The 2nd RD20 Summer School 2024

Diversity of Knowledge on Decarbonization in Just Energy Transition Mechanism

Waste Management, Circular Economy and Life Cycle Assessment

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Current Global Landscape

Figure 8: Regional distribution of municipal solid waste destinations (2020).

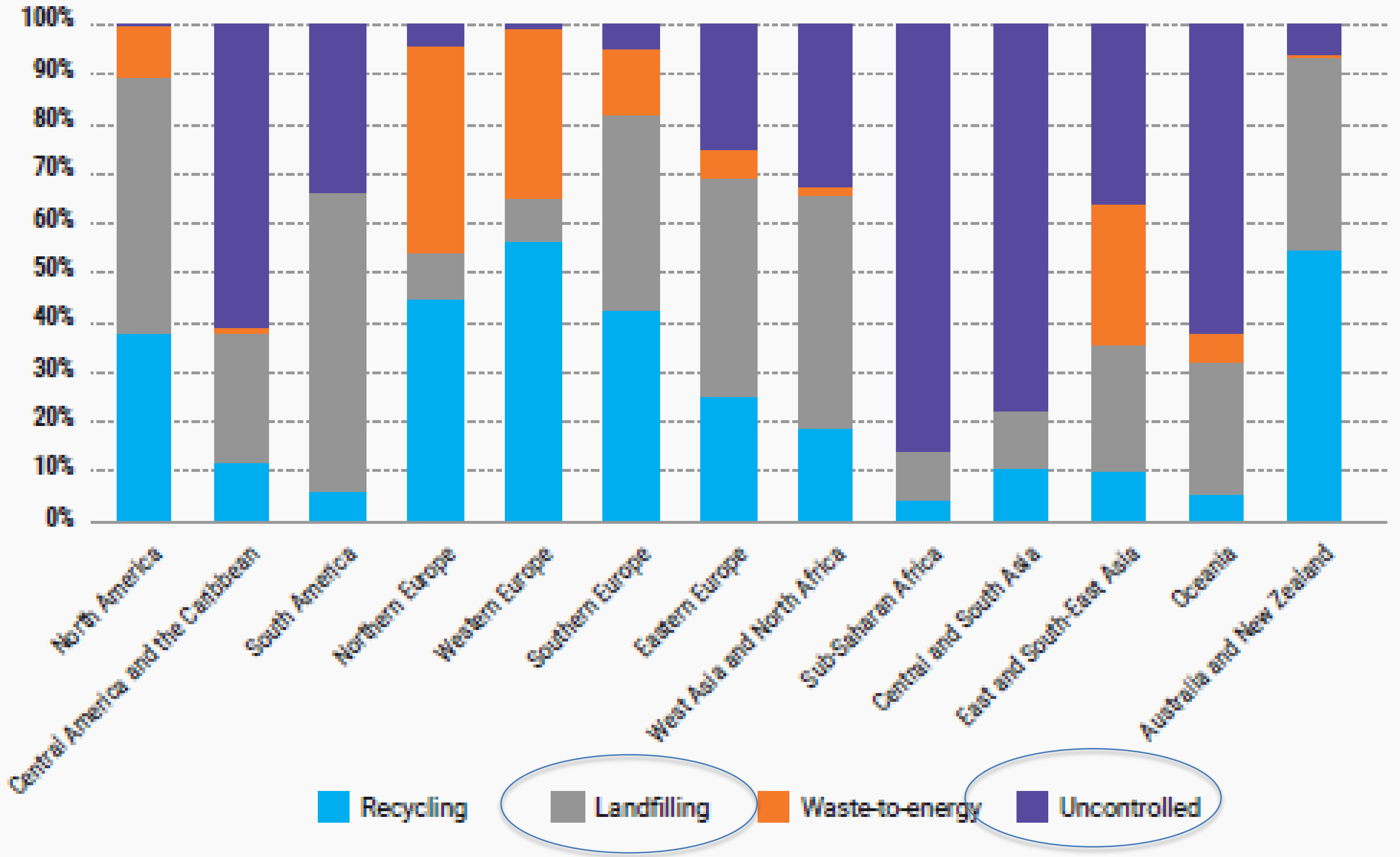
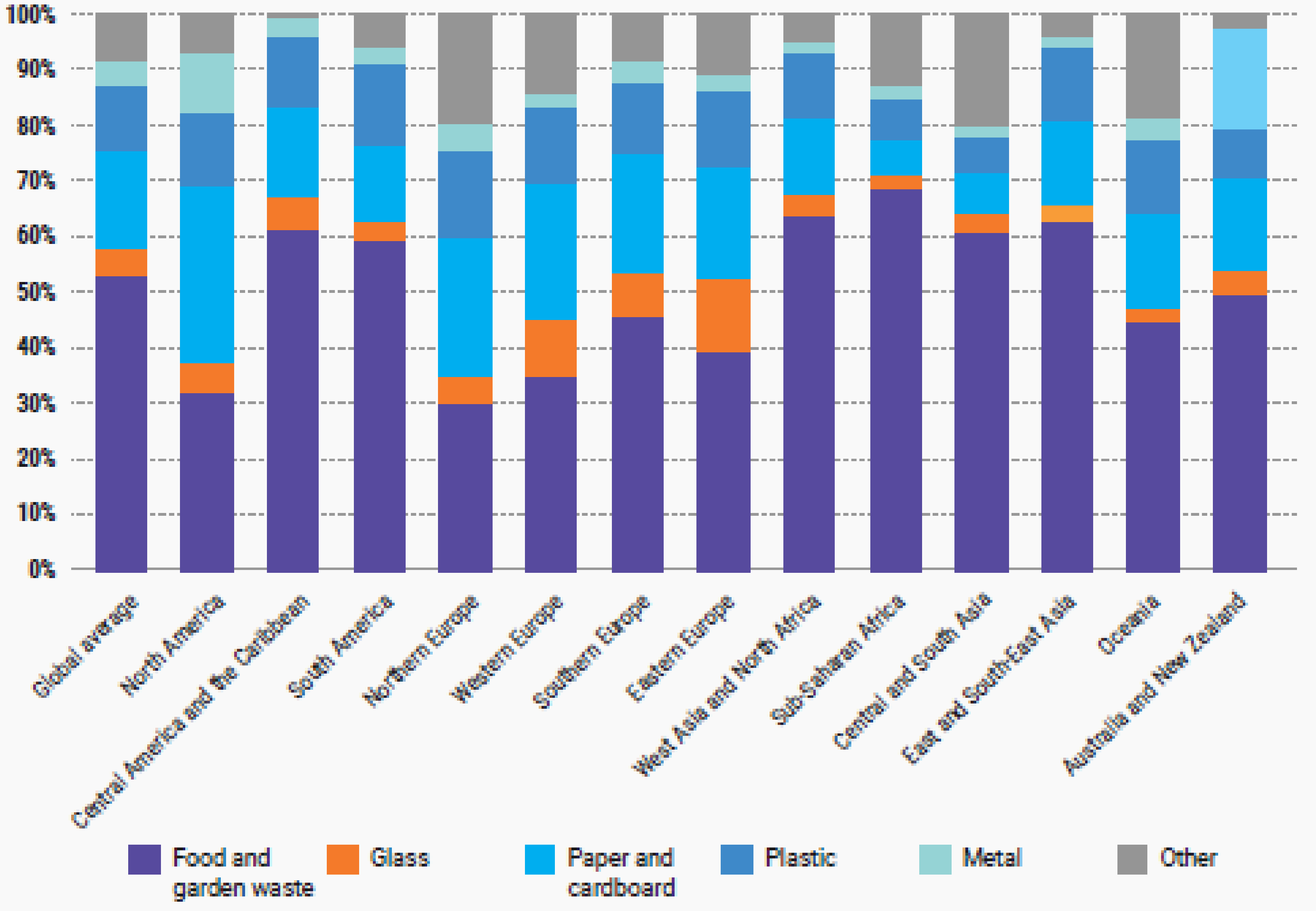


Figure 6: Global average and regional breakdown of municipal solid waste composition.
"Other" includes items such as textiles, wood, rubber, leather and household and personal hygiene products.



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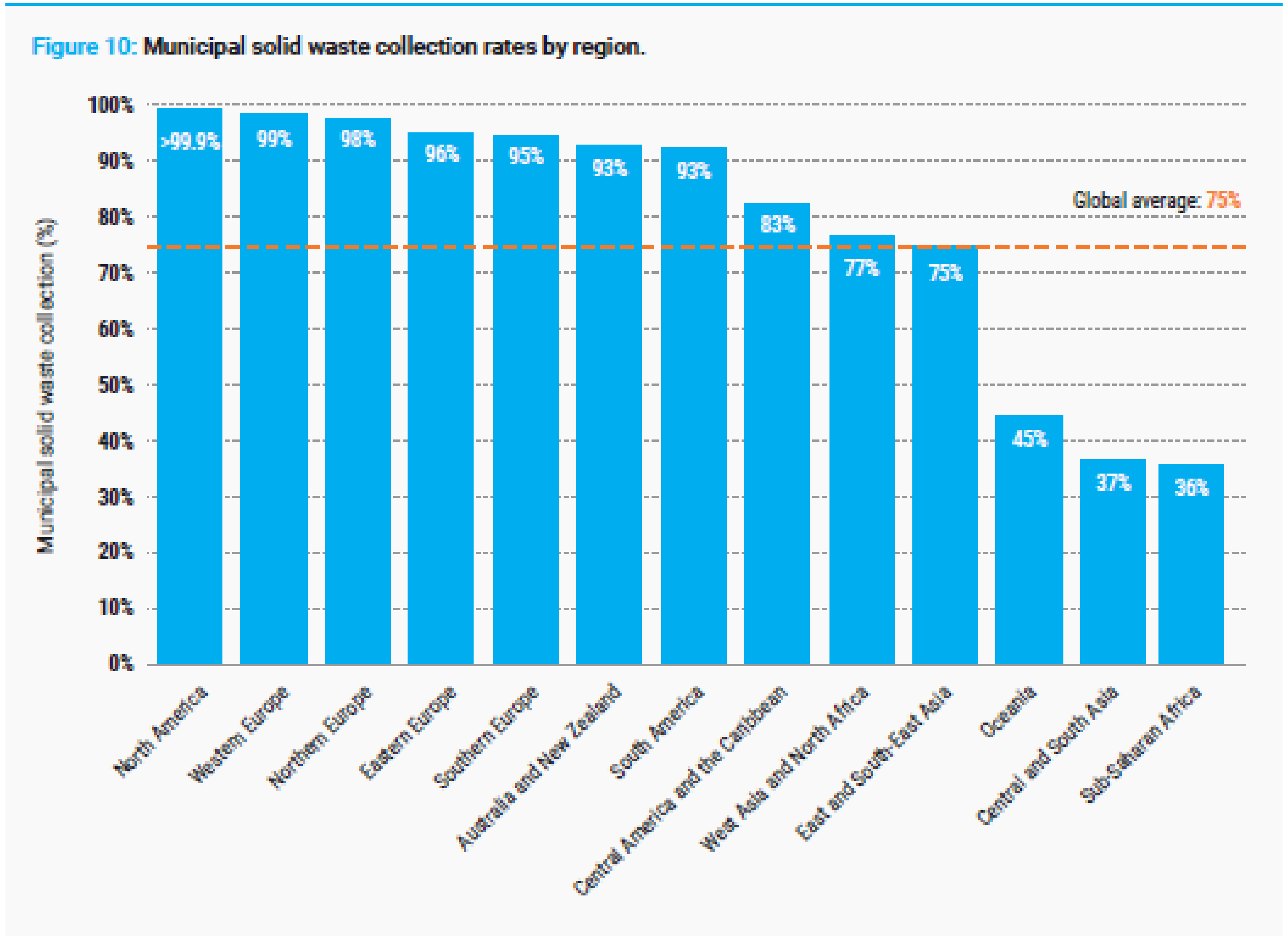
Waste Collection



Note: Collection rates are calculated as the total amount of municipal solid waste (MSW) collected divided by the total amount of MSW generated. Regional averages (weighted by tonnes of MSW) are based on data from those countries for which data is available.

Without a waste collection system, the uncontrolled waste problem cannot be mitigated and solved, and a recycling/recovery system cannot be implemented

Some **2.7 billion** people do not have their waste collected.

UNEP Global Waste Management Outlook 2024

End-of-life pathway systems exist for recycling and waste-to-energy, but are not perfect nor implemented effectively everywhere

Figure 11: Municipal solid waste recycled (million tonnes) and recycling rates by region (2020).

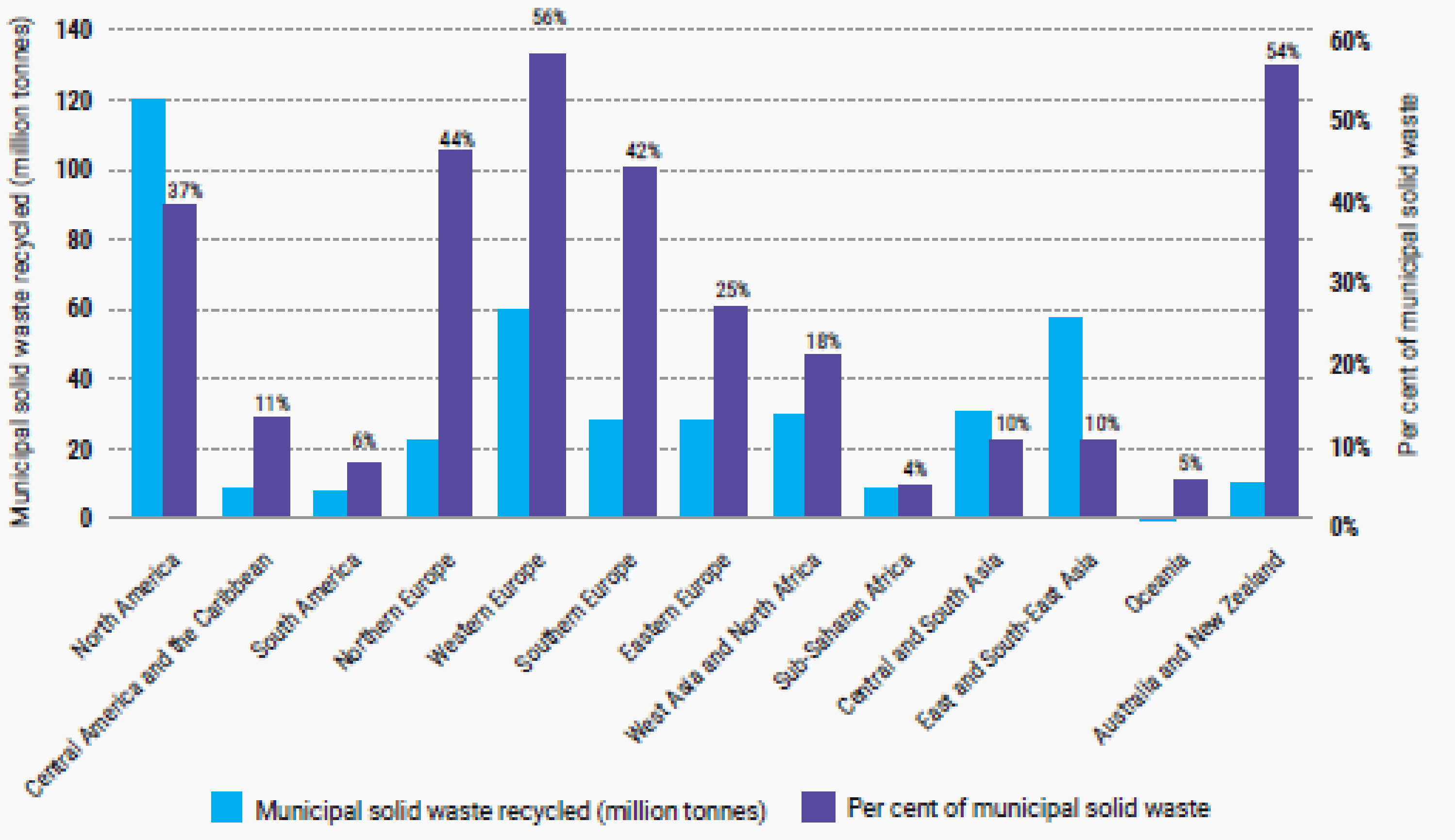
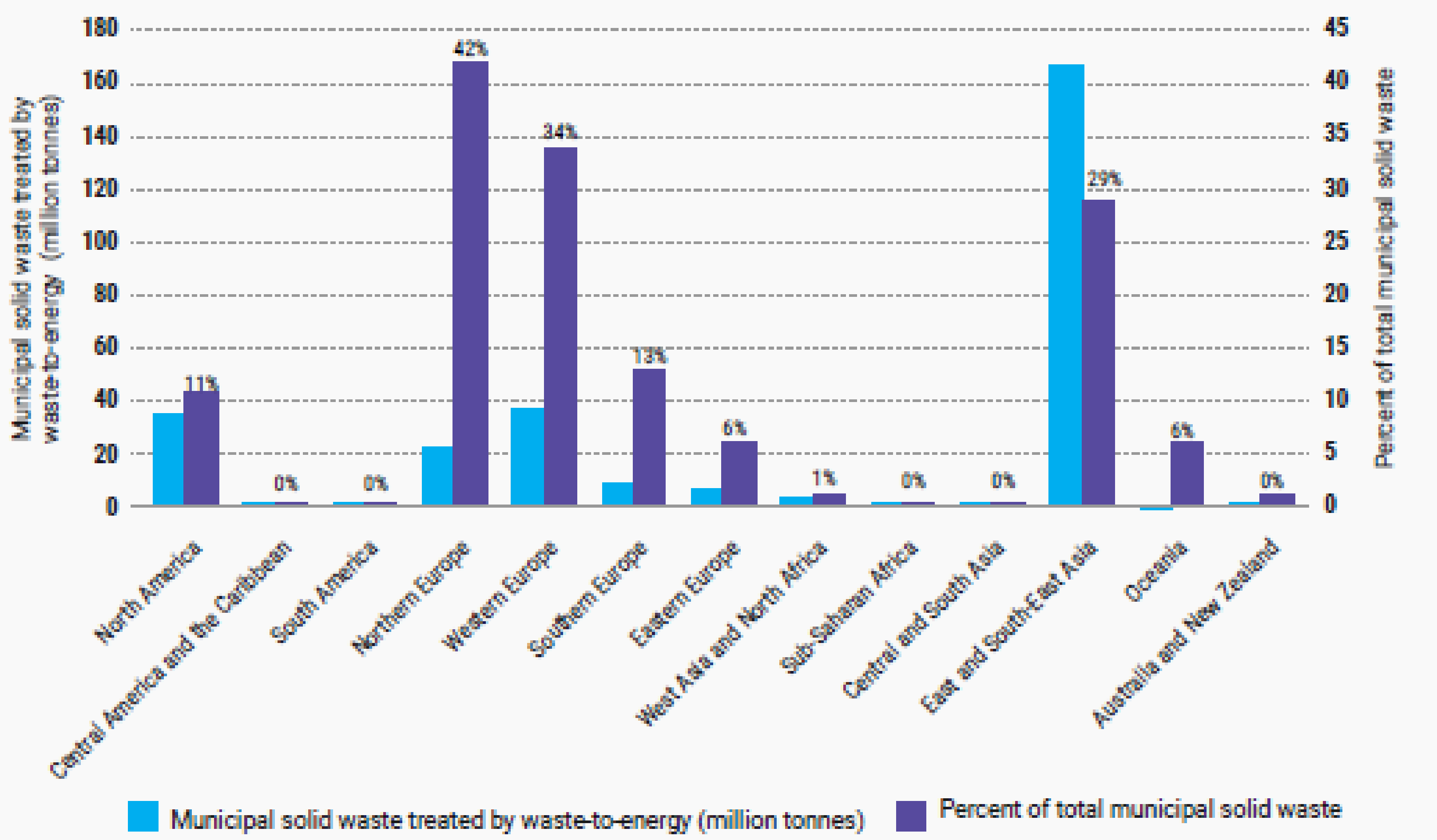


Figure 12: Municipal solid waste treated by waste-to-energy plants (million tonnes) and percentage of total municipal solid waste treated by waste-to-energy, across regions.



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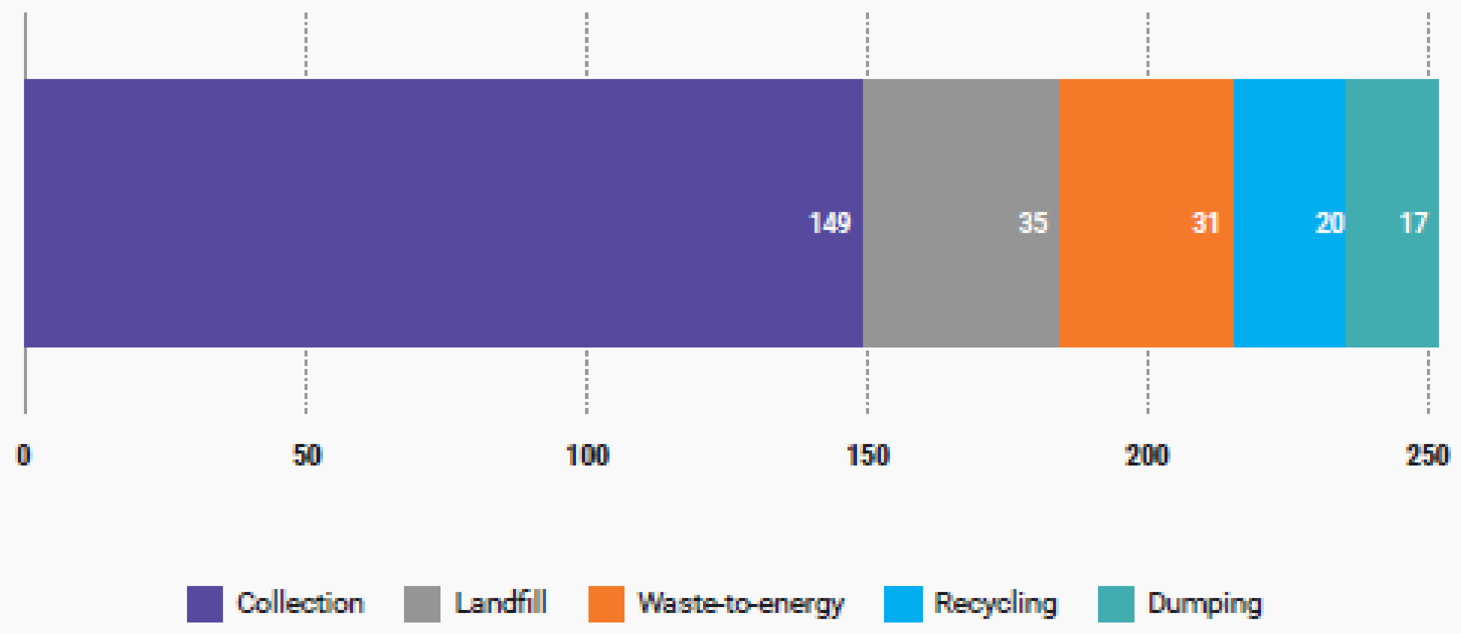
Costs can be prohibitive, but cost of not managing can be just as high,

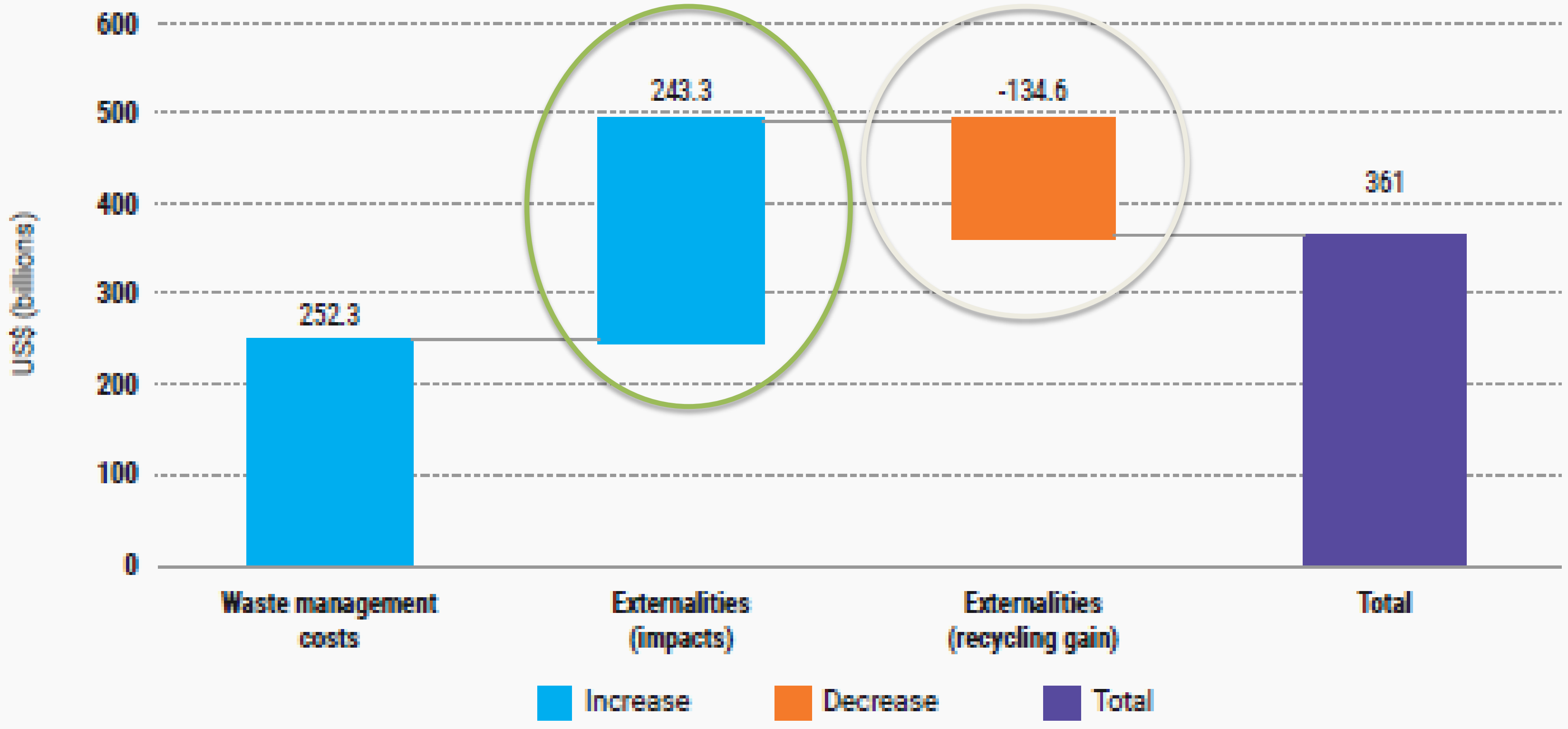
and benefits from management are not realized.

Figure 15: Estimated direct costs of municipal solid waste management globally in 2020.



Note: These costs take into account the regional averages of costs for each step in the waste management chain, estimated by the World Bank (Kaza et al. 2018) and updated to 2020 with consideration given to inflation and currency changes (US$ 2020).

Figure 16: Direct costs, externalities and total overall costs of municipal solid waste and its management (2020) (US$ 2020).



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Impact of Potential Municipal Solid Waste (MSW) Futures

- If we can reduce the quantity of MSW generated
- We can also reduce GHG emissions, biodiversity loss and human health impacts.

Figure 20: Comparative analysis of the three scenarios for global municipal solid waste generation.

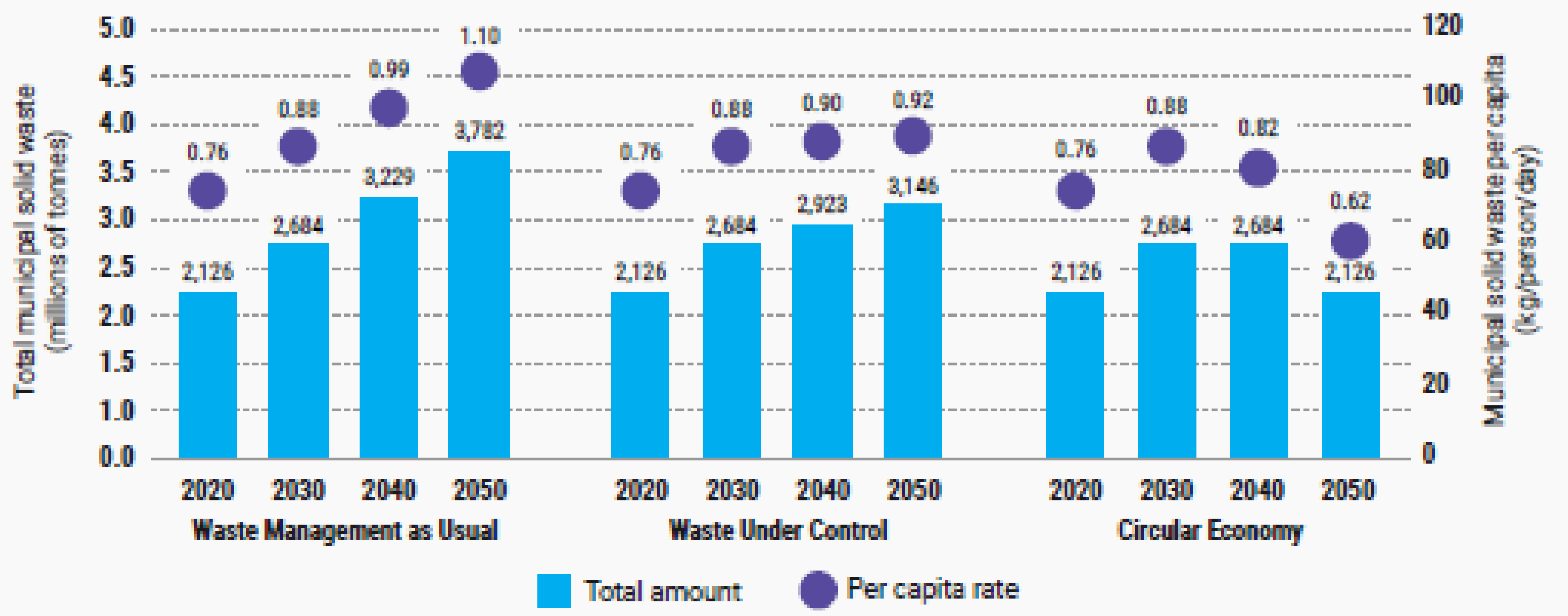


Figure 21: Estimated negative impact on greenhouse g

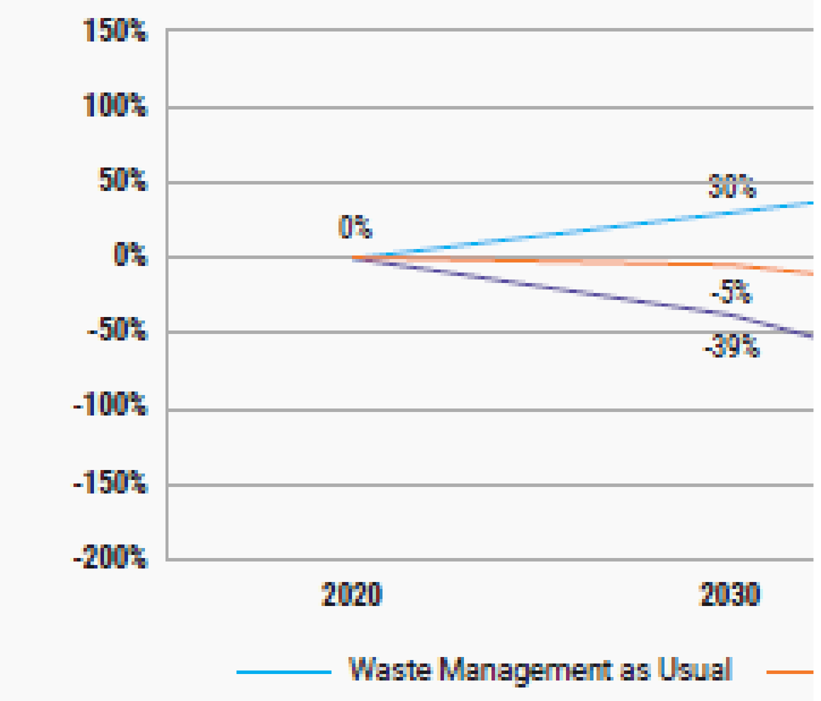


Figure 22: Estimated negative impact on potential loss of

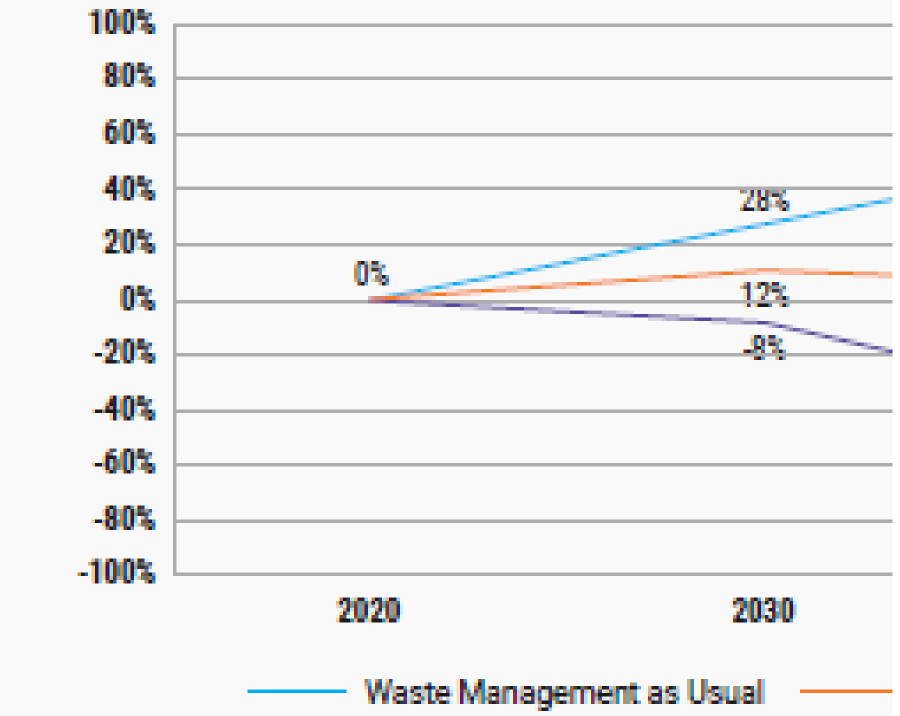
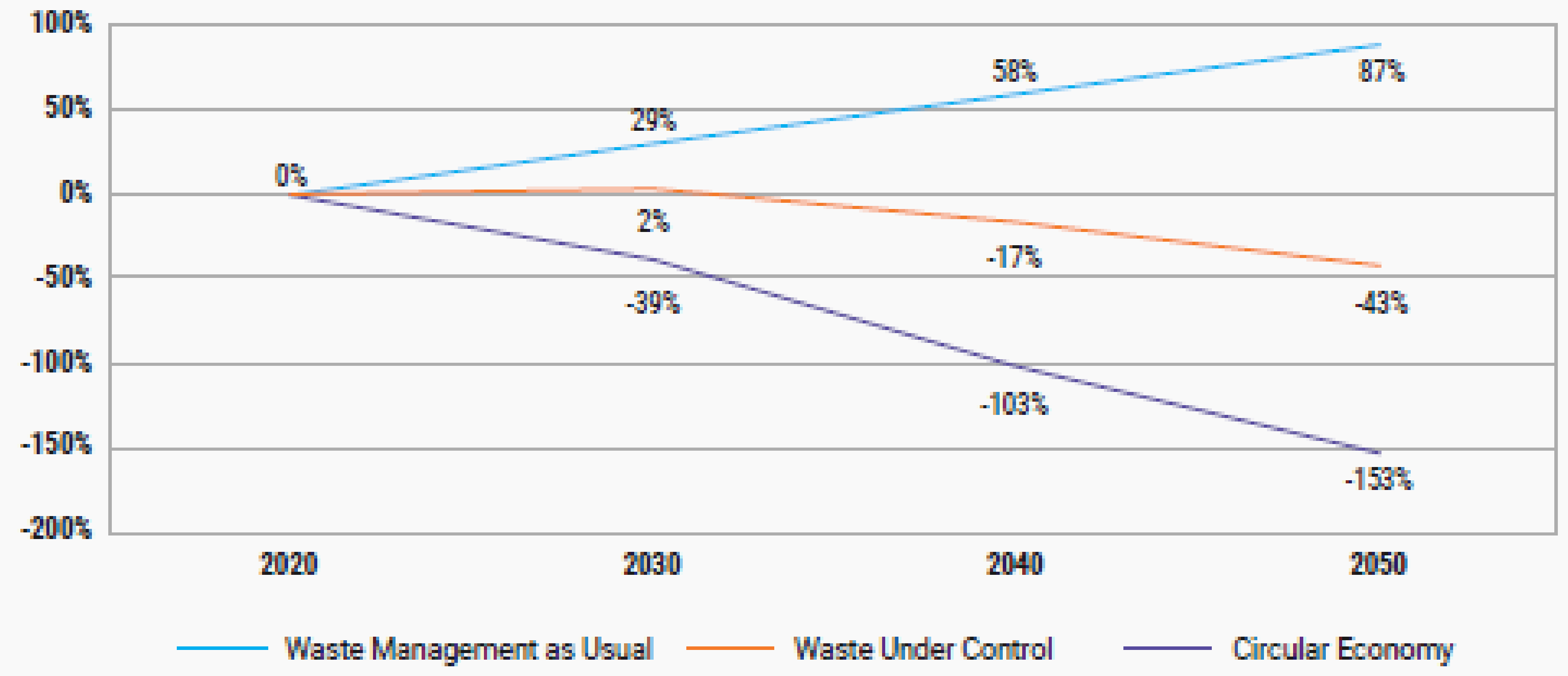


Figure 23: Estimated negative impact on human health from waste relative to 2020.



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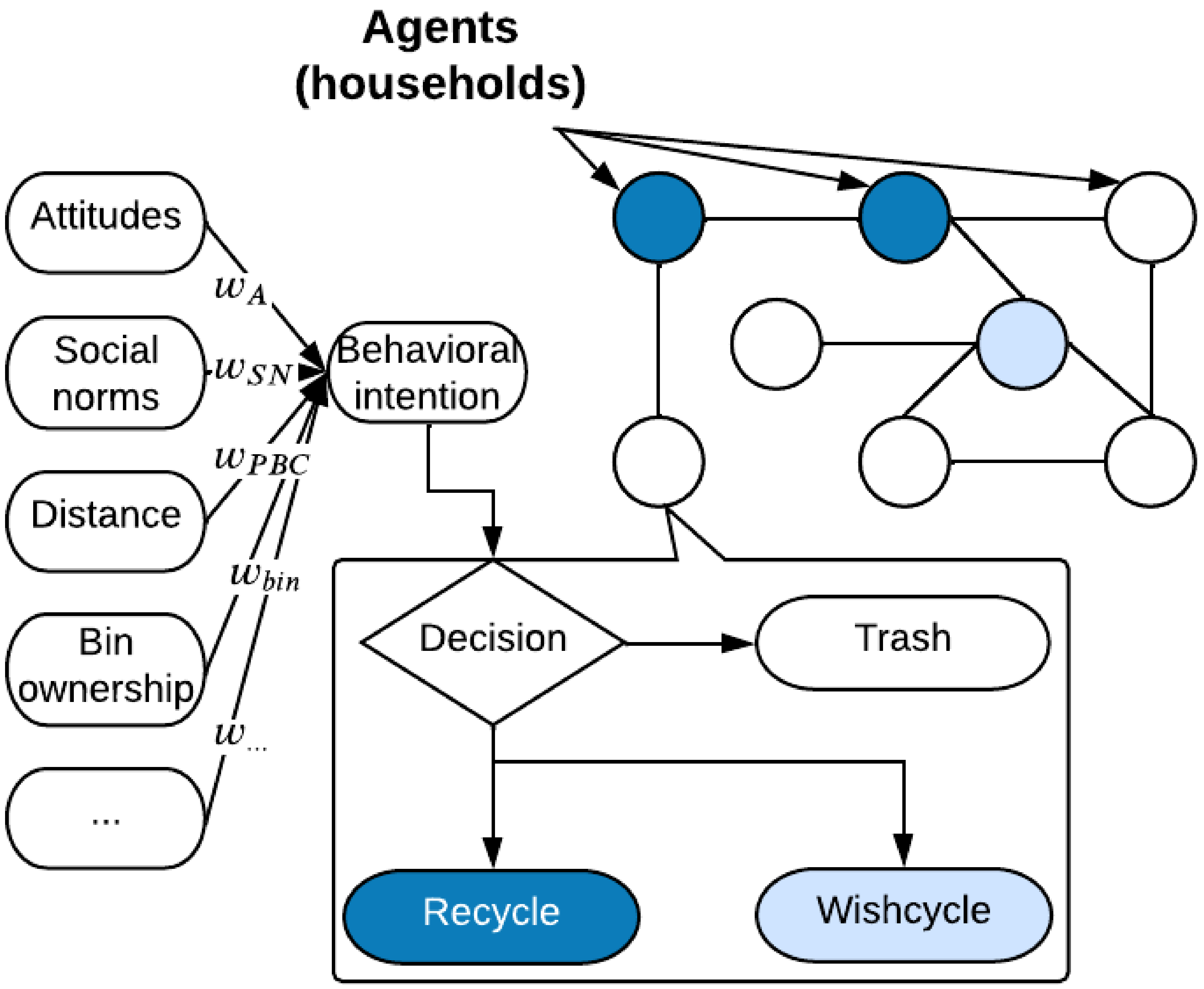
ABM on Waste Management

A good method to model human behaviors is **agent-based modeling** (ABM):

- Models individual decisions and **peer effects**
- Captures a population **heterogeneity** in a complex system
- Enables studying the effect of **behavioral interventions**

- Case study looking at how to improve PET bottle collection in the United States

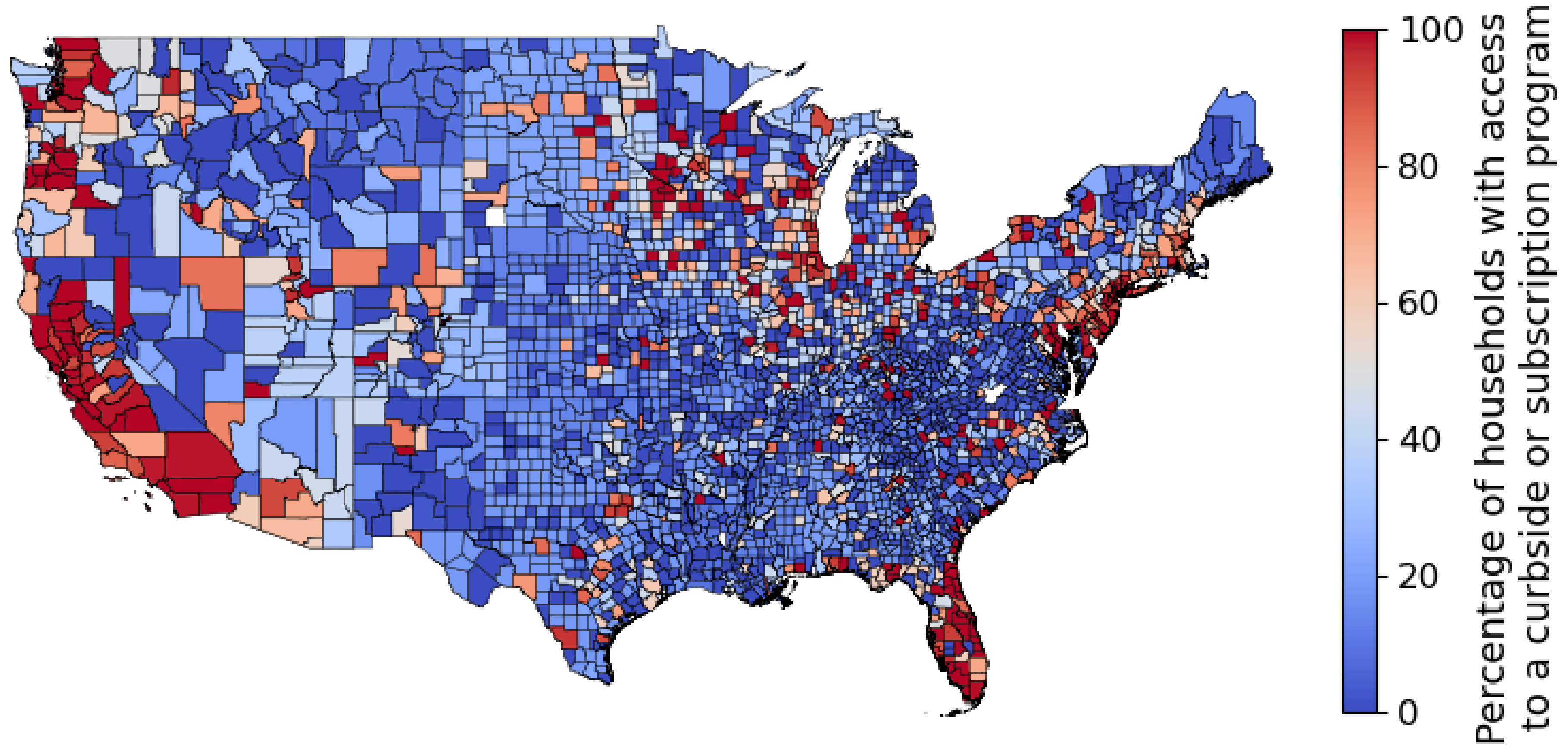


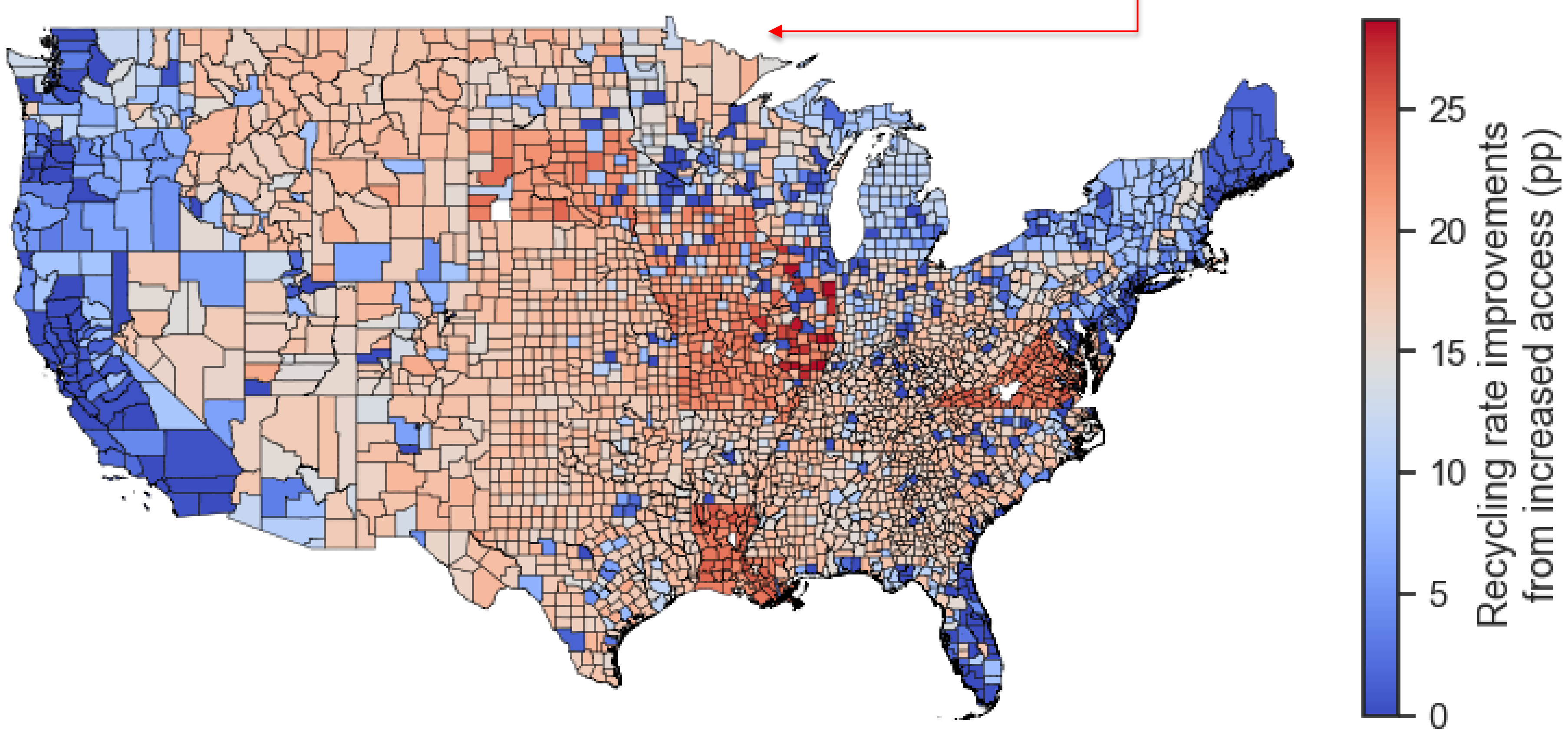
Walzberg, et al, 2023

Walzberg, et al, 2023

Behavioral Intervention 1: Increased Access to Recycling Programs

Recycling improvements when 100% of households without easy access are targeted





- **Generally, counties with a low access initially see the highest improvements** in recycling rates due to the "improved access" intervention (e.g., in Louisiana and Virginia)
- However, there are nuances: **states with low access** to curbside recycling but with **bottle bills** (e.g., Maine) already have high collection rates → increasing access to recycling programs has a lower effect.
- **Prioritizing investments in certain counties** could more efficiently increase the amount of recycled PET bottles.
- Improved access is only one factor affecting recycling behaviors, **other factors such as recycling knowledge, habits, and social norms** can also be targeted to improve recycling rates.

Relevance to the Circular Economy

- Waste management systems are the final recovery/circularity option
- If it is not recovered, it is lost from the economy
- To be recovered, there needs to be infrastructure and mechanisms in place to collect, sort, separate, transport, etc.
  - This is a big challenge in all economies – no country does this perfectly or even very well

Circular Economy

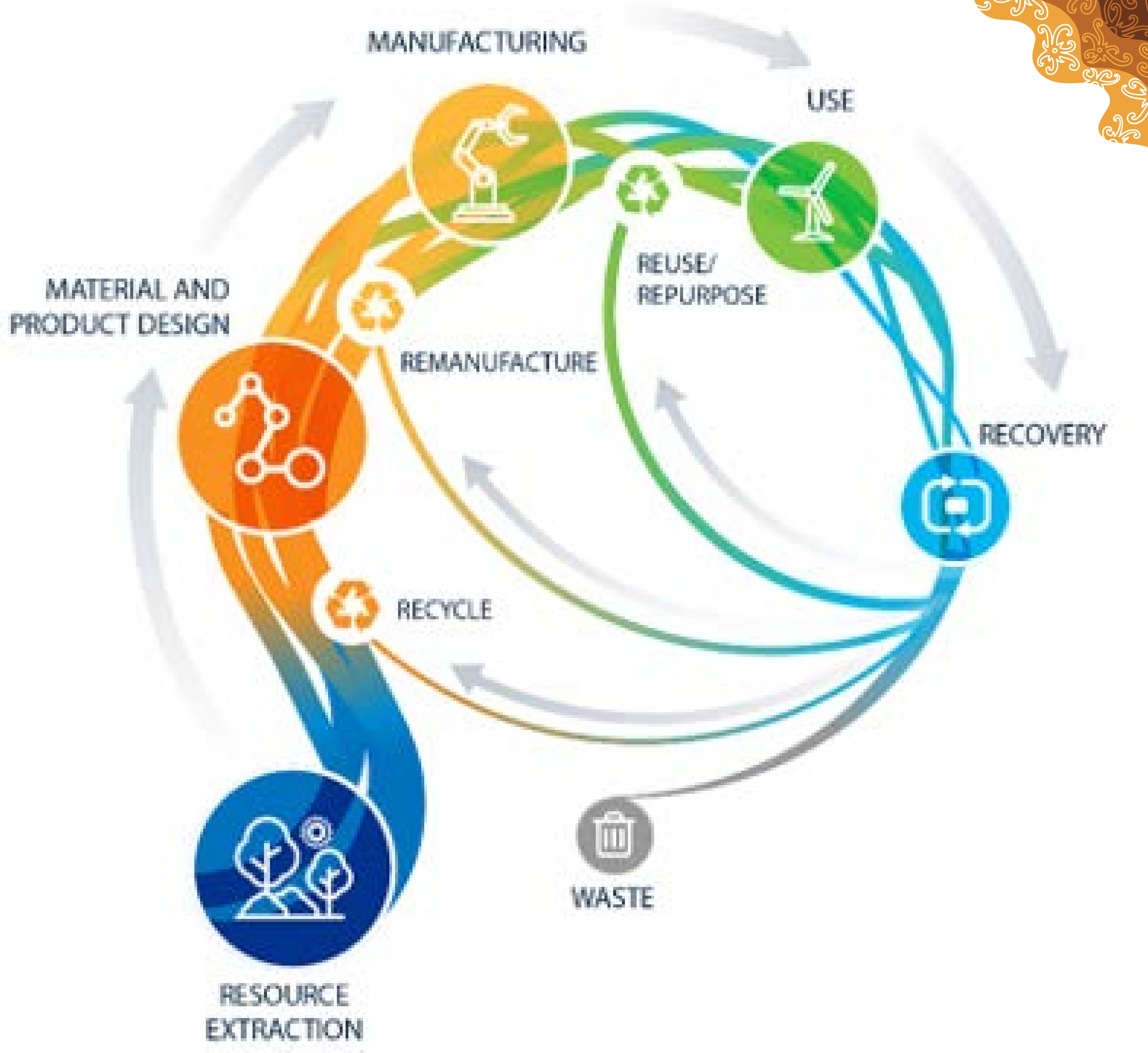


Illustration by Joelynn Schroeder, NREL

Circular Economy (CE) definitions

ISO 59020: economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development

Background

Problem: In the next decades demand for raw materials is expected to increase

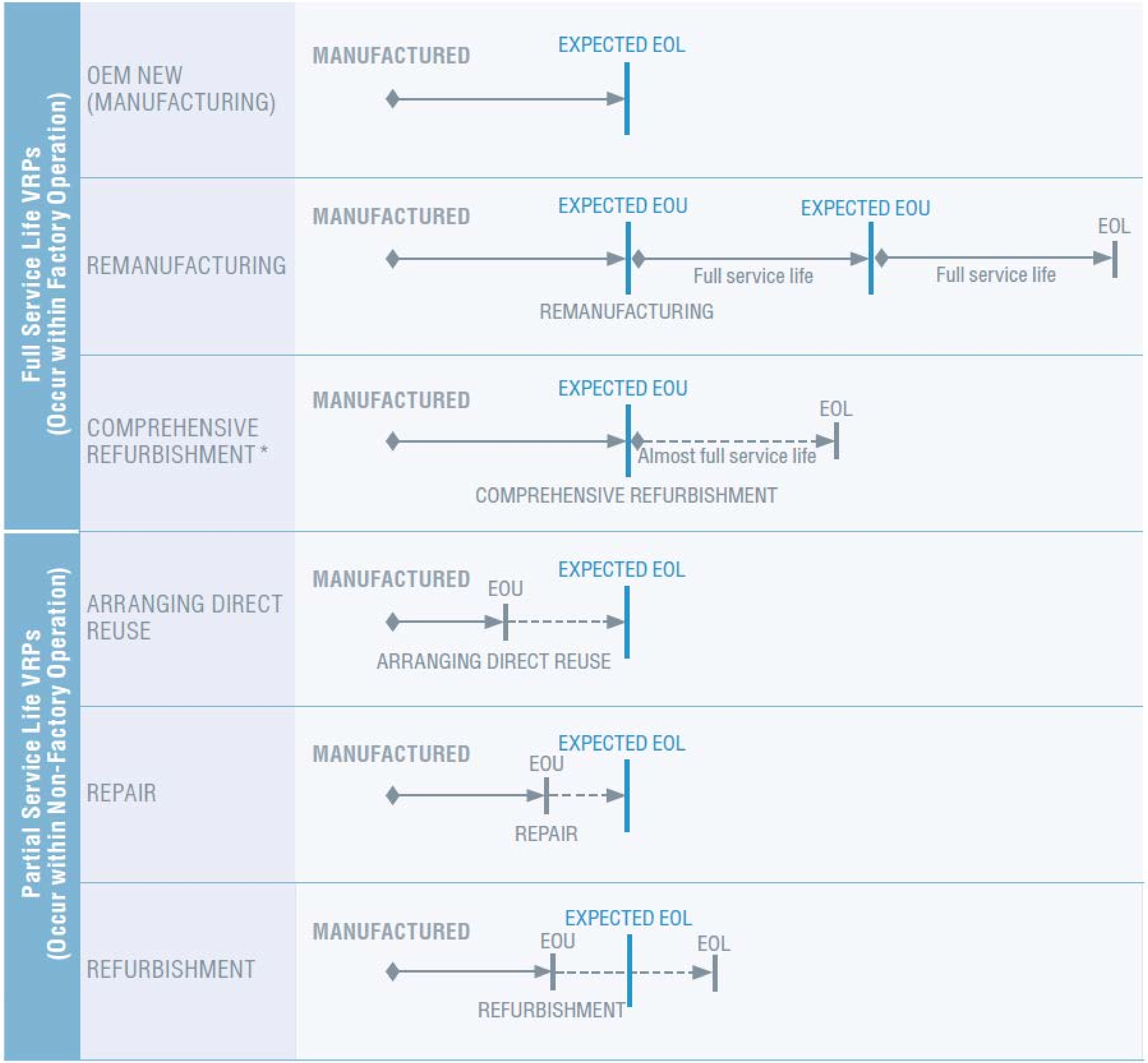
- 100 billion metric tonnes of materials consumed each year, 177 billion by 2050 (Circle Economy, 2021)
- Increases the risk posed by sudden supply restrictions (*Schrijvers et al., 2020*)
- Contributes to global GHG emissions due to their embodied energy (*Circle Economy, 2021*): cradle-to-gate materials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

CE Strategies (Rx)

		Strategy	Description
Circular Economy ↑ Increasing Circularity	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
Linear Economy		**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



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.

Why CE?

Is circularity the goal?

Or a tool?

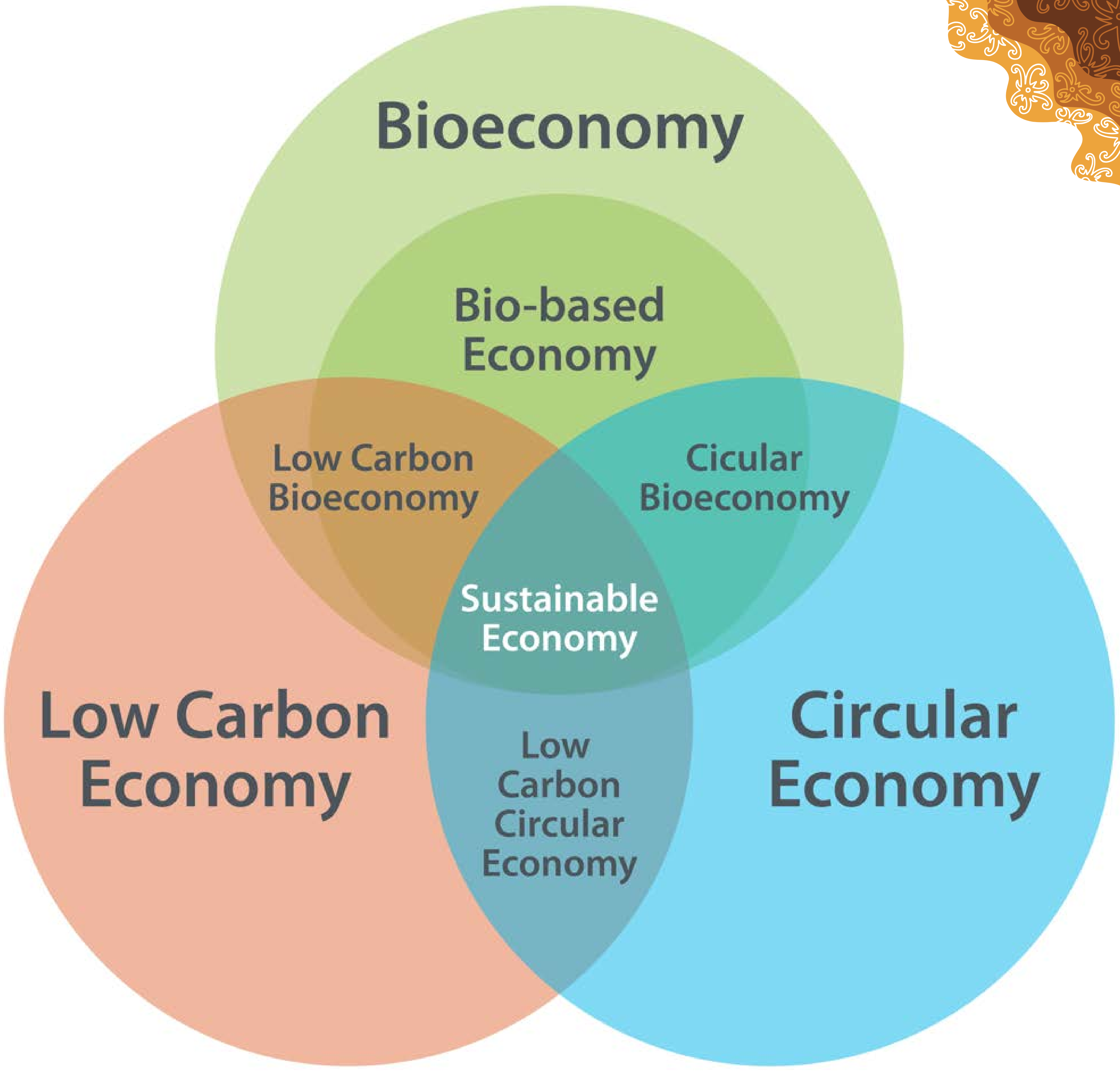


Illustration by Nicole Leon , NREL. Adapted from Kardung and Wesseler 2019

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

Direct contribution of CE to goals

- SDG7 – Affordable and Clean Energy
- SDG8 – Decent work & economic growth
- SDG12 – Responsible consumption and production
- SDG6 – Water and sanitation
- SDG15 – Life on land

Indirect contribution to goals

- SDG1 – No poverty
- SDG11 – Sustainable cities and communities
- SDG2 – Zero hunger
- SDG14 – Life below water

SDGs contribute to CE

- SDG9 – Industry innovation and infrastructure
- SDG10 – Reduced inequalities
- SDG4 – Quality education
- SDG13 – Climate action

Data 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*

Why do/should society and communities care?

Short term: better value for our products, better control of materials at EOL (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 do we evaluate CE?

This depends on the research question.

Assessment Methods

- Life cycle assessment (LCA)
- System dynamics (SD)
- Environmentally extended input output analysis (EEIOA)
- Discrete event simulation (DES)
- Material flow analysis (MFA)
- Agent-based modeling (ABM)
- Emergy/exergy
- Operations research (OR)

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

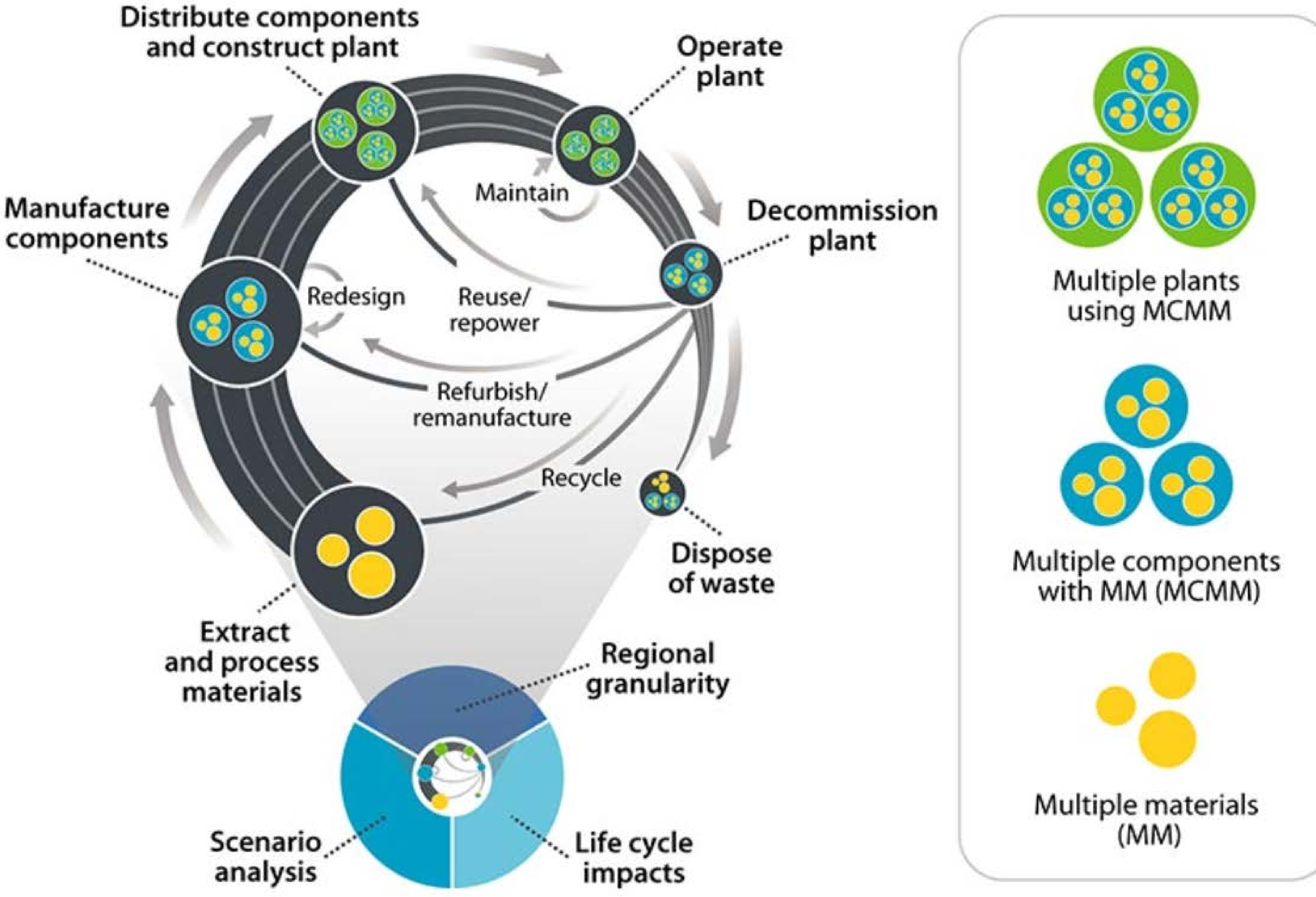
Some Approaches Being Used at NREL

- 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.

Plastic Parallel Pathways Platform

- 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.

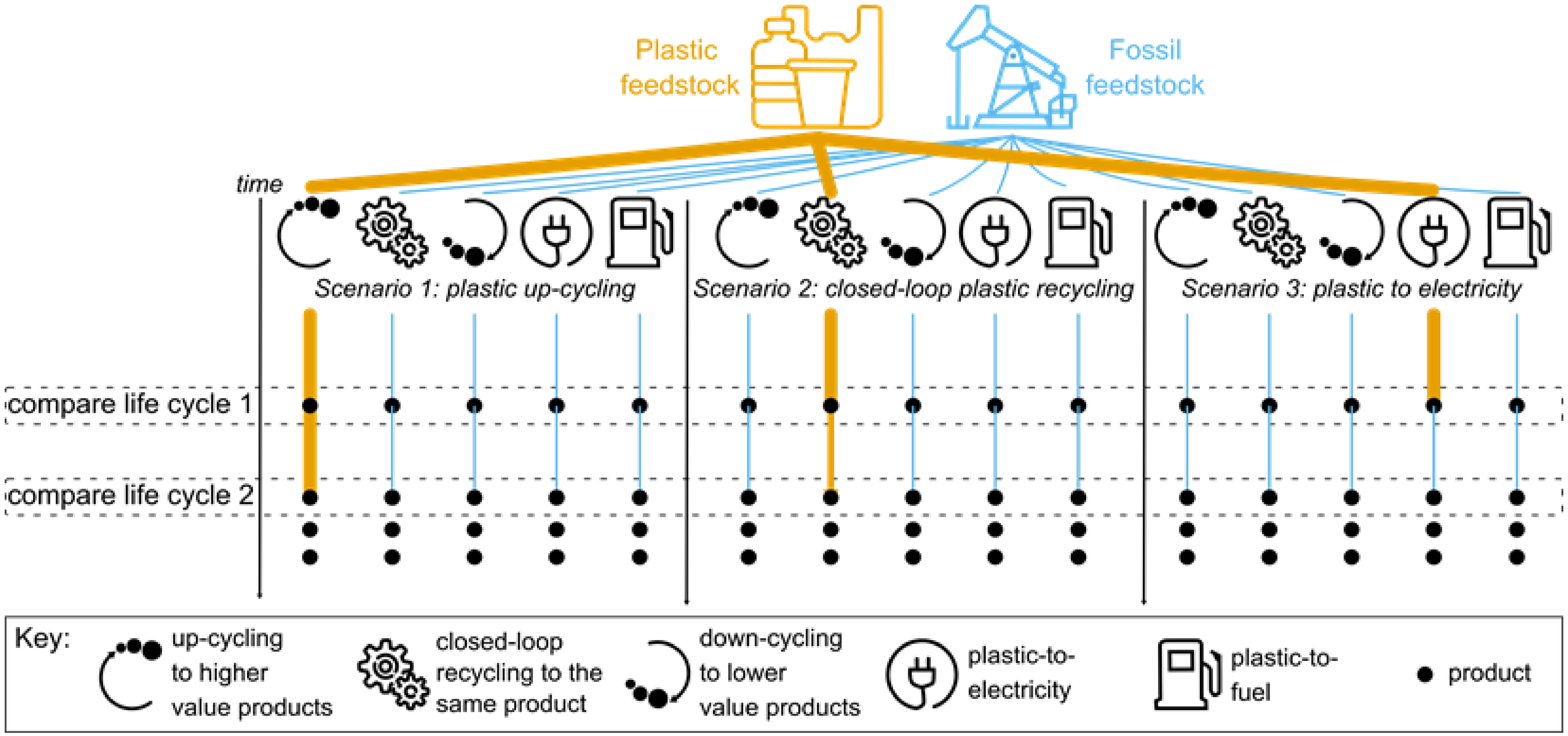


Illustration by Taylor Uekert, Tapajyoti Ghosh and Julian Walzberg, NREL

Other Questions

- How to include and evaluate bio-based feedstocks and biodegradable products?
- What strategies can be applied to help reduce demand associated with different sectors and support industrial decarbonization?
- What about the other environmental and social challenges of our time?
  - Biodiversity
  - Equity & Justice
  - Water scarcity

frontiers | Frontiers in Sustainability

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A framework for integrating supply chain, environmental, and social justice factors during early stationary battery research

Victoria L. Putsche[1], Jasmine Pattany[1], Tapajyoti Ghosh[1], Swaroop Atnoorkar[1], Jarett Zuboy[1], Alberta Carpenter[1,2], Esther S. Takeuchi[3,4,5,6], Amy C. Marschilok[3,4,5,6], Kenneth J. Takeuchi[3,4,5,6], Anthony Burrell[1] and Margaret K. Mann[1*]

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Letter

Strategies for Considering Environmental Justice in the Early-Stage Development of Circular Economy Technologies

Taylor Uekert,* Julien Walzberg, Hope M. Wikoff, Meredith M. Doyle, and Alberta C. Carpenter*

Cite This: https://doi.org/10.1021/acssuschemeng.4c02205

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ABSTRACT: The circular economy could transform how industry and society approach resources and waste, resulting in significant environmental justice (EJ) implications. However, there are few resources for analyzing the EJ impacts of new circular economy technologies before they are deployed. This work presents an EJ framework tailored for early stage circular economy technologies and showcases its capabilities through a case study on enzymatic plastic recycling. By providing concise, actionable, and accessible guidelines based on technology readiness levels and a series of 20 questions, the framework empowers both experts and nonexperts to evaluate the justice implications of circular economy solutions. Preliminary user feedback highlights the approachability of the framework and its corresponding interactive worksheet, as well as their potential to stimulate innovative thinking toward a more just and sustainable future.

We need to apply **out of the box** thinking… but solutions might need an out of the box ecosystem to be successful

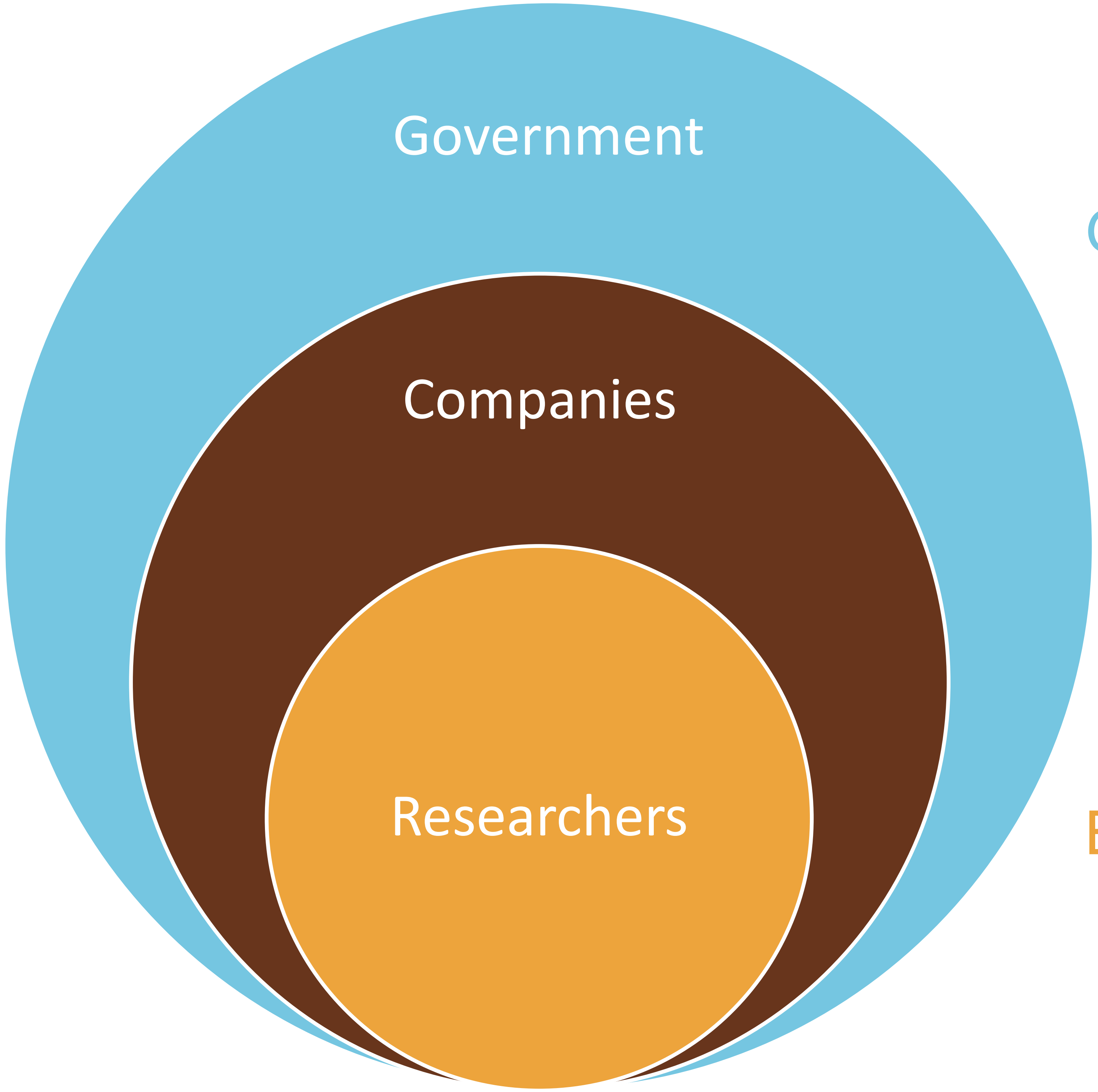
Illustration by Nicole Leon, NREL

Life Cycle Assessment (LCA)

What is LCA?

- Life cycle assessment (LCA) is **a comprehensive approach** that quantifies ecological and human health impacts of a product or system over its complete life cycle
  - Using **credible scientific methods** to model steady-state, global environmental and human health impacts
  - Can help decision makers understand the scale of many environmental and human health impacts of competing products, services, policies or actions.
- "LCA is a technique to assess the environmental aspects and potential impacts associated with a product, process, or service, by:
  - Compiling an inventory of relevant energy and material inputs and environmental releases
  - Evaluating the potential environmental impacts associated with identified inputs and releases
  - Interpreting the results to help you make a more informed decision“

Why is LCA important/useful?



Guide policy decisions on sustainability

Marketing

Improve supply chain & procurement

Comply with regulations

Place your technology within context

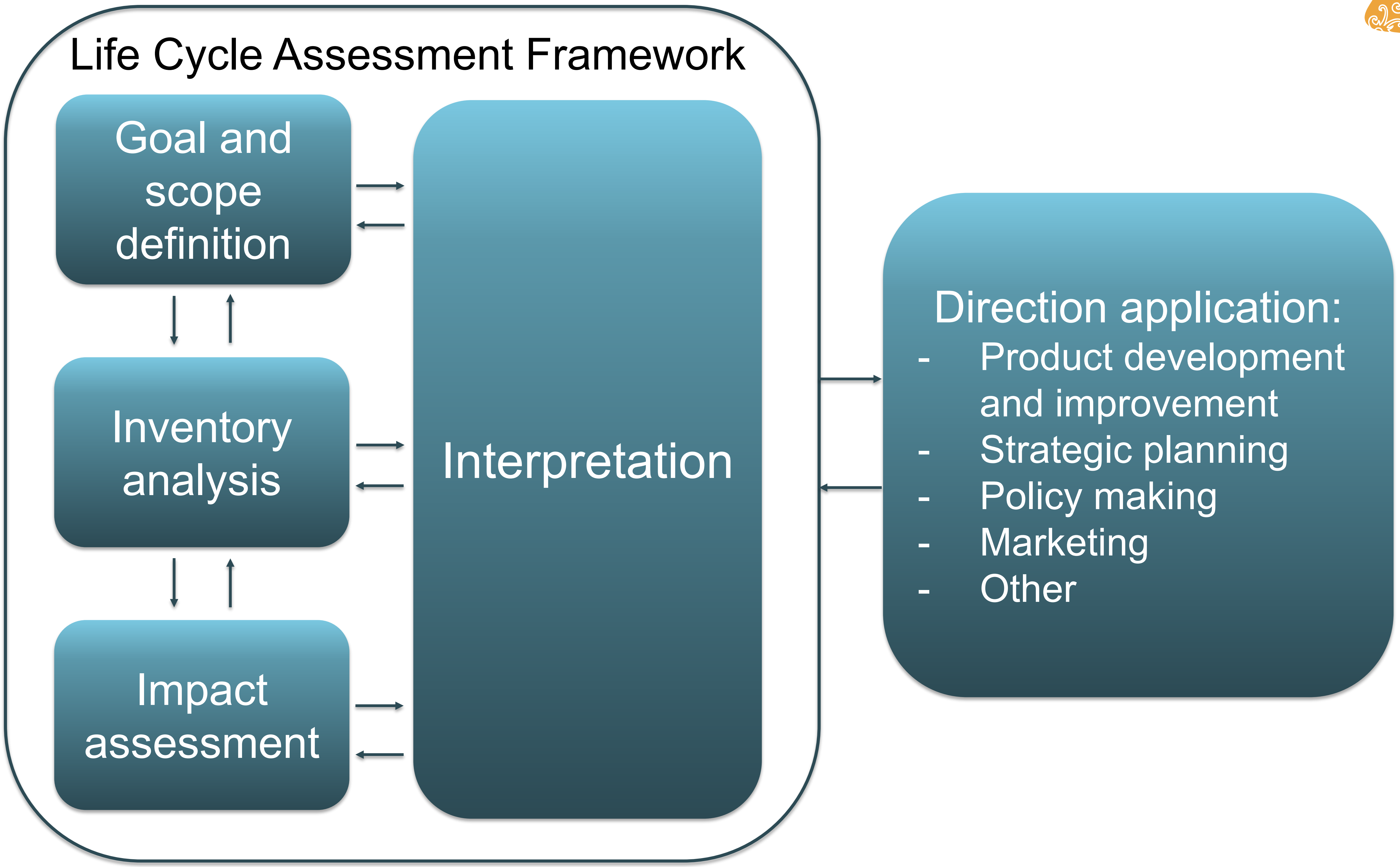
Identify areas for improvement

Benchmark new processes

Types of LCAs

- **Attributional** - describes the environmentally relevant flows to and from a life-cycle and its sub-systems
- **Consequential** - how environmental relevant flows will change in response to possible decisions
- **Streamlined or simplified** - Identifies and focuses in on the main impacts in relation to a product or process, and allows key issues to be explored in more detail where necessary
- **Environmentally extended input-output (EEIO)** - estimates the materials and energy resources required for, and the environmental emissions resulting from, activities in our economy
- **Hybrid EEIO** – combination of process- and IO-based LCA, with different degrees of integration between the two constituent methods
- **Dynamic LCA** – accounts for changing social, economic, and material conditions
- **Prospective LCA** – evaluates early-stage technology to understand potential impacts and inform that technology development

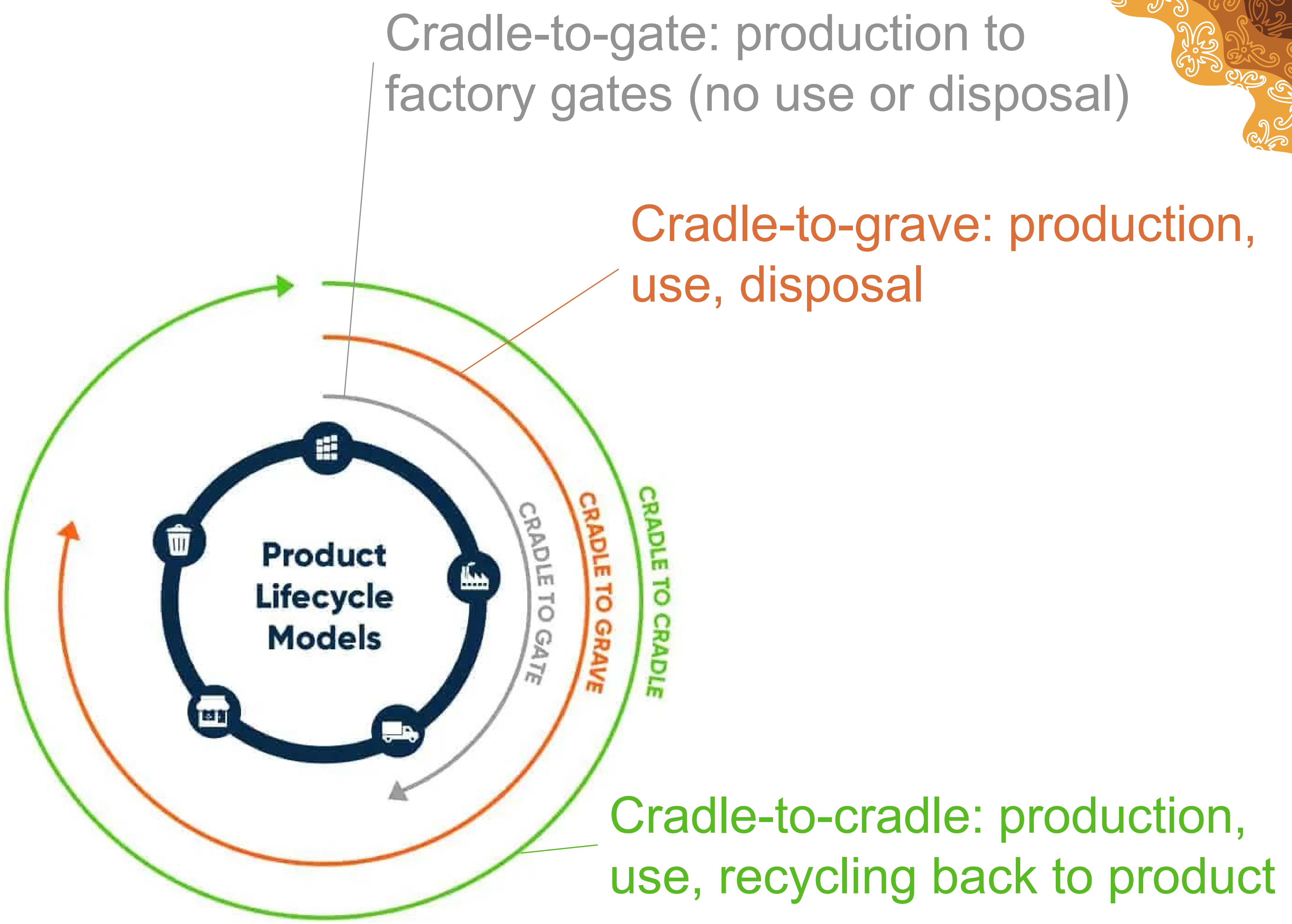
LCA Steps



[ISO 14040]

Step 1: Goal & Scope Definition

- The scope, including system boundary and level of detail, of an LCA depends on the subject and the intended use of the study.
- Your goal & scope should answer:
  - Why are you doing an LCA?
  - Who is your audience?
  - What are you assessing?
  - Are you doing a comparison?
  - What is the boundary of your system?
  - What are your assumptions?



Step 2: Life Cycle Inventory (LCI)

An LCI involves the collection of the data necessary to meet the goals of the defined study:

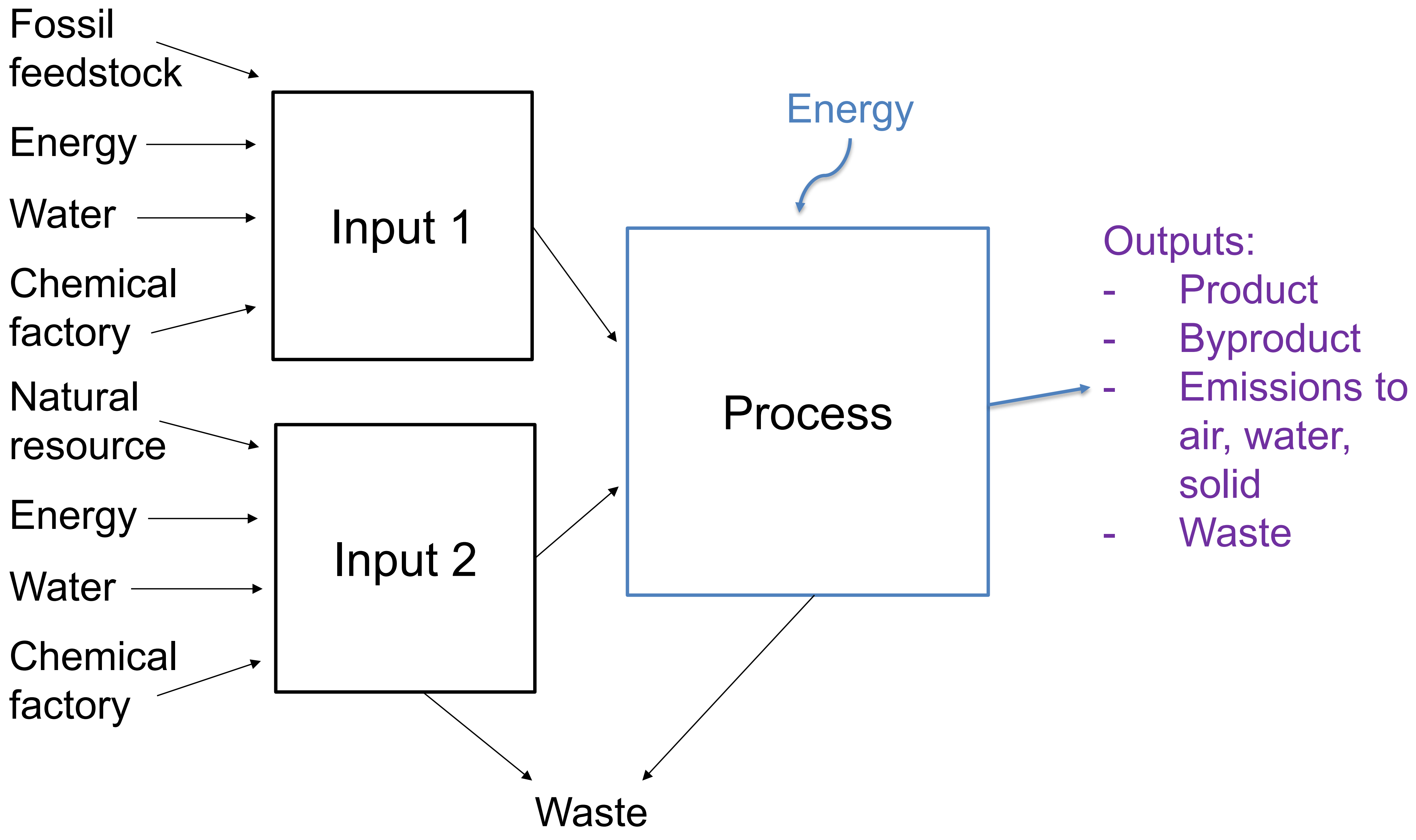
– Material inputs

– Energy inputs

– Product (& side products)

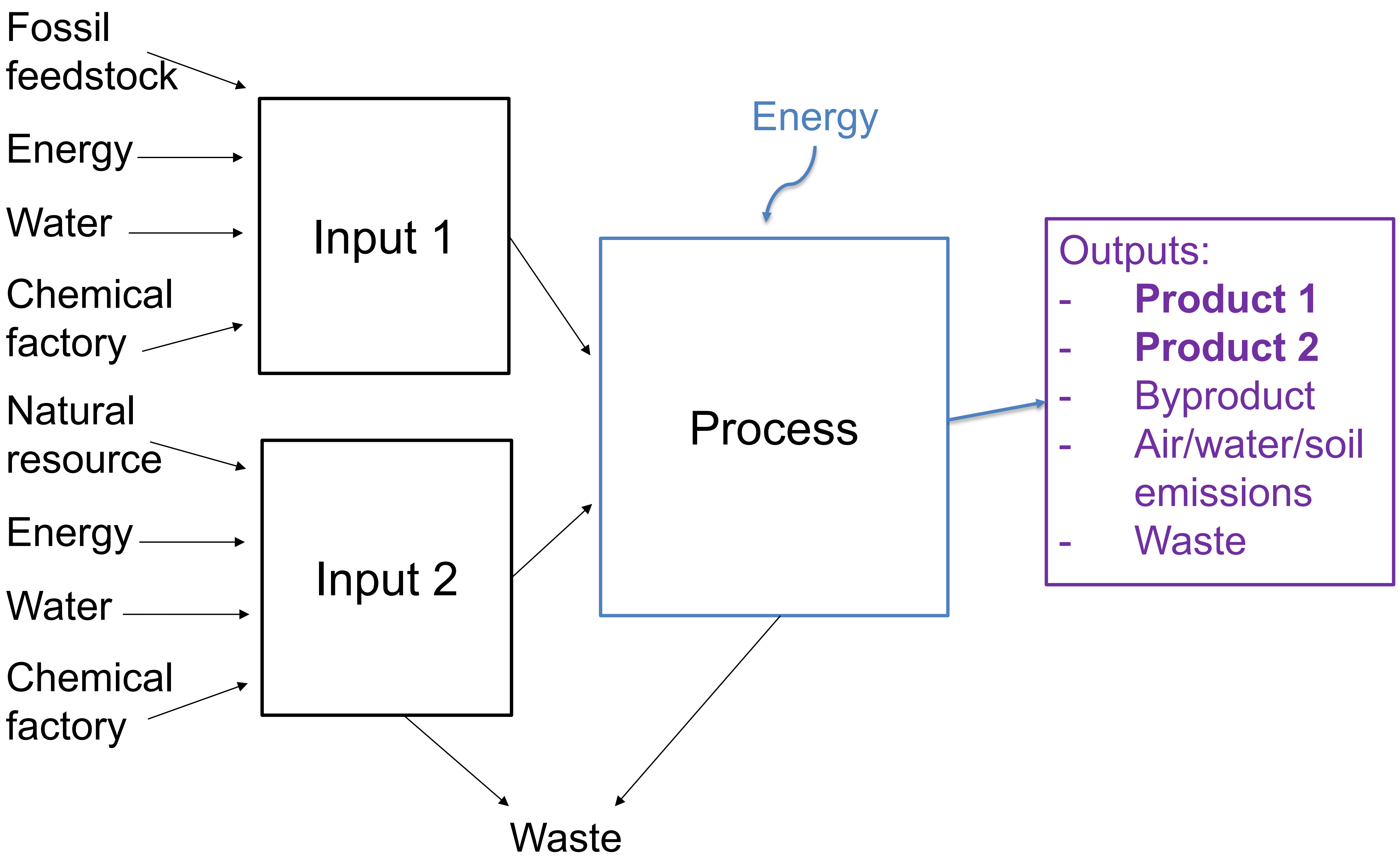
– Emissions to air/soil/water

– Waste



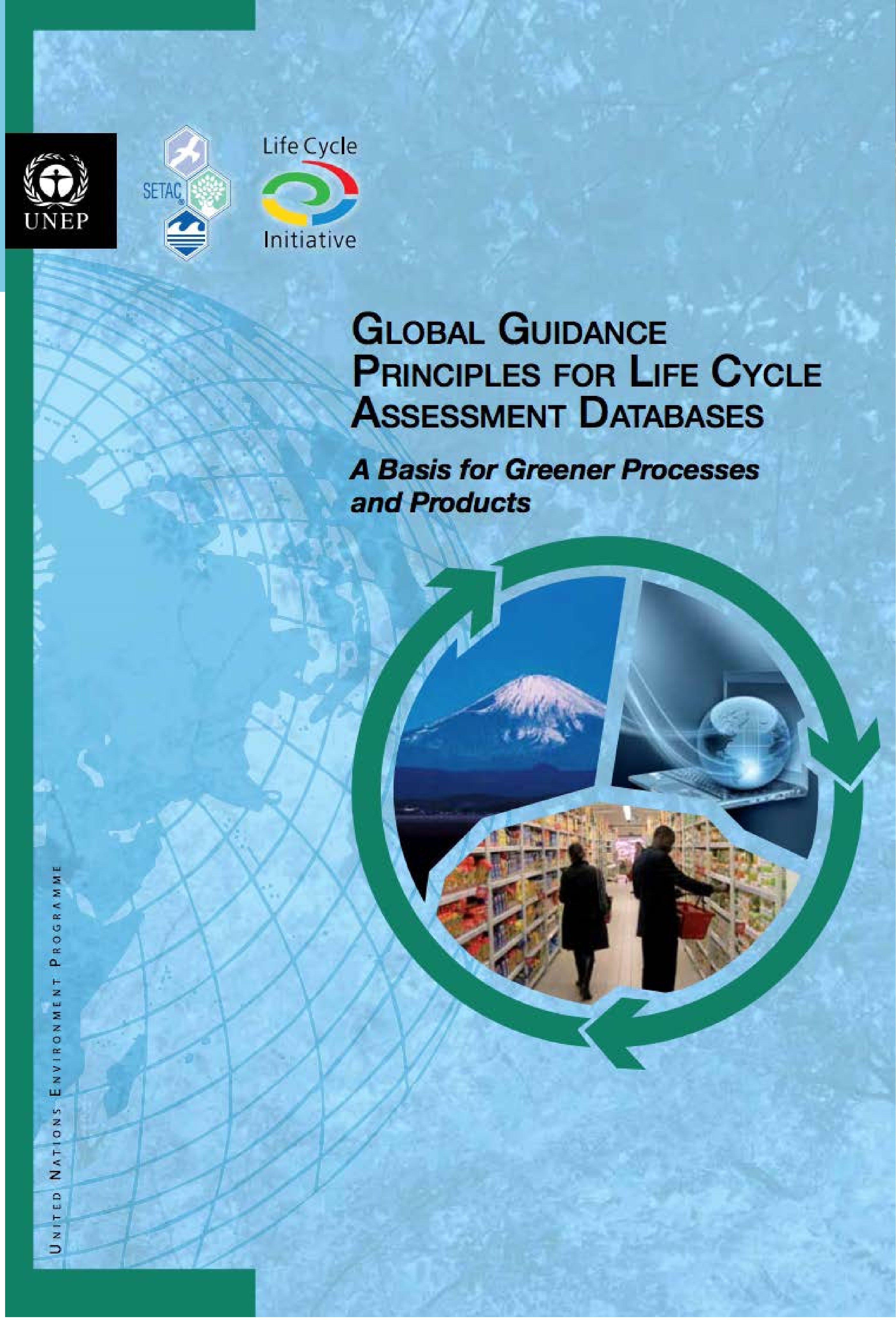
Allocation

- What do you do if your process has more than one product? How do you distribute the impacts of your system between those products?
- And what is the difference between a co-product and a byproduct?



A Model Is Only As Good As Its Data

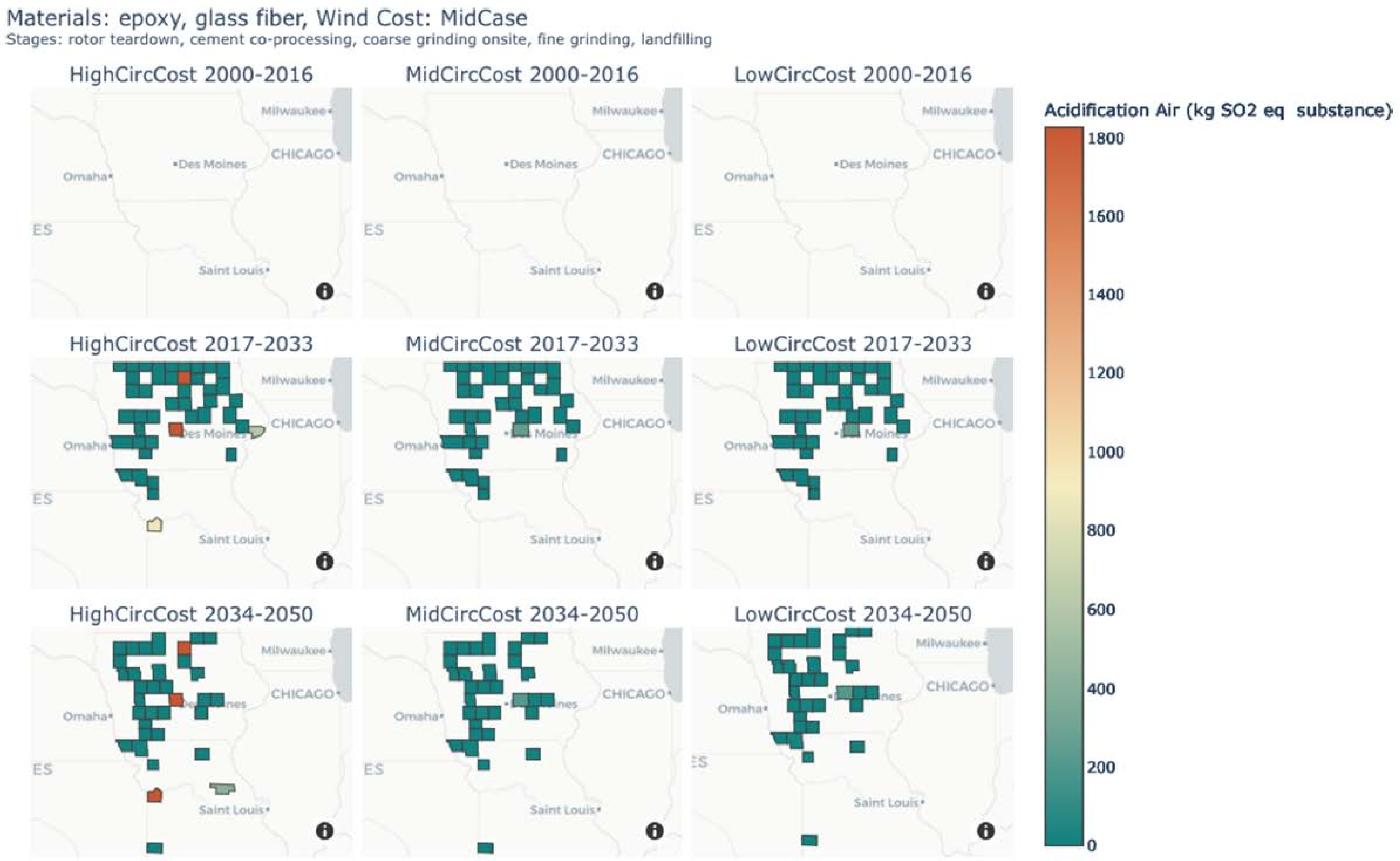
- **Foreground system:** the specific process or product being modeled.
- **Background system:** all upstream and downstream processes from the foreground system.
- **Primary:** data collected or measured directly by company – usually related to your foreground system.
  - *Most accurate, authentic, and reliable data*
- **Secondary:** data usually related to the background system that is sourced from a third-party life-cycle-inventory database, often using industry averages.
  - **Industry average:** secondary data aggregated to represent general average vs. specific process.
  - **Proxy:** when data for a specific product is not available, a product that is assumed to be very similar in nature and impact is used.
  - **Meta data:** how well does a dataset represents a system?
    - Age, Geography, Technology, Source



https://www.lifecycleinitiative.org/library/training-kit-global-guidance-principles-ggp-on-life-cycle-assessment-data-and-databases/

Recent Developments in LCI

- Prospective and dynamic modeling
- Use of ABM, system dynamics, computable general equilibrium models etc. to improve the system modeling realism
- Regionalization, bigger systems (e.g., vehicle fleet instead of a single car), inclusion of temporal aspects
- Development of new approaches to study the circular economy
- Block chain technologies can help with data collection



The Circular Economy Life Cycle Assessment & Visualization framework optimizes reverse supply chains and computes a regionalized and dynamic LCI, Walzberg, et al, NREL

Step 3: Impact Assessment

The life cycle impact assessment phase (LCIA) is the third phase of the LCA. The purpose of LCIA is to provide additional information to help assess a product system's LCI results to better understand their environmental significance.

[ISO 14040]

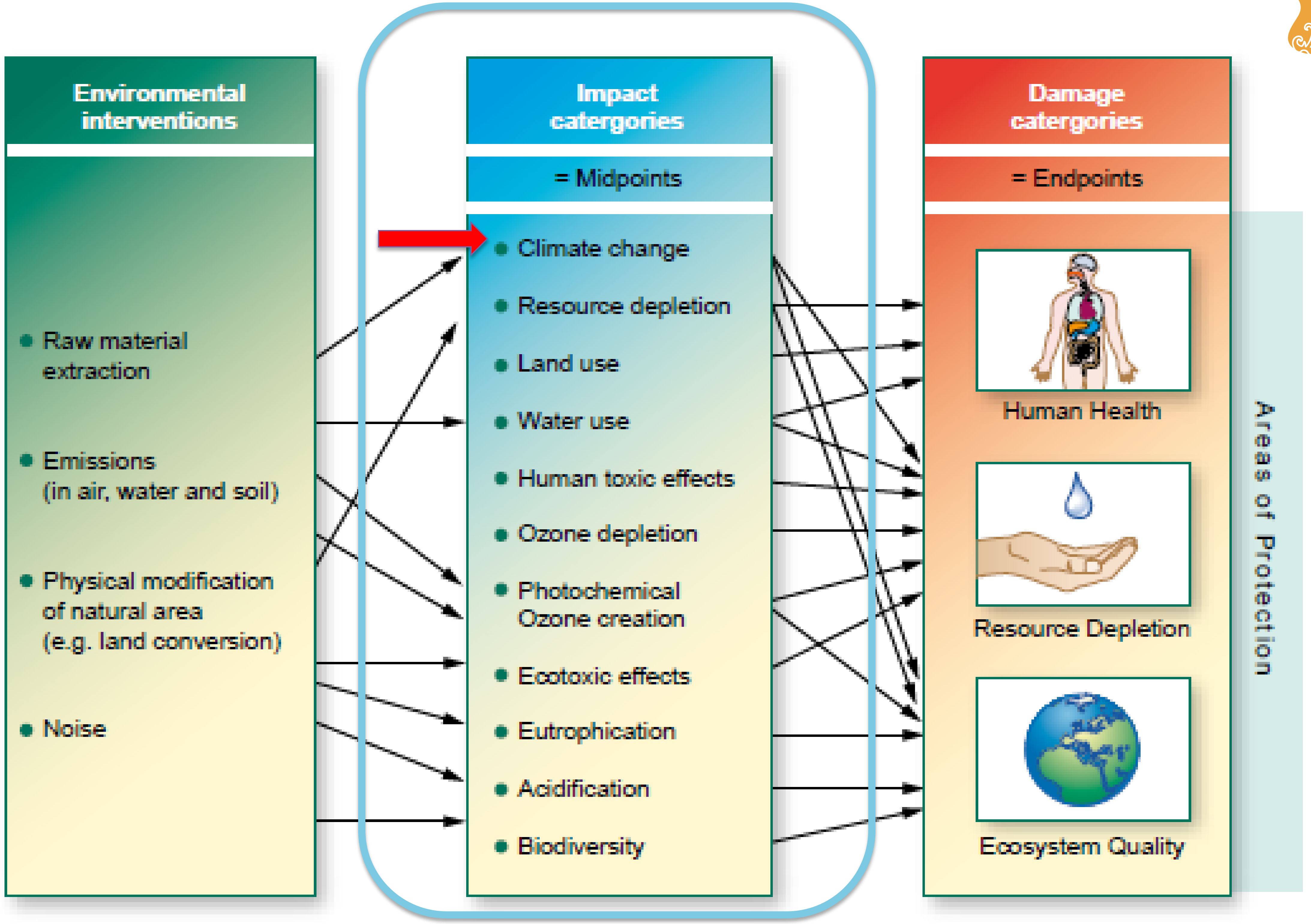


Figure 0.2: UNEP/SETAC Life Cycle Impact Assessment Midpoint-Damage Framework

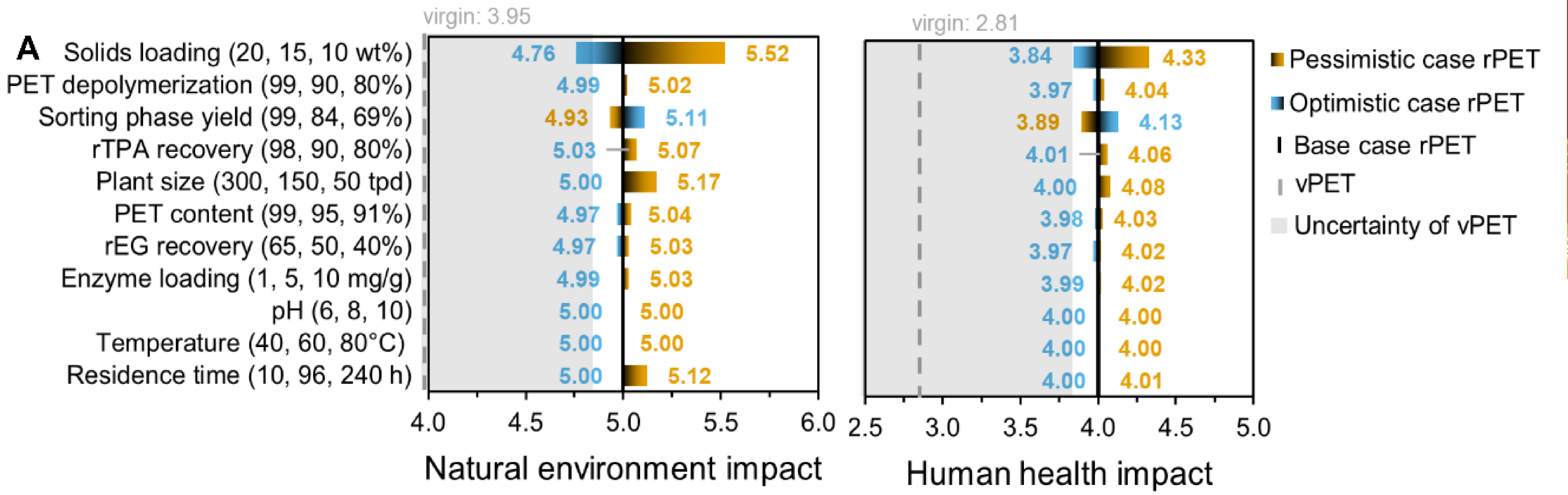
Recent developments in LCIA

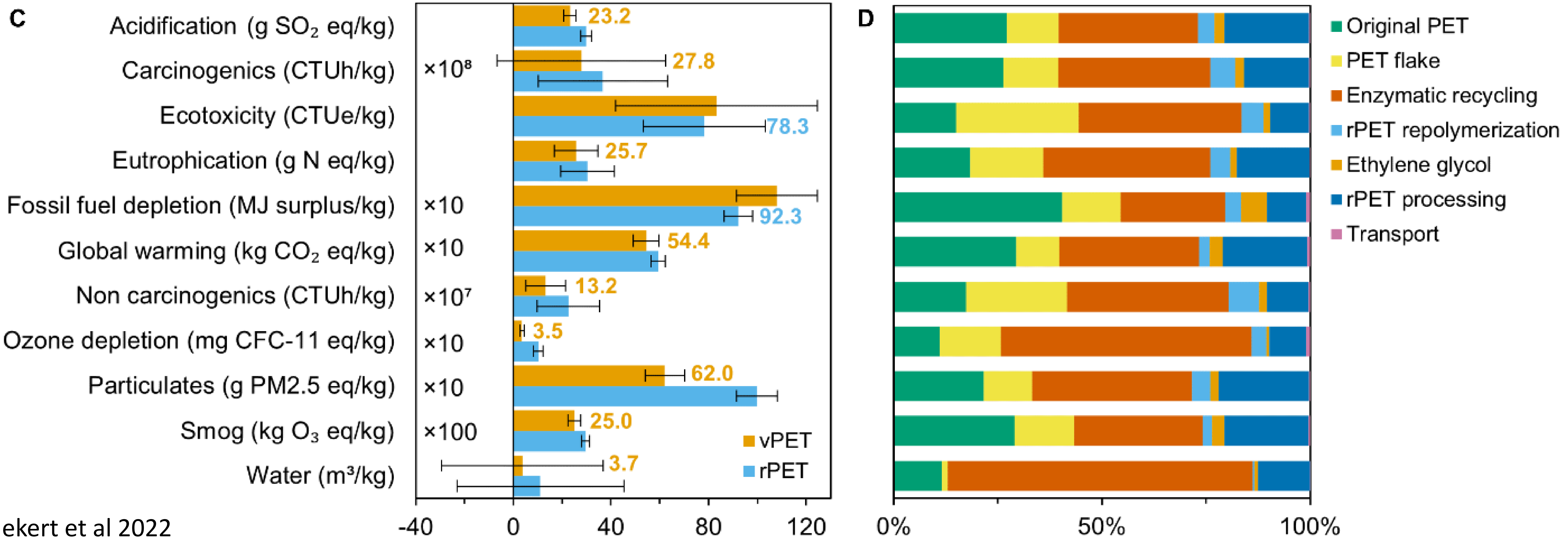
- Regionalization of impacts: some ecosystems may be more or less resilient to a given environmental problem (e.g., a brownfield vs a tropical forest)
- Relative vs absolute impacts → contribution to planetary boundaries: how much can the planet support and how much does my technology/product contribute to reaching that limit?
- New impact categories: microplastic impacts (on ecosystems and human health), hydropower impacts on freshwater ecosystems, noise impact (on ecosystems and human health)

Step 4: Interpretation

- Identify significant issues
  - How does the process compare to others?
  - What are the biggest contributors to impacts?
- Evaluate completeness & consistency of study
  - What are the sources of error and how could these affect the results?
  - What aspects of the life cycle might be missing?
  - Which data needs improving?
- Provide conclusions and recommendations
  - Which aspects can be changed/improved to reduce impacts?

Enzymatically Recycled PET

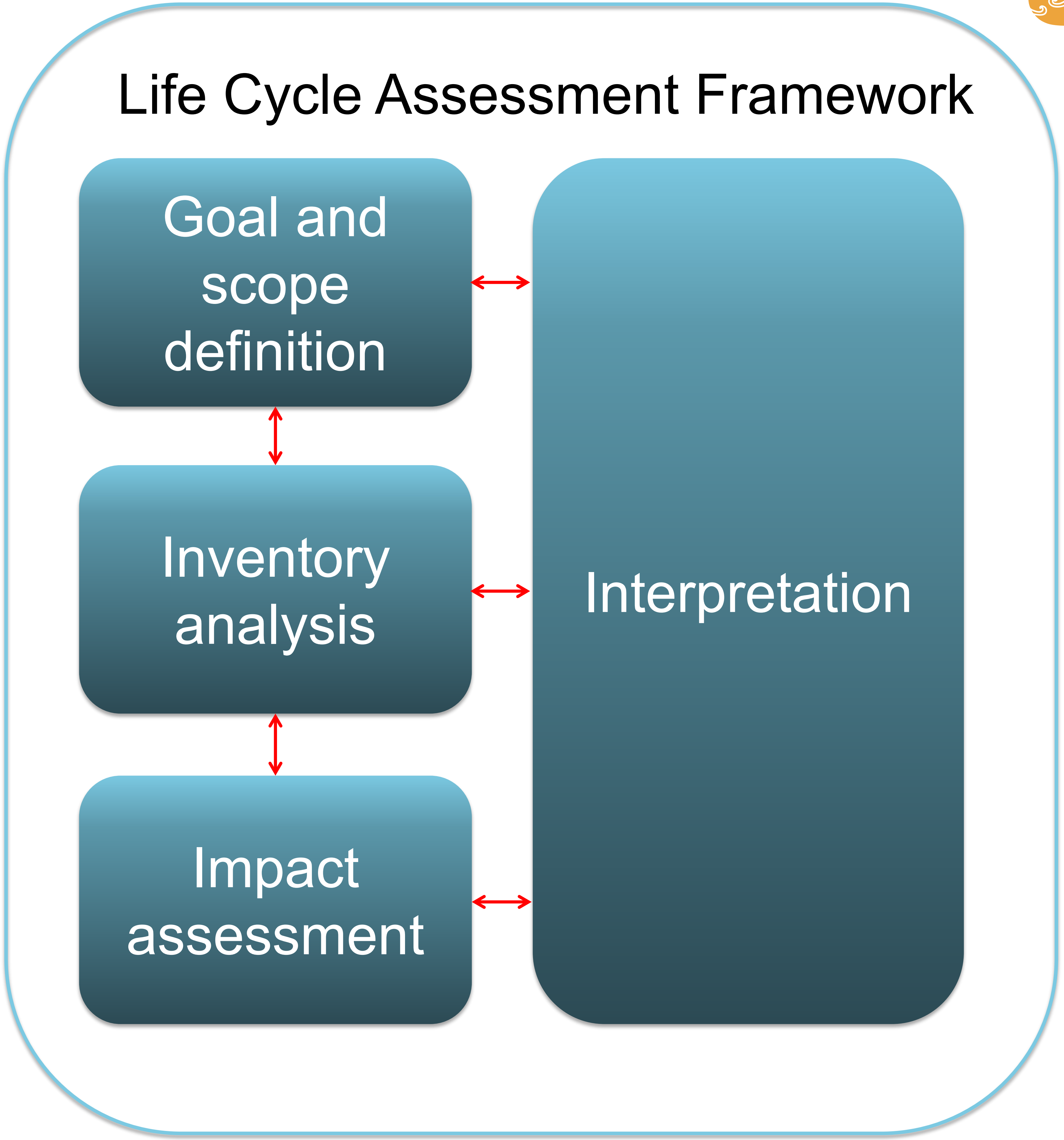




Uekert et al 2022

Iterate

No LCA is perfect the first time – as you are reviewing your results, you may find that it is necessary to go back and shift the scope or include other types of impacts to fully capture all the important impacts.



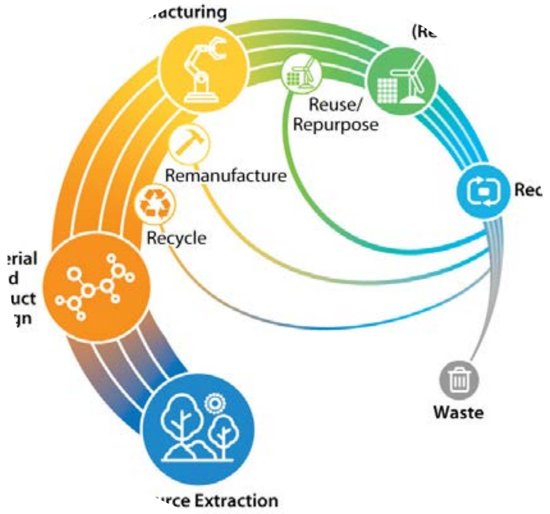
Issues and limitations with LCA

- Data
  - Often not available
  - Or are often industry averages, rather than actual data
  - Expensive and time consuming to collect
- Results are impacted by selected system boundaries
- Doesn’t consider economic impacts
- Social impacts are new to the field and not well developed or established
- Lack of transparency
- Typical results are
  - Static – transitions or projections are more complex
  - Not geospatially explicit
- Comparisons can be difficult
- Critical review to provide credibility

Want to know more?

Justice Analysis

Justice Analysis at NREL

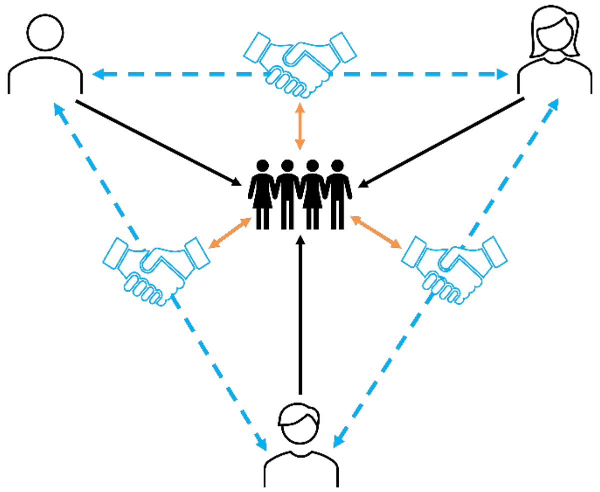


Circular Economy for Energy Materials

Circular Economy Research at NREL

Analysis Informed Research

BOTTLE Consortium Analysis



Agent Based Modeling

ABM work at NREL

Life Cycle Assessment

American Center for LCA or UNEP SETAL Life cycle initiative

Call to Action

Consider circularity and sustainability early and often. It is better to be forward thinking and avoid having unintended consequences that must be cleaned up later. Keep our planet and our world clean.

Questions?

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NREL Transforming ENERGY

References

- ISO 14040: 2006(E) Environmental management — Life cycle assessment — Principles and framework. https://www.iso.org/standard/37456.html
- Sala, et al, Environmental sustainability of European production and consumption assessed against planetary boundaries, Journal of Environmental Management, 269 (2020), https://doi.org/10.1016/j.jenvman.2020.110686.
- Singh, Avantika , Nicholas A. Rorrer, Scott R. Nicholson, Erika Erickson, Jason S. DesVeaux, Andre F.T. Avelino, Patrick Lamers, Arpit Bhatt, Yimin Zhang, Greg Avery, Ling Tao, Andrew R. Pickford, Alberta C. Carpenter, John E. McGeehan, Gregg T. Beckham. Techno-economic, life cycle, and socio-economic impact analysis of enzymatic recycling of poly(ethylene terephthalate). Joule (Jun 2021).
- Uekert, T., S.R. Nicholson, A. Singh, J.S. DesVeaux, T. Ghosh, J.E. McGeehan, A.C. Carpenter, G.T. Beckham. Life cycle assessment of enzymatic poly(ethylene terephthalate) recycling. Green Chemistry. 2022. Issue 17. https://doi.org/10.1039/D2GC02162E.
- Kirchherr, Reike and Hekkert, Marko. 2017. Conceptualizing the Circular Economy: An Analysis of 114 Definitions. http://dx.doi.org/10.2139/ssrn.3037579
- ISO 59020:2024 Circular economy — Measuring and assessing circularity performance. https://www.iso.org/standard/80650.html
- Potting, et al, Circular economy: measuring innovation in the product chain (PBL Publishers, 2017), vol. No. 2544.
- IRP (2018). Re-defining Value – The Manufacturing Revolution. Remanufacturing, Refurbishment, Repair and Direct Reuse in the Circular Economy. Nasr, et al. A Report of the International Resource Panel. United Nations Environment Programme, Nairobi, Kenya
- *Schroeder, et al (2019). The Relevance of Circular Economy Practices to the Sustainable Development Goals. Journal of Industrial Ecology, 23(1), 77-95. https://doi.org/10.1111/jiec.12732*
- Walzberg, et al. 2021. "Do We Need a New Sustainability Assessment Method for the Circular Economy? A Critical Literature Review." *Frontiers in Sustainability*. 1:620047. https://doi.org/10.3389/frsus.2020.620047.
- Hanes, et al. 2021. "The Circular Economy Lifecycle Assessment and Visualization Framework: A Case Study of Wind Blade Circularity in Texas." *Frontiers in Sustainability* 2: 671979. https://doi.org/10.3389/frsus.2021.671979.
- Ghosh, et al. Towards a circular economy for PET bottle resin using a system dynamics inspired material flow model. Journal of Cleaner Production. V383, 135208. 10.1016/j.jclepro.2022.135208.
- United Nations Environment Programme (2024). Global Waste Management Outlook 2024: Beyond an age of waste – Turning rubbish into a resource. Nairobi. https://wedocs.unep.org/20.500.11822/44939
- Walzberg et al. *Think before you throw! An analysis of behavioral interventions targeting PET bottle recycling in the United States*. Energy Research & Social Science, 100, 2023, https://doi.org/10.1016/j.erss.2023.103116.
- Uekert et al., *Strategies for Considering Environmental Justice in the Early-Stage Development of Circular Economy Technologies*,. ACS SusChemEng 2024. https://pubs.acs.org/doi/10.1021/acssuschemeng.4c02205
- Putsche, et al, *A Framework for Incorporating Supply Chain, Environmental, and Social Justice Considerations During Early-Stage Stationary Battery Research*. 2023. Frontiers in Sustainability.