Role of Life Cycle Assessment in the Circular Economy

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ASTM Workshop - Fostering a Circular Economy for Manufacturing Materials

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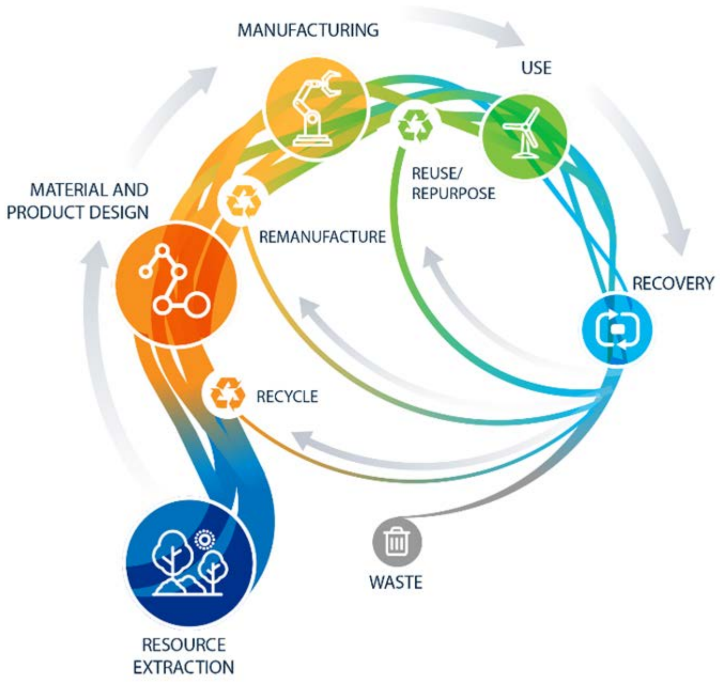
Outline

- Why circular economy (CE)?
- Why life cycle assessment (LCA)?
- How to evaluate CE
- Analysis questions and goals
- Examples of approaches used by the National Renewable Energy Laboratory (NREL)



Source: Upasani et al. (2022); Illustration by Joelynn Schroeder, NREL

Why CE?

An industrial system that is **restorative or regenerative** by intention and design replaces 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)**.

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 (Draft ISO Standard).

Ultimately, CE is not the goal but rather a tool or mechanism to achieve other sustainability goals.

Why CE?

From the perspective of the U.S. Department of Energy (DOE), CE provides strategic opportunity to:

- Support robust and secure supply chains
- Enhance domestic manufacturing and industry
- Support the growth of the material recovery industry
- Lead in the development and commercialization of end-of-life processing technologies
- Maximize product and material value
- Minimize **life cycle** impacts of U.S. manufacturing products

Why LCA?

- The goal of the circular economy is to transition from today's take-make-waste linear pattern of production and consumption to a circular system in which the societal value of products, materials, and resources is maximized over time.
- Yet circularity in and of itself **does not ensure social, economic, and environmental performance** (i.e., sustainability).
- Sustainability of CE strategies needs to be measured against their linear counterparts to identify and avoid strategies that increase circularity yet lead to **unintended externalities or burden shifting**.

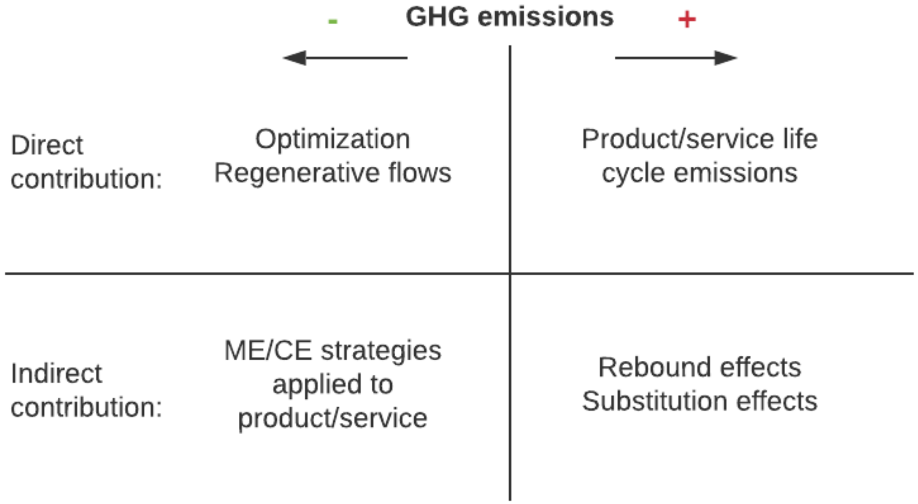
Why LCA? - *Decarbonization*

- Doubling global circularity from its current figure of 8.6% (i.e., only closing the circularity gap partially) could contribute up to 85% of the greenhouse gas (GHG) emission reductions needed to limit global warming below 2°C (Haigh et al. 2021) → however, the gap is growing (9.1% circular in 2018 to 8.6% in 2020)!

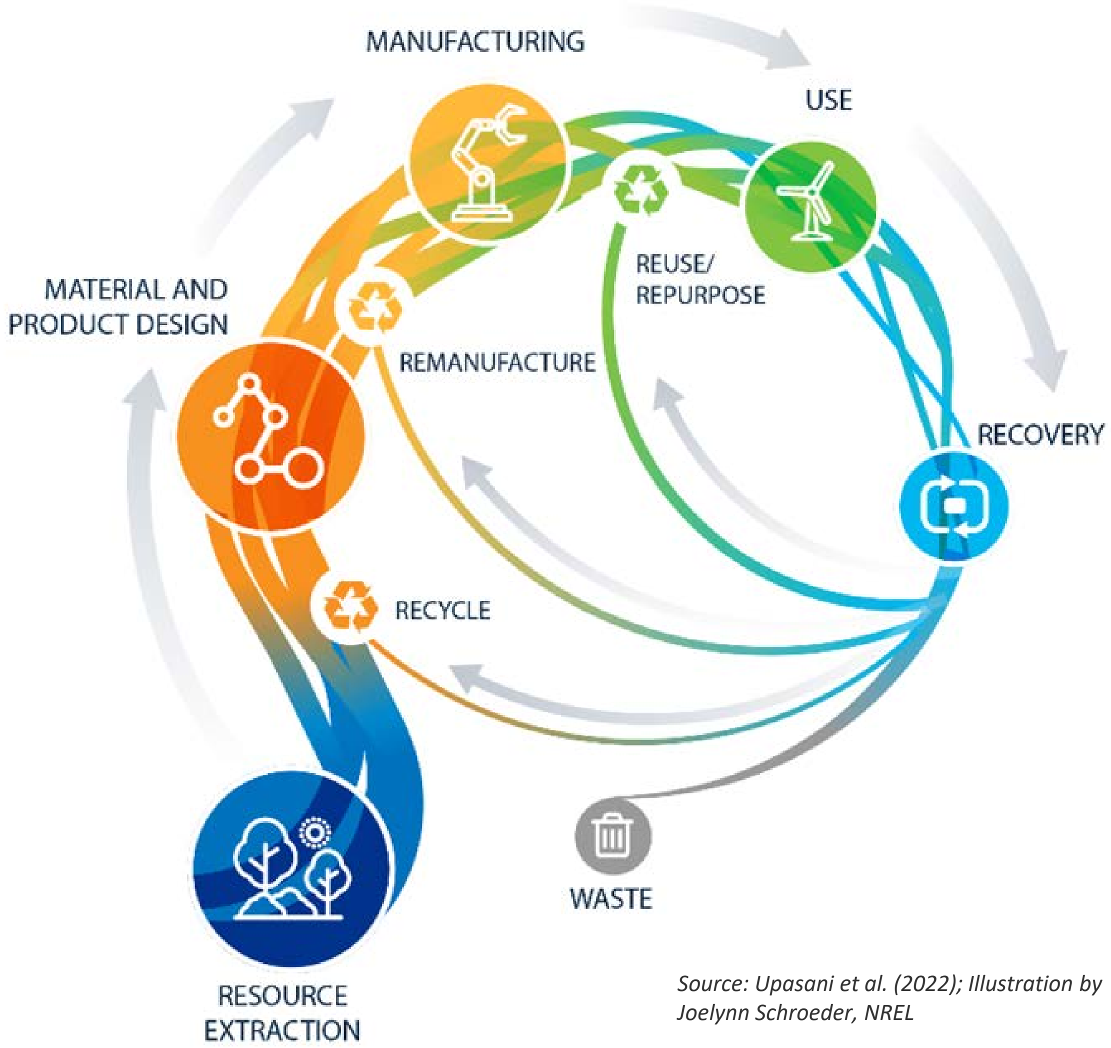
- Examples of contribution of CE to decarbonization:
  - Extending a building's lifetime by 50 years could save 400 Mt of CO_2eq/year (Cai et al. 2015)
  - Light-weighting (e.g., using aluminum) ↓ mass by 26%, avoiding 8% of cars' GHG emissions (Modaresi et al. 2014)
  - Energy sector (Cantzler et al. 2020): Repurposed electric vehicle batteries in houses ↓ GHG emission by 58%

- Two contribution levels of CE to decarbonization can be distinguished:
  - Direct: the CE relies on renewable energy and efficiency, which directly contribute to decarbonization
  - Indirect: e.g., recycle renewables at their EOL

The two contribution levels of a product / service to decarbonization



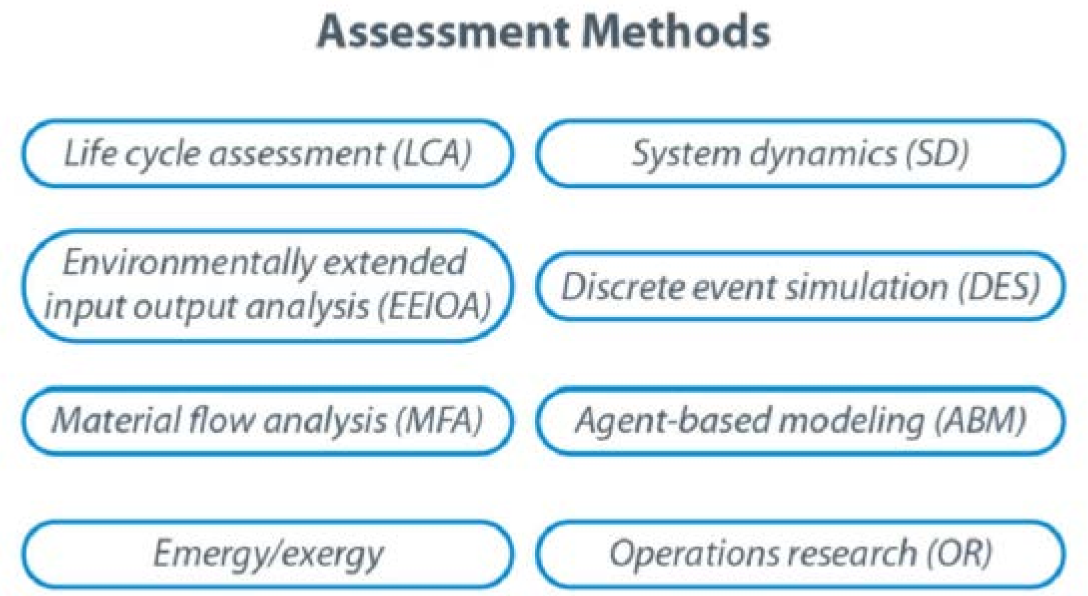
How can we capture the complexity of the problem?



Source: Upasani et al. (2022); Illustration by Joelynn Schroeder, NREL

How do we evaluate CE?

This depends on the research question.



Source: Adapted from Walzberg, Lonca, et al. (2021)

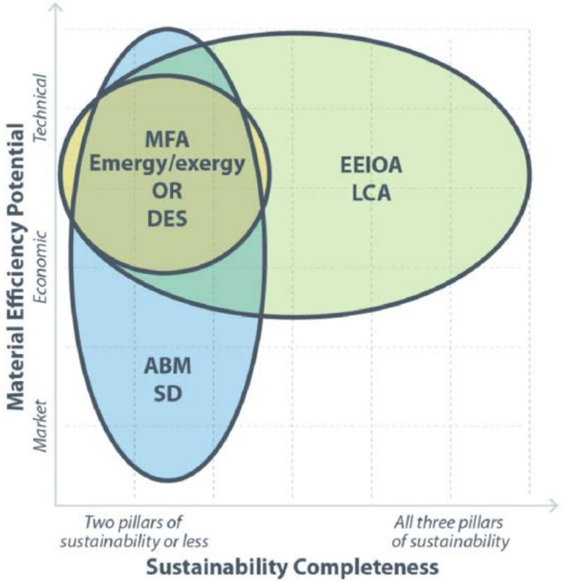
Strengths and weaknesses with respect to CE

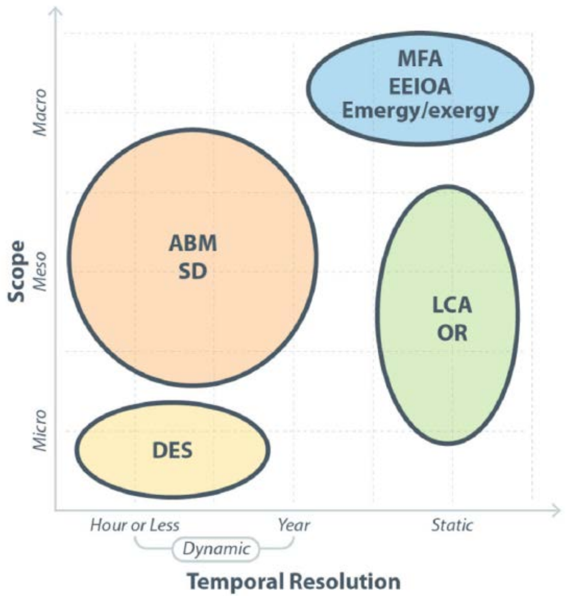
Method	Research question	Scale of most common application	Strengths	Relevance to CE *(numbers 1, 2…correspond to related strengths)*	Weaknesses	Potential solution *(letters A, B… correspond to related weaknesses)*	Circularity metric(s)
Industrial ecology							
LCA	What are the environmental impacts related to a product or system?	Micro/meso (product, supply chain)	1. Models technological processes and their various impacts on the environment 2. Systemic view 3. Also accounts for socio-economic impacts	(1) Able to assess the sustainability of the CE (2,3) Avoidance of impact displacements	A. Data intensive B. Does not model market potential C. Static	(A) Sensitivity analysis (B,C) Combination with other methods (e.g., EEIOA, ABM)	Raw Material Consumption (RMC), Environmental Interventions (LCI), Environmental Impact (LCIA)
EEIOA	What are the environmental impacts related to an economic system?	Macro (world, country)	1. Models economic sectors and their various impacts on the environment 2. Systemic view 3. Can account for socio-economic impacts 4. Incorporates system boundary beyond a single process	(1) Able to assess the sustainability of the CE (2) Avoidance of impact displacements (3) Looks at CE as a whole	A. Fewer environmental interventions accounted for than in LCA B. Does not model market potential C. Static	(A) Use of LCA databases to complement environmental assessment (B,C) Combination with other methods (e.g., ABM, SD)	Raw Material Consumption (RMC), Material Footprint (MF), Circularity gap index (CGI), Waste ratio, Environmental Interventions (LCI), Environmental Impact (LCIA)

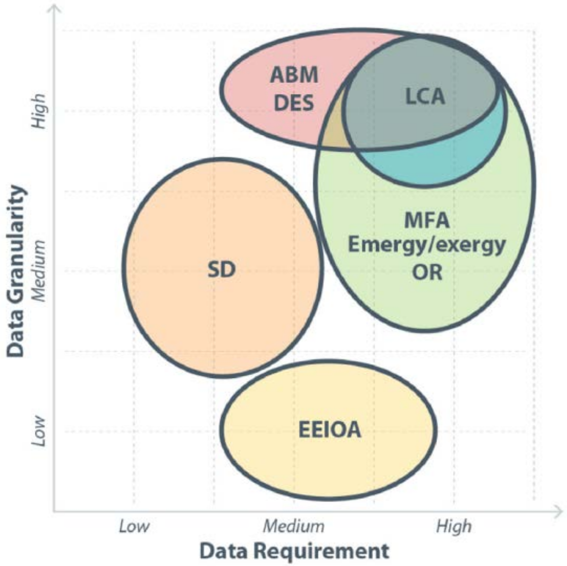
Source: Walzberg, Lonca, et al. (2021)

ABM = agent-based modeling; EEIOA = environmentally extended input-output analysis; LCI = life cycle inventory; LCIA = life cycle impact assessment; SD = system dynamics

How do we evaluate CE?







Source: Walzberg, Lonca, et al. (2021)

EXAMPLE: evaluating methods to satisfy CELAVI research

Circularity transition modeling requirements		LCA	EEIO	MFA	ABM	SD	DES	OR
Capabilities:	Modeling externalities	Green	Green	Yellow	Orange	Orange	Orange	Orange
	Modeling the market potential	Orange	Orange	Orange	Green	Green	Yellow	Yellow
	Modeling uncertainties	Orange	Orange	Yellow	Green	Yellow	Green	Green
	Flexible scope	Yellow	Yellow	Yellow	Orange	Green	Orange	Yellow
Resolution:	Inclusion of temporal aspects	Orange	Orange	Orange	Green	Green	Green	Green
	High spatial definition	Orange	Yellow	Green	Yellow	Green	Yellow	Yellow
	Individual technologies	Green	Yellow	Yellow	Green	Yellow	Green	Green
Scope:	Wide spatial	Orange	Green	Green	Yellow	Green	Yellow	Yellow
	Wide economic	Yellow	Green	Green	Orange	Green	Yellow	Yellow
	Several years	Orange	Orange	Orange	Green	Green	Green	Green

Orange = the method does not meet the requirement; yellow = the method partially meets the requirement; green = the method fully meets the requirements

LCA = life cycle assessment; EEIO = environmentally extended input-output; MFA = material flow analysis; ABM = agent-based modeling; SD = system dynamics; DES = discrete event simulation; OR = operations research

Source: Table recreated from Hanes et al. (2021) and Walzberg, Lonca, et al. (2021)

Guiding Research Questions

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 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 for 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?

CE analysis challenges

- The circular economy requires taking a systemic approach that includes the manufacturers, waste infrastructure, and consumers
  - Who are the stakeholders and decision makers, how do they interact with each other, and what drives their decision-making?
  - Where are the activities?
  - What are the impacts on the different stakeholders and different communities where they are located?
  - How will the activity and impacts change over time?
- Solutions need to be both economically viable) and environmentally friendly
  - The CE keeps value within the economy but also requires new investments
  - The relationship between CE and sustainability is sometime ambiguous (e.g., if recycling a material is more energy-intensive than extracting it)
- Multiple technology pathways
- Multiple application pathways

What are the challenges and research questions?

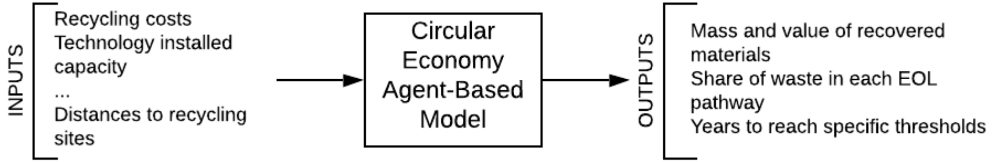
- Will/can the new technology/business model/behavior be adopted and how can we facilitate that?
  - Driven by economics, policy, societal choices, industry practices and knowledge and skills
- What are the environmental and economic impacts of transitioning to a circular supply chains for energy materials?
  - How do these impacts vary across regions and across industrial sectors?
  - What are the uncertainties associated with these impacts?
  - How can this information be used to inform decisions around circularity transitions?

Current NREL CE Approaches

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

Primary research questions:

*What are the **technical, economic, and market conditions** that **maximize the value retention** and **minimize raw material inputs** when applying CE strategies to energy-generating and energy-consuming technologies?*



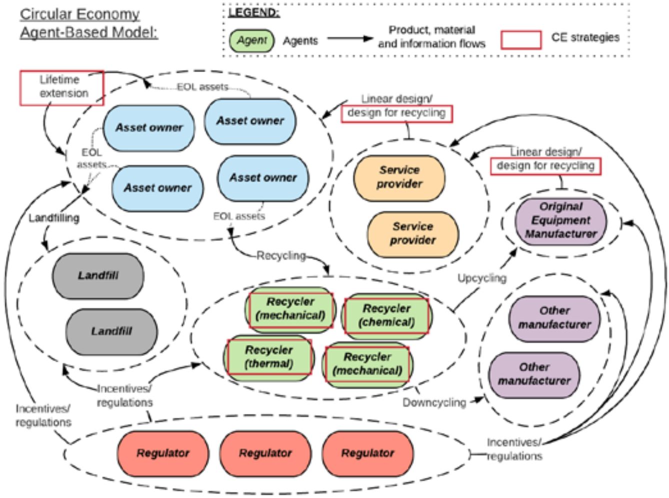
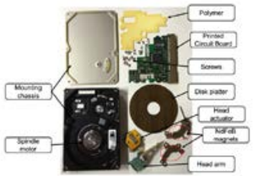


Illustration by Julien Walzberg, NREL

3 case studies:



Hard-disk drives

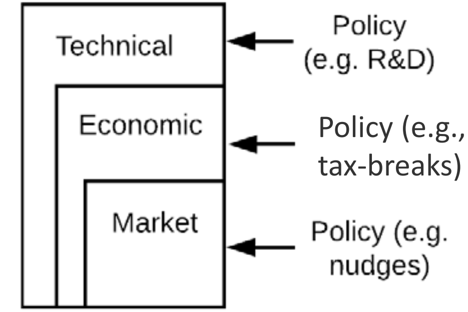
Source: München and Veit (2017)

PV

Photo by Dennis Schroder, NREL 31465

Wind

Photo by Werner Slocum, NREL 62956



Material efficiency potentials

PI: Julien Walzberg

(Walzberg et al. 2022)

(Walzberg, Carpenter, and Heath 2021)

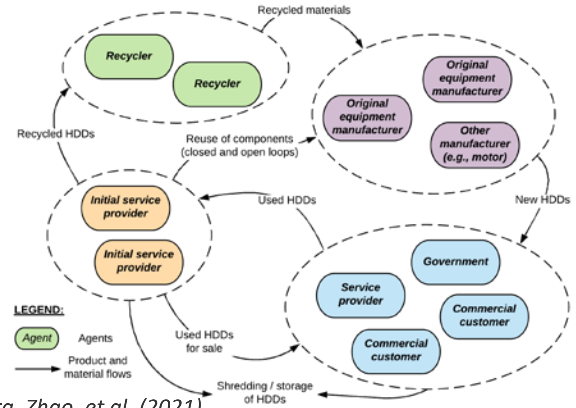
CE Hard-Disk Drives ABM

Investigation of hard-disk drive circularity accounting for socio-technical dynamics and data uncertainty

Model overview:

- 4 types of agents: end-users, initial service providers, recyclers, manufacturers
- 5 end-of-life (EOL) options: reuse, magnet reuse, recycling with rare earth elements recovery, shredding, storage
- EOL Option chosen according to the Theory of Planned Behavior (highest score):

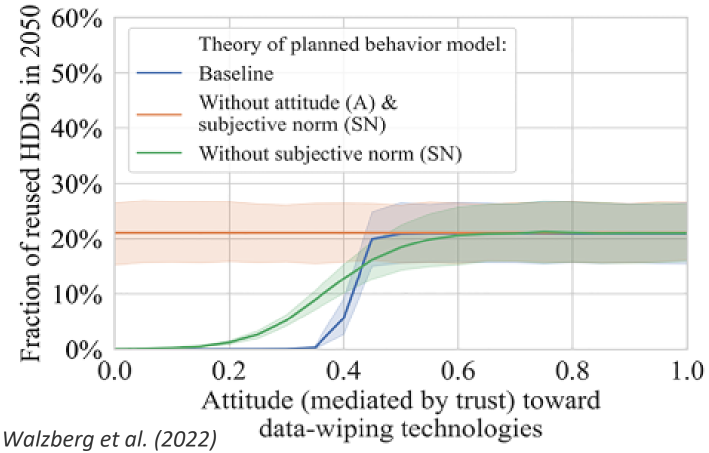
$$B_{ij}^{t} = w_A A_{ij}^{t} + w_{SN} SN_{ij}^{t} + w_{PBC} PBC_{ij}^{t} \ *$$



Source: Walzberg, Zhao, et al. (2021)

Results:

- Peer pressure acts as a double-edged sword (blue and green curves): it reinforces the lack of trust toward data-wiping (necessary for the more circular reuse pathways) when low among agents but also enhances that trust once established.
- If end-users' decisions were based only on value recovery, hard-disk drive (HDD) circularity rate would be maximal (orange curve).



Source: Walzberg et al. (2022)

*Where at t, for each agent i and option j: BI = behavioral intention of performing the behavior; A = attitude toward the behavior; SN = subjective norms; PBC = perceive behavioral control over the behavior; w_A, w_{SN}, w_{PBC} = regression coefficients

CELAVI

Circular Economy Lifecycle Assessment and VIsualization

Research Question: What are the environmental and economic impacts of transitioning to circular supply chains for energy materials?

- How do these impacts vary across regions and across industrial sectors?
- What are the uncertainties associated with these impacts?
- How can this information be used to inform decisions around circularity transitions?

Current approaches for modeling and analyzing circular supply chains:

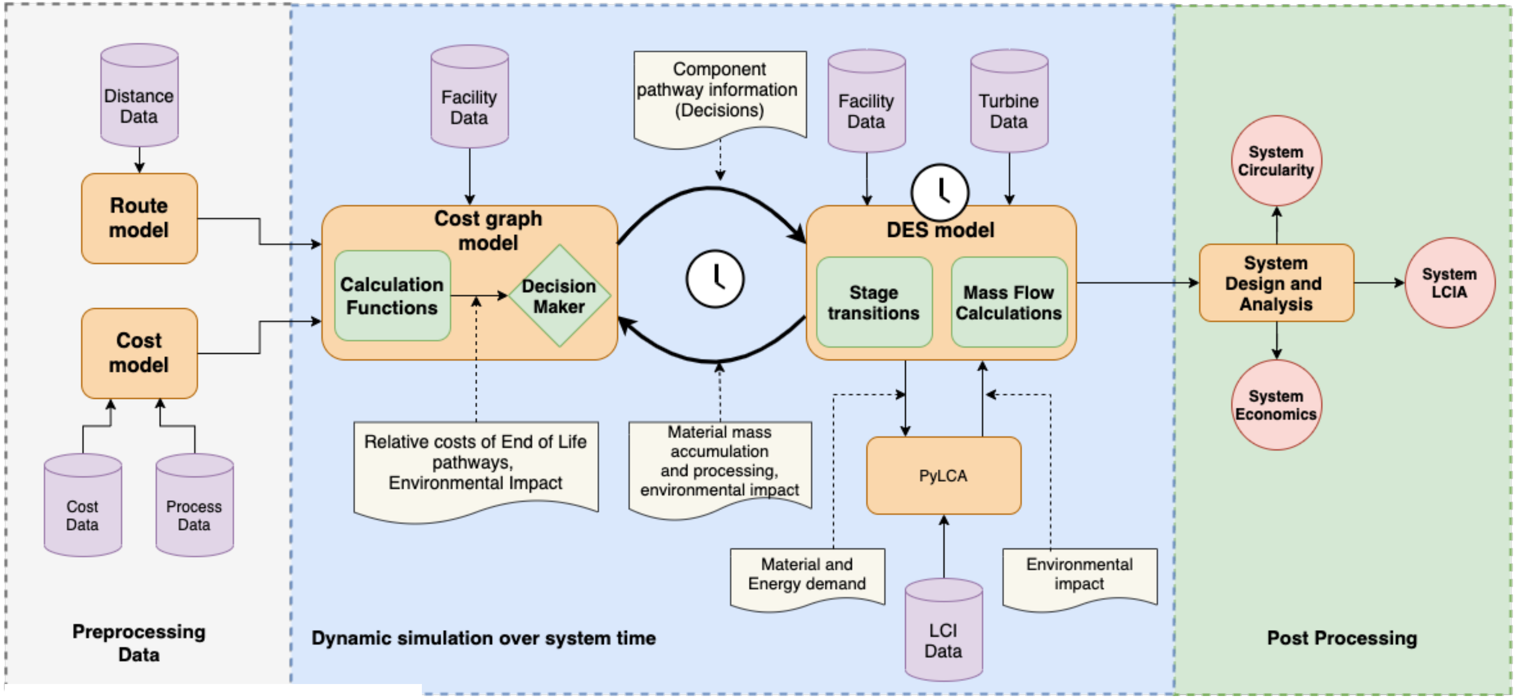
- *Exclude* market dynamics
- *Exclude* economy-wide structural and sectoral changes
- *Lack* endogenous models of decision processes
- *Lack* uncertainty quantification

PI: Annika Eberle

(Hanes et al. 2021)

CELAVI hybridizes existing methods to meet the demands of modeling circularity transitions and associated impacts.

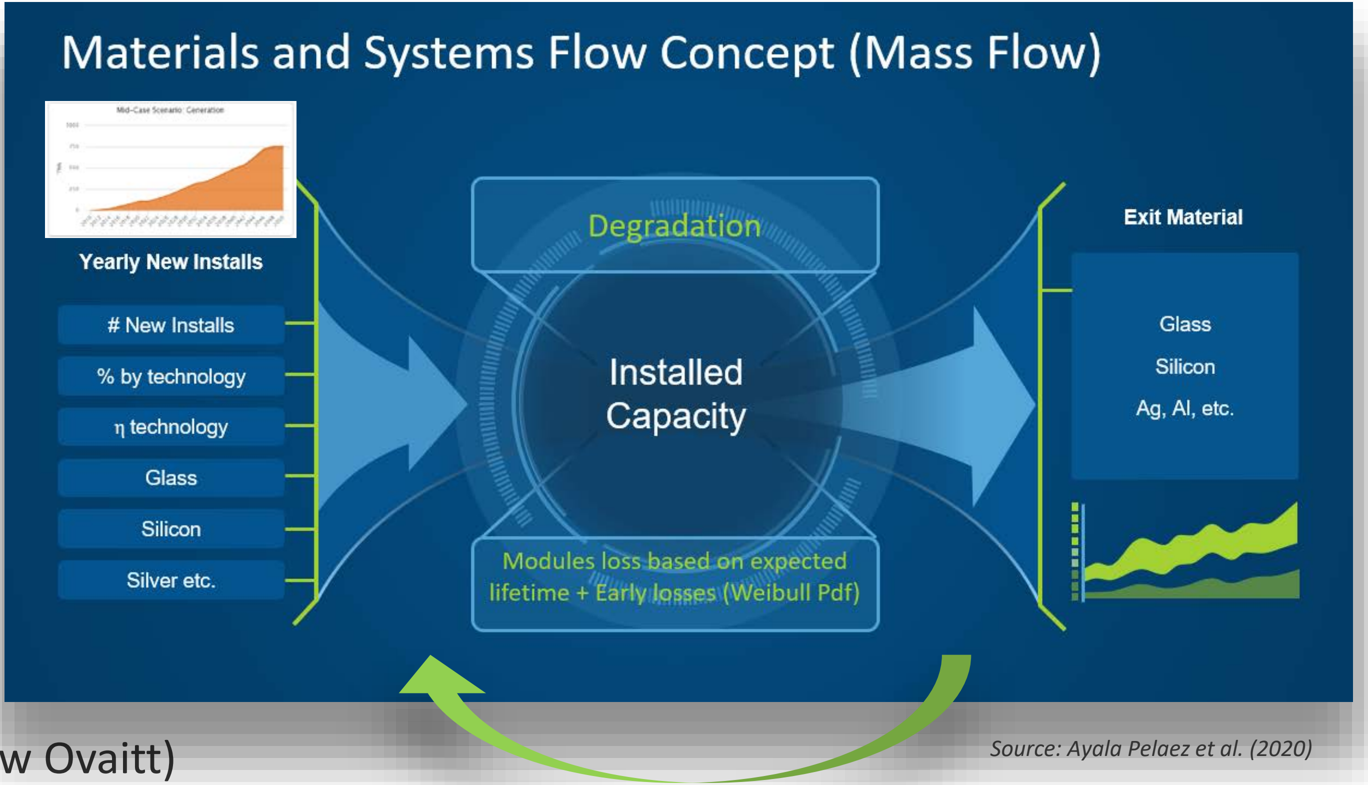
Discrete event simulation, a network-based supply chain cost model, and life cycle impact assessment are integrated into a generalized, data-driven modeling framework for quantifying the externalities of circularity transitions.



Source: Upasani et al. (2022)

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.



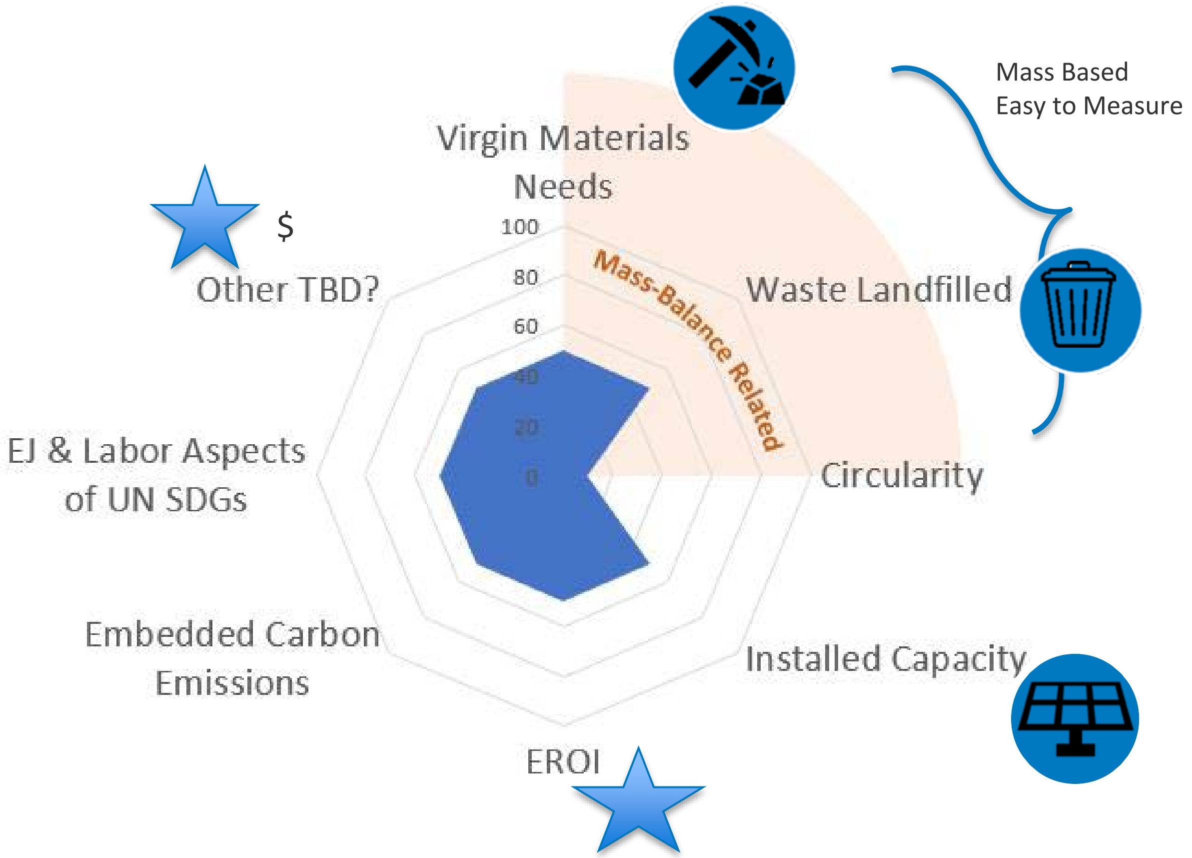
Source: Ayala Pelaez et al. (2020)

PI: Silvana Ayala Pelaez (now Ovaitt)

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

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

Sustainability Dimensions



PV_ICE

In progress

PV ICE's Integrated NREL Circular Approach

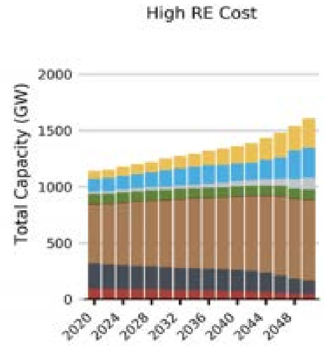
NEW INSTALLS

MANUFACTURING

INSTALLED CAPACITY AND EXTENDED USEFUL LIFE

EOL MODES

CIRCULAR PATHWAYS

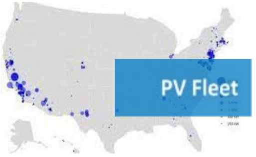


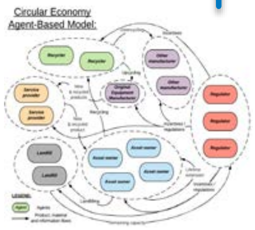
ReEDS

MFI

PV Reliability Group

DuraMAT
Durable Module Materials Consortium



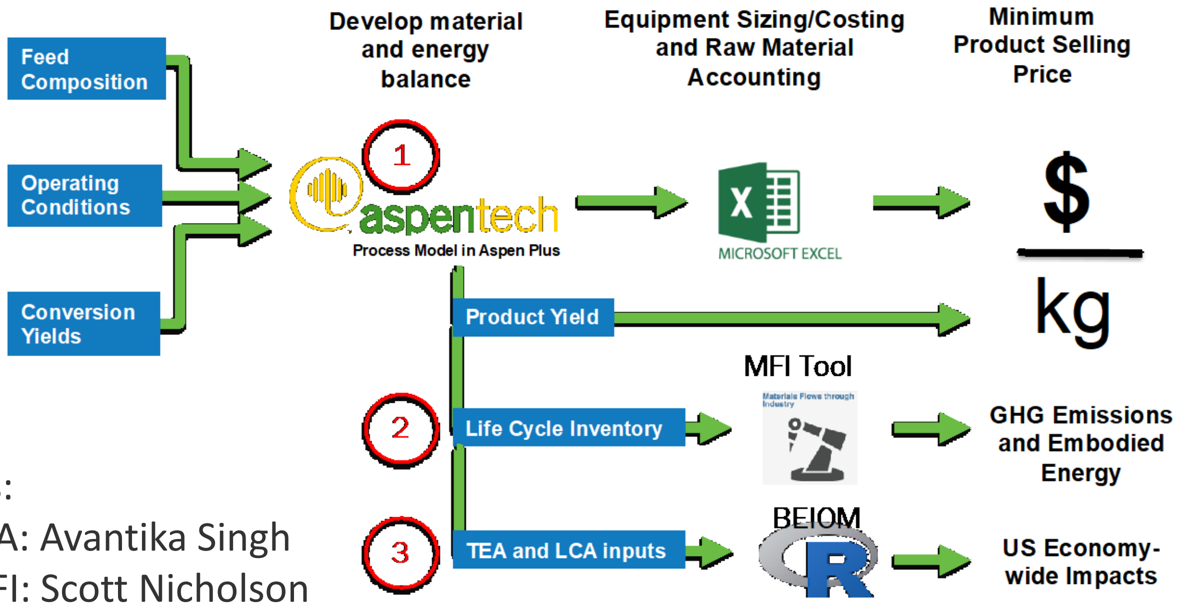


Walzberg's Agent-Based Model

CELAVI Landfill Calculation Approach

Analysis-Guided R&D

- Analysis guides which polymers we work on
- Techno-economic analysis (TEA) using Aspen Plus
- Energy/GHG assessment via Materials Flows through Industry (MFI)
- All major BOTTLE[TM] projects evaluated for C, $, and E metrics



Approach to analysis

- Work with analysis in parallel to lab R&D
- Mass and energy balances early in projects
- Evaluate ability to meet key metrics based on "theoretical maximum" case
- As projects increase in technology readiness level (TRL), they merit more in-depth analysis

PIs:
TEA: Avantika Singh
MFI: Scott Nicholson
BEIOM: Patrick Lamers

https://www.bottle.org/publications.html BOTTLE = Bio-Optimized Technologies to keep Thermoplastics out of Landfills and the Environment

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Questions?

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