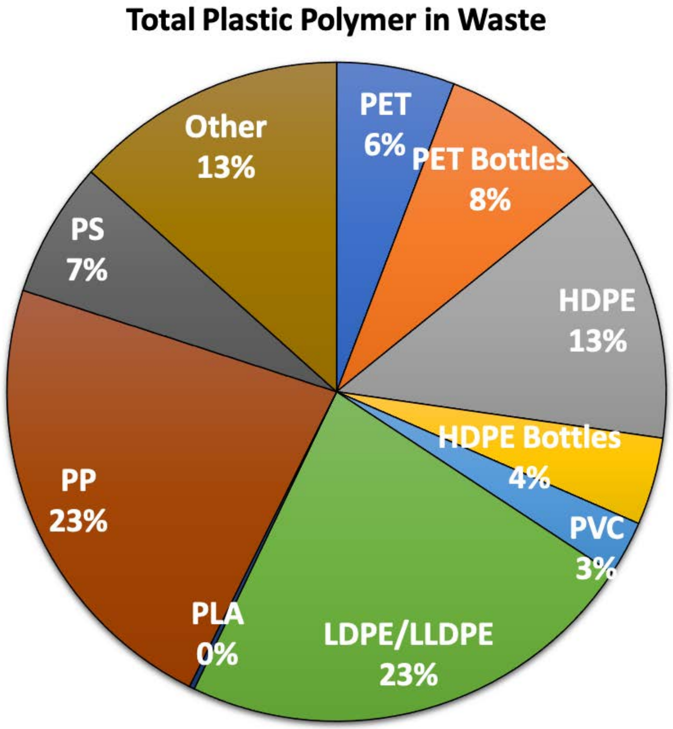
Polymer
- PET
- HDPE

Type
- Durable
- Non-Durable
- Containers & Packaging

Product
- Bottles
- Bags
- Films

The framework is capable of handling only one resin and one product at a time.

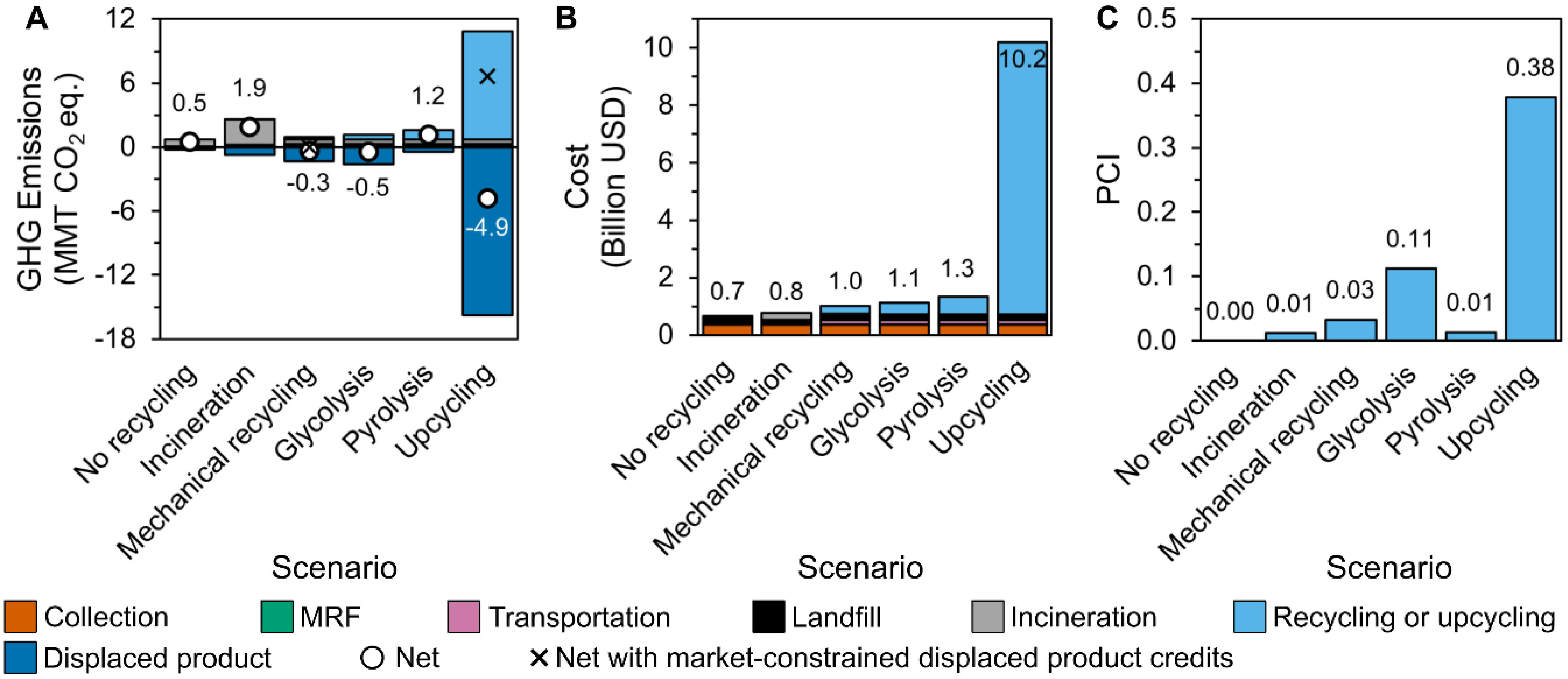
End of life processing is dependent on resin as well as the product produced from it.



	Calendar Year 2017			Calendar Year 2018		
Plastic Bottle Type	Plastic Recycled [2]	Resin Sales [3,4]	Recycling Rate	Plastic Recycled [2]	Resin Sales [3,4]	Recycling Rate
PET [4]	1726	5913	29.2%	1813	6270	28.9%
HDPE Natural	473.8	1541	30.7%	430.8	1500	28.7%
HDPE Pigmented	568.0	1806	31.4%	575.7	1815	31.7%
Total HDPE Bottles	1042	3347	31.1%	1006.4	3315	30.4%
PVC [5]	0.8	32	2.5%	0.5	32	1.7%
LDPE [5]	0.7	70	1.0%	0.8	70	1.2%
PP [6]	31.1	181	17.2%	30.6	180	17.0%
Other [7]	5.3			3.5		
TOTAL BOTTLES	2800	9543	29.3%	2852	9867	28.9%

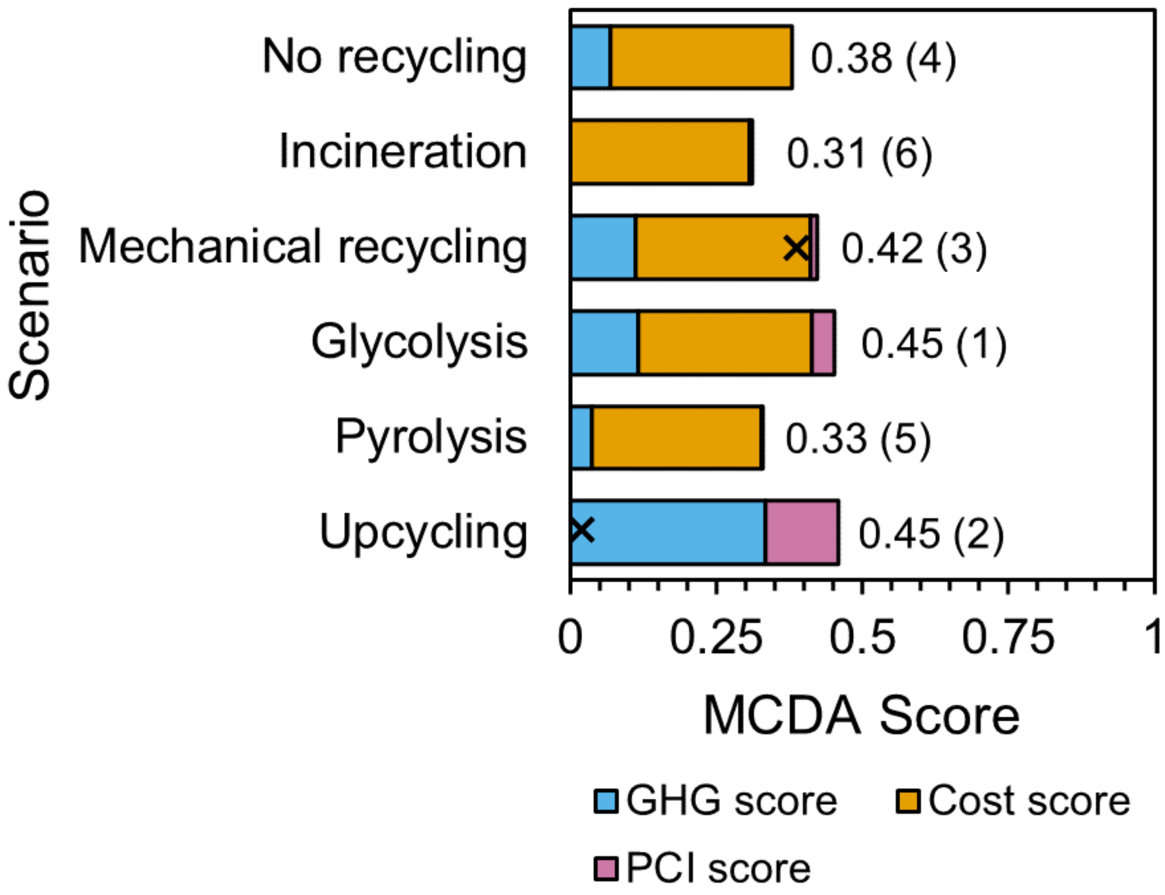
https://plasticsrecycling.org/images/library/2017-postconsumer-bottle-recycling-report.pdf

Comparison of Scenarios



Comparison of the (A) GHG emissions, (B) cost, and (C) PCI if all PET bottles collected for recycling in the U.S in 2020 were used to produce lower-quality PET resin by mechanical recycling, food-grade PET resin by glycolysis, electricity from incineration, fuel oil from pyrolysis, or fiber-reinforced resin by upcycling.

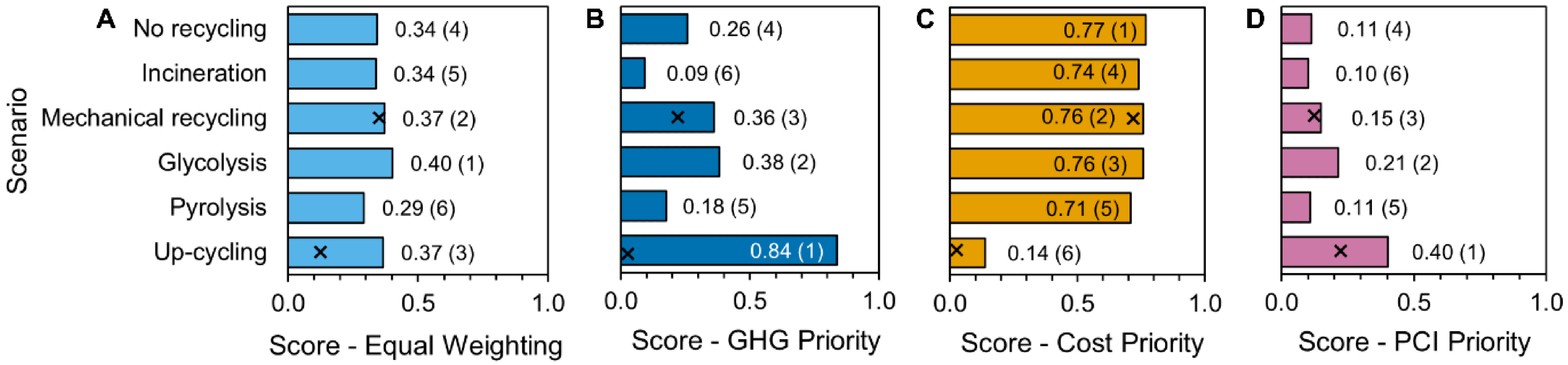
Multi Criteria Decision Analysis



The black x's indicate MCDA scores for mechanical recycling and upcycling when GHG emission displacement credits are capped at the market demand for PET chip and GFRP, respectively

- The EoL pathways with the best balance of all metrics – glycolysis and mechanical recycling – therefore emerge as the most favorable.
- The close scores across most scenarios could indicate that there is no "best" technology under the assessed criteria.
- Furthermore, the uncertainty of such MCDA estimates is high.

Multi Criteria Decision Analysis



Providing weights to the values of GHG impacts, Cost and Plastic Circular Index and combining them to provide final scores for decision making.

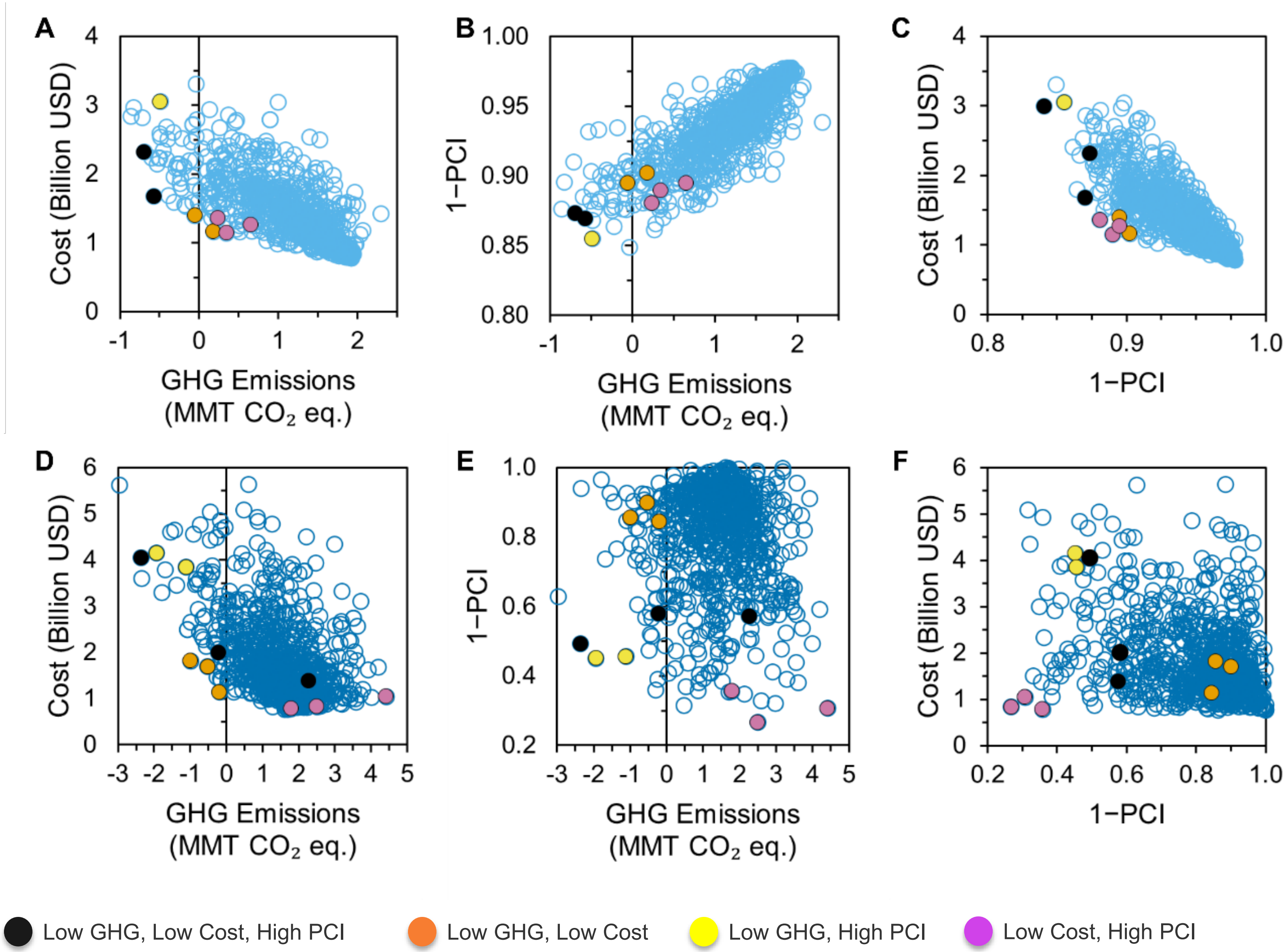
Equal weightage – Upcycling
GHG weightage – Upcycling

Cost weightage - Glycolysis
MCI weightage - Upcycling

Uncertainty Quantification

- 4P can also design systems while accounting for uncertainty in the system parameters.
- Upper and lower bounds are provided for the parameters.
- A triangular distribution is assumed for each of these parameters as there is insufficient data to predict a more accurate probability distribution function.
- For each run of 4P, a sample is randomly drawn from the distribution for the parameters as well as from the uniform distribution of design variables.
- Uncertainties of system parameters only.

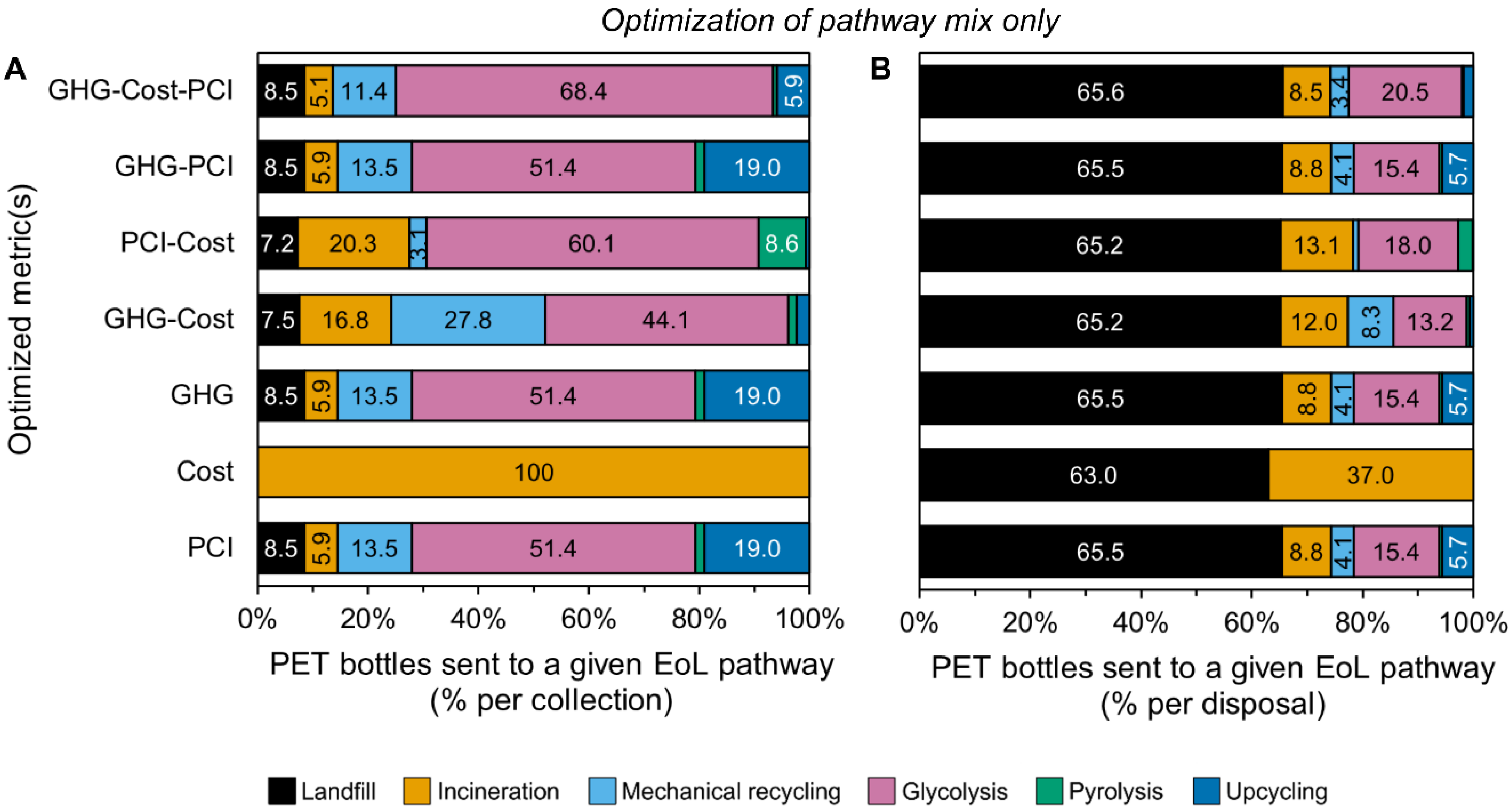
Brute force optimization for exploration of pathways



Exploration of EoL pathway mix only

Exploration of EoL pathway mix while accounting for parameter uncertainties

Design of end-of-life pathways via optimization under different goal-based metrics



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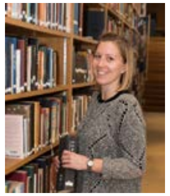
Thank You

www.nrel.gov

tghosh@nrel.gov


Tapajyoti Ghosh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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 Advanced manufacturing office Department of Energy. 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/PR-6A20-86553

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