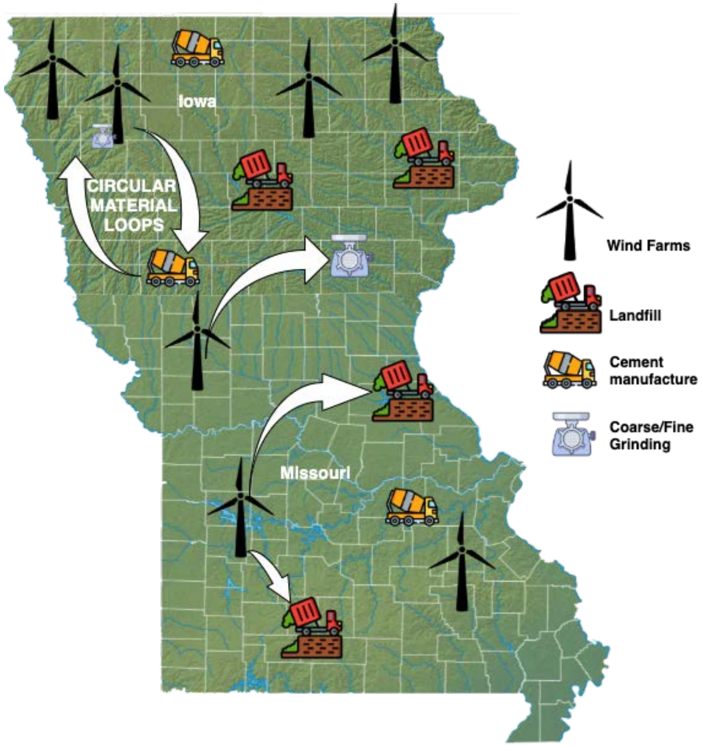
The Circular Economy Lifecycle Assessment & Visualization (CELAVI) Framework: Current & Future Capabilities & Applications



Thursday, June 16, 2022

1:00 pm EDT (will start promptly)

Presenters:
Julien Walzberg and Rebecca Hanes,
National Renewable Energy Laboratory (NREL)

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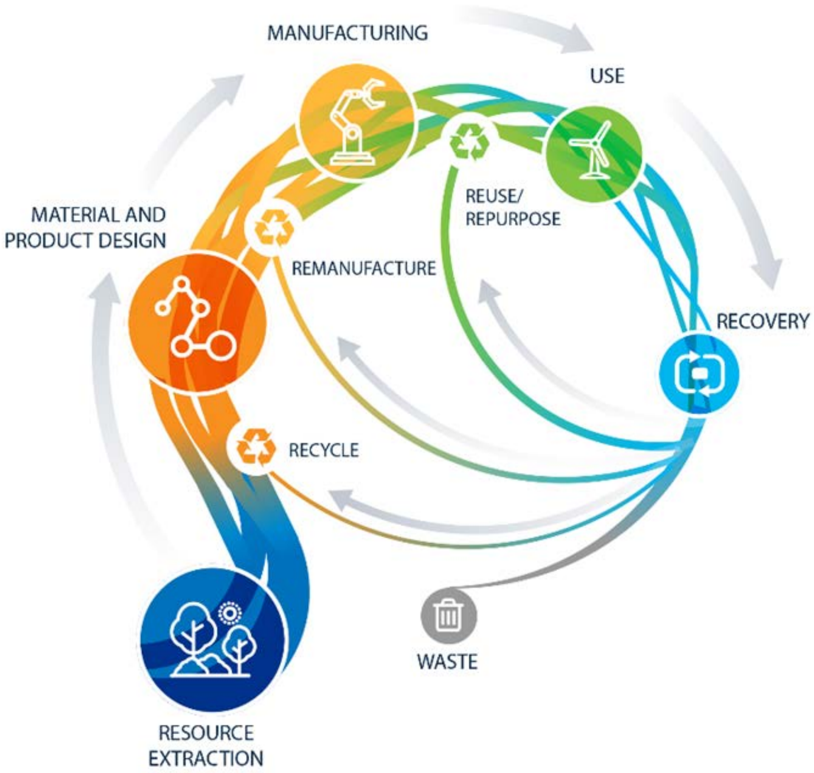
Circular Economy Modeling Efforts at NREL

Circular Economy Lifecycle Analysis and Visualization (CELAVI) and the Circular Economy Agent-Based Model (ABM)

Rebecca Hanes and Julien Walzberg

June 16, 2022

The Circular Economy



Objectives

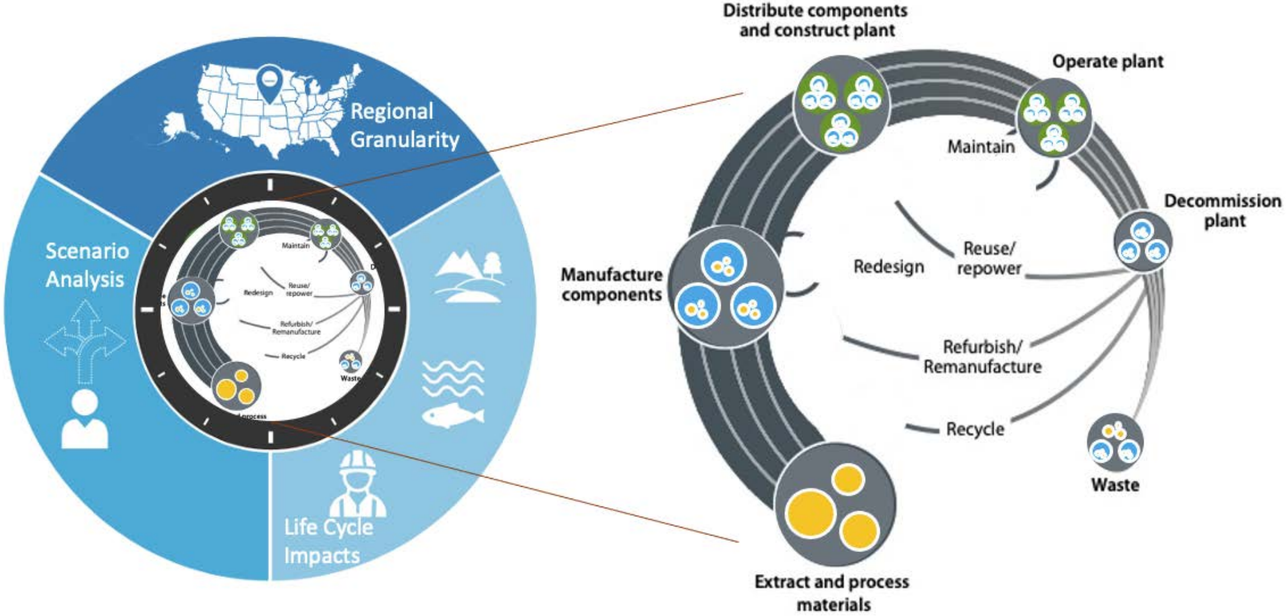
- Optimize resource yields by circulating products, components and materials in use at the highest possible utility
- Preserve and enhance natural capital by controlling finite stocks and balancing renewable resource flows
- Foster system effectiveness by revealing and designing out negative externalities

Four Overarching Principles

- Narrow flows (use less)
- Slow flows (use longer)
- Use regenerating flows (make cleaner)
- Cycle flows (use again)

CELAVI Overview

Objective: Assess the type, quantity, and spatio-temporal distribution of impacts that occur when a supply chain transitions from linearity towards circularity.



Outcome: The Circular Economy Lifecycle Assessment and Visualization (CELAVI) modeling framework simulates circularity transitions within supply chains and quantifies the associated environmental and economic impacts.

Circularity Transition Modeling Requirements

Walzberg et al., *Front. Sustain.* (2021)
Hanes et al., *Front. Sustain.* (2021)

Discrete event simulation

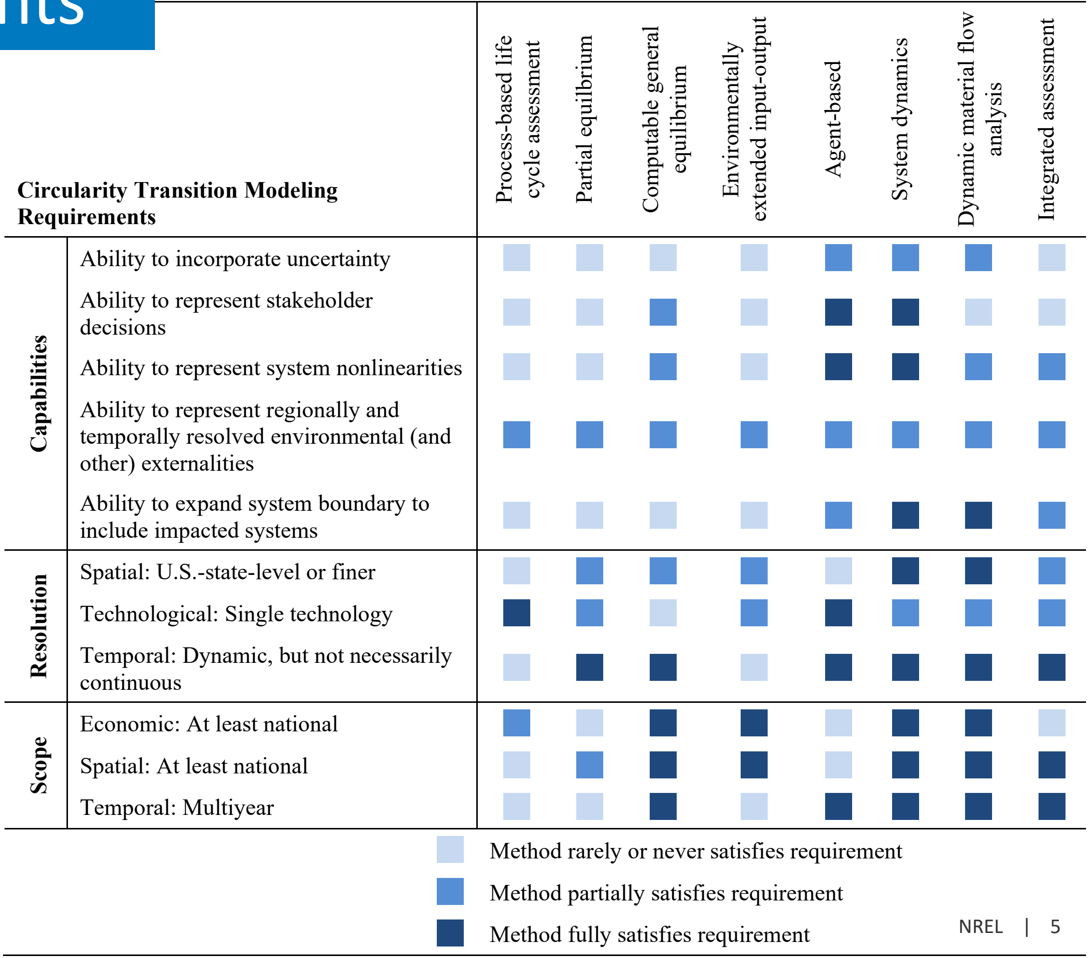
- Tracks material and component flows.

Directed network supply chain model

- Calculates pathway costs.
- Models stakeholder decisions.

Process-based, attributional **life cycle impact assessment**

- Calculates TRACI 2.1 midpoint indicators.
- Models electric grid changes over time.



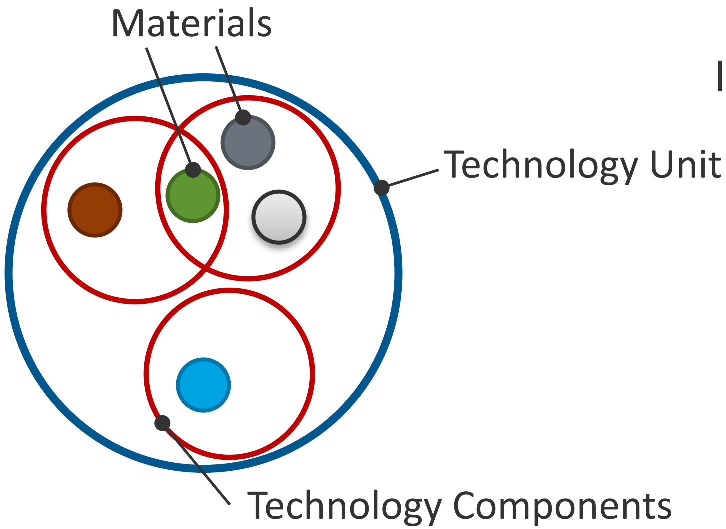
Circularity Transition Modeling Requirements		Process-based life cycle assessment	Partial equilbrium	Computable general equilibrium	Environmentally extended input-output	Agent-based	System dynamics	Dynamic material flow analysis	Integrated assessment
Capabilities	Ability to incorporate uncertainty	□	□	□	□	◧	◧	◧	□
	Ability to represent stakeholder decisions	□	□	◧	□	■	■	□	□
	Ability to represent system nonlinearities	□	□	◧	□	■	■	◧	◧
	Ability to represent regionally and temporally resolved environmental (and other) externalities	◧	◧	◧	◧	◧	◧	◧	◧
	Ability to expand system boundary to include impacted systems	□	□	□	□	◧	■	■	◧
Resolution	Spatial: U.S.-state-level or finer	□	◧	◧	◧	□	■	■	◧
	Technological: Single technology	■	◧	□	◧	■	◧	◧	◧
	Temporal: Dynamic, but not necessarily continuous	□	■	■	□	■	■	■	■
Scope	Economic: At least national	◧	□	■	■	□	■	■	□
	Spatial: At least national	□	◧	■	■	□	■	■	■
	Temporal: Multiyear	□	□	■	□	■	■	■	■

□ Method rarely or never satisfies requirement
◧ Method partially satisfies requirement
■ Method fully satisfies requirement

CELAVI Overview

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

- Discrete event simulation (DES)
- A network-based supply chain model (Cost Graph)
- Life cycle impact assessment (PyLCIA)



It includes **three levels** of technology resolution:

1. Individual materials (e.g., cement)
2. Individual components (e.g., wind blade)
3. Technology unit or plant (e.g., all turbines, grouped by power plant, within a region)

CELAVI Model Structure

Discrete Event Simulation

- Simulates and tracks material flows and transportation
- Runs Cost Graph and PyLCIA at user-specified intervals

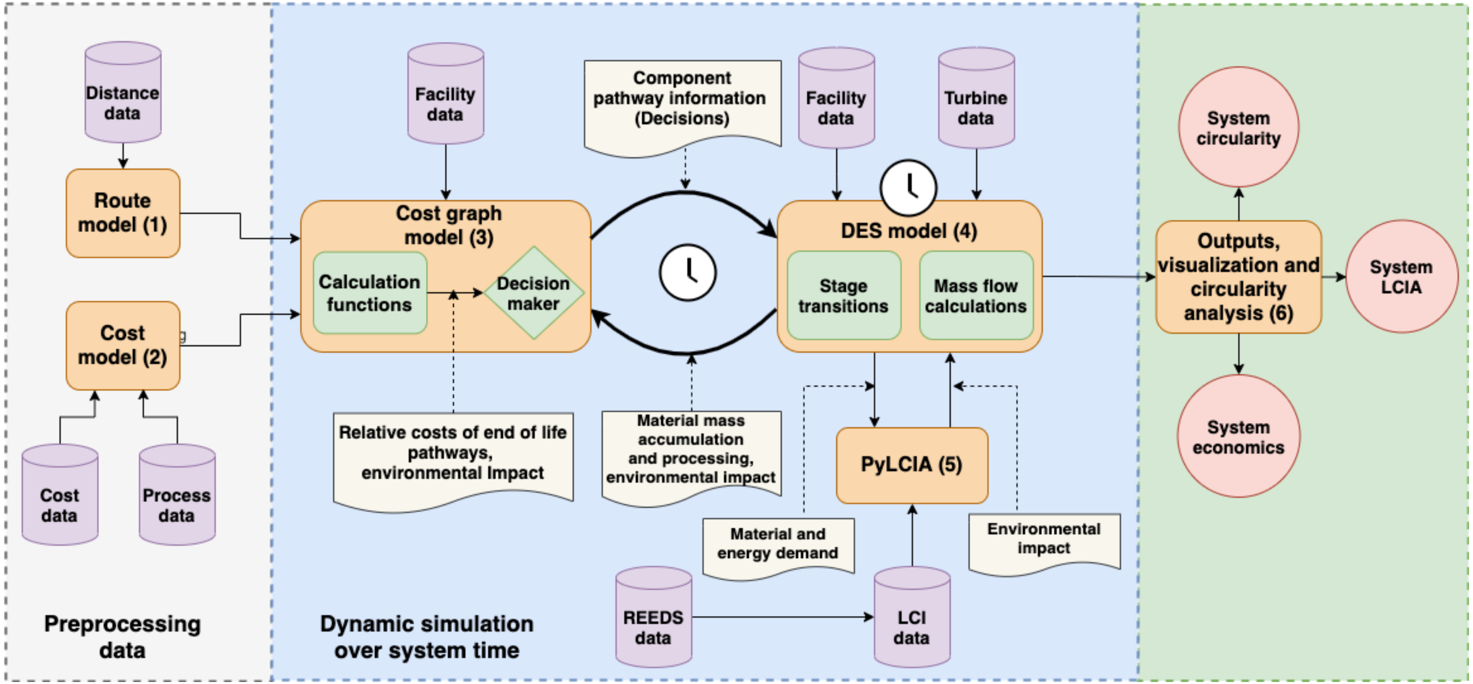
Cost Graph

- Calculates end-of-life (EOL) pathway characteristics: cost, distances, and total environmental impacts
- Identifies preferred EOL pathways and associated facility locations

PyLCIA

- Calculates environmental materials by material and processing step
- Updates electricity grid mix in foreground LCI over time

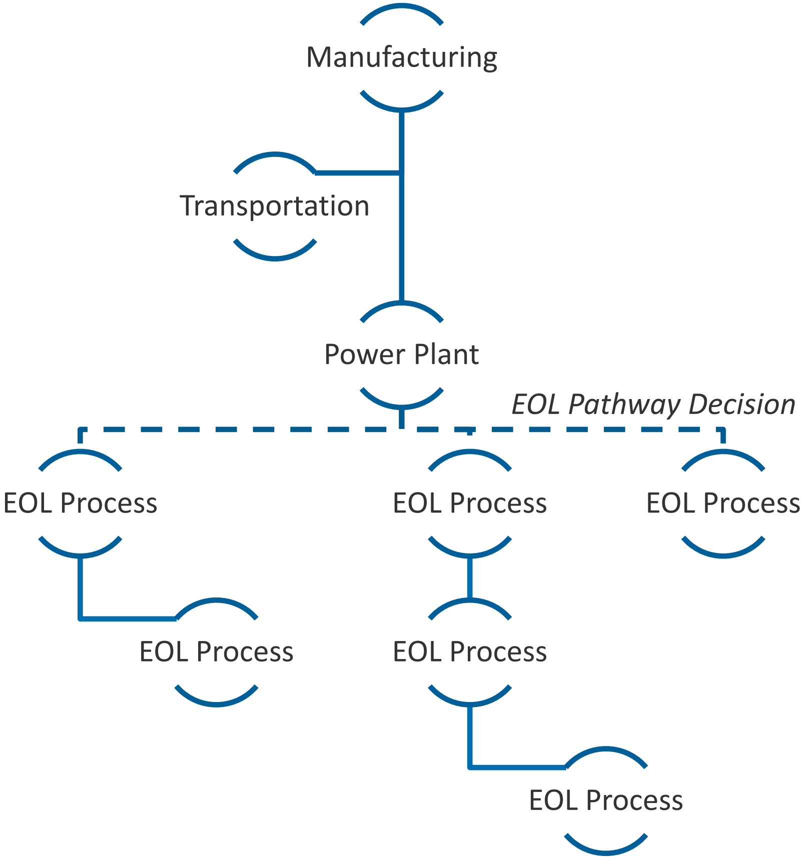
CELAVI Model Structure



- Codebase is available at https://github.com/NREL/celavi/releases
- Written in Python 3 with CSV file format for input datasets.
- Executable on personal machines or on NREL’s supercomputer.

DES Module

The DES simulates material flows as technology component transitions between facilities and processes.

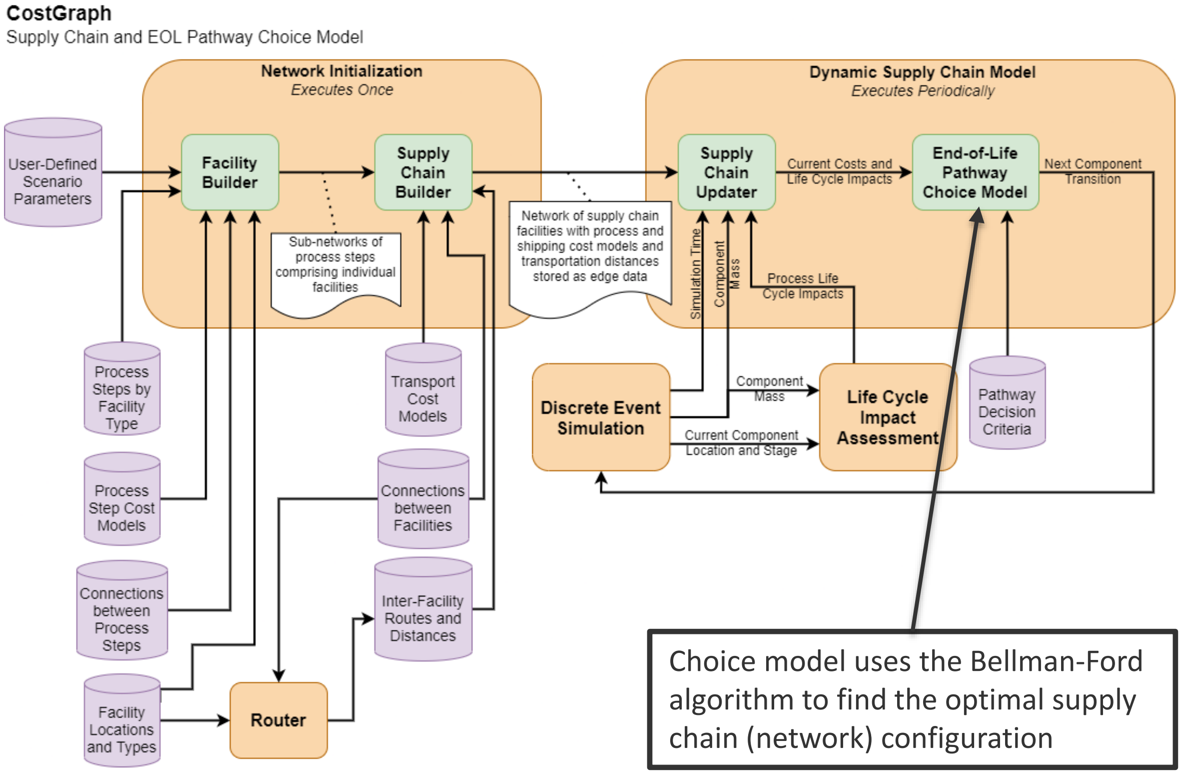


Material flows are simulated by modeling individual technology components and their constituent materials as the components transition between supply chain facilities and processes.

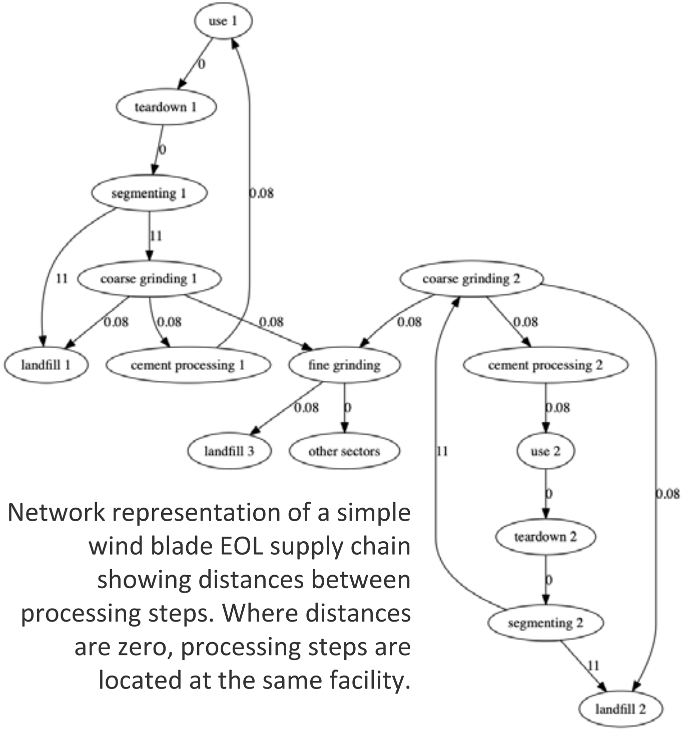
- Every component is initialized with a type, a set of material masses, an installation year, and a lifetime.
- Component and material movements are tracked with facility-level inventories and a transportation tracker.
- End-of-life component transitions are determined by querying the Cost Graph model to determine the preferred pathway.

Cost Graph Module

The Cost Graph is a network representation of the supply chain superstructure, used to identify and update preferred EOL pathways during the simulation.



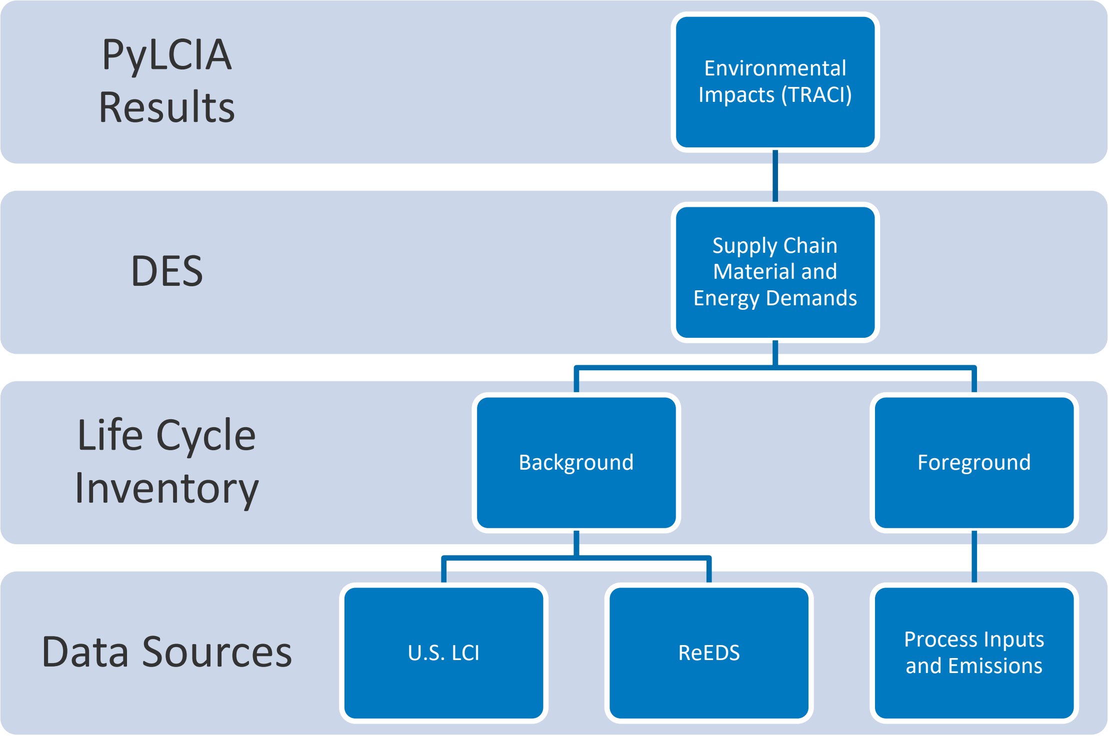
Choice model uses the Bellman-Ford algorithm to find the optimal supply chain (network) configuration



Network representation of a simple wind blade EOL supply chain showing distances between processing steps. Where distances are zero, processing steps are located at the same facility.

PyLCIA

Environmental impacts are calculated for the supply chain as it transitions towards circularity.



PyLCIA Results

Environmental Impacts (TRACI)

DES

Supply Chain Material and Energy Demands

Life Cycle Inventory

Background

Foreground

Data Sources

U.S. LCI

ReEDS

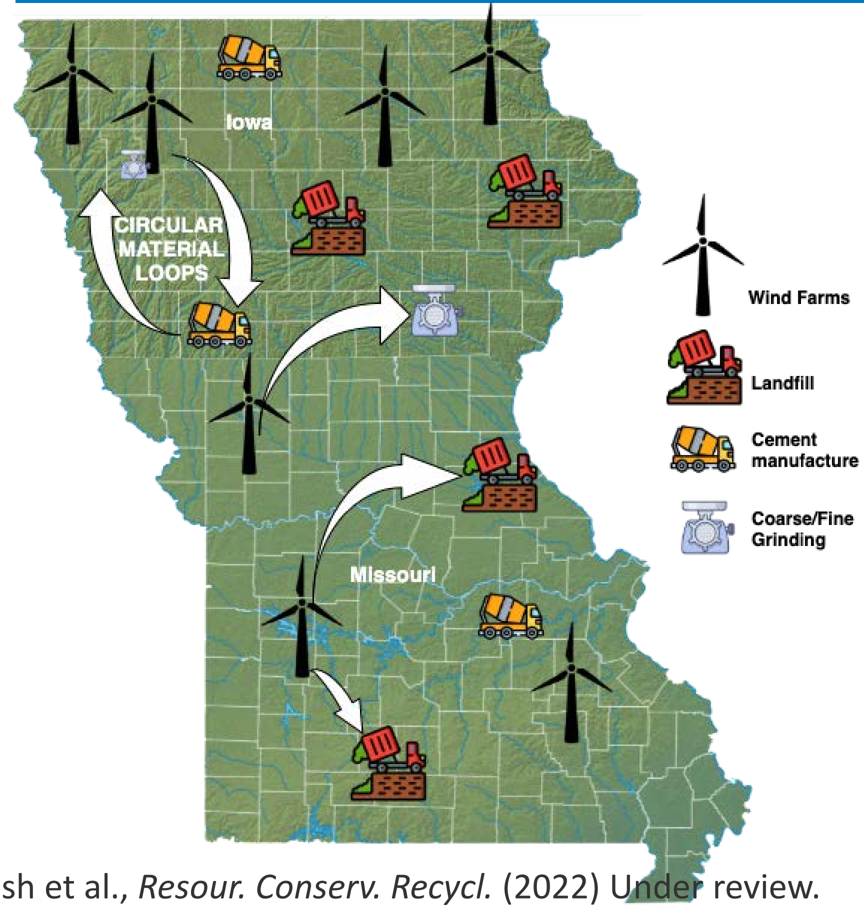
Process Inputs and Emissions

- The supply chain modeled by the DES requires material and energy inputs to operate.
- The PyLCIA module combines the U.S LCI, data from ReEDS, and process-specific inputs to calculate spatially and temporally disaggregated environmental impacts.
- PyLCIA results indicate how circularity affects the magnitude, location, and timing of environmental impacts associated with the supply chain.

Cole et al. (2020)
cambium.nrel.gov

Iowa & Missouri Case Study

Wind Turbine Blade Circularity



Ghosh et al., *Resour. Conserv. Recycl.* (2022) Under review.

Scope

- Turbines installed and retired in the U.S. states of Iowa & Missouri, 2000 – 2050
- Glass fiber and epoxy materials contained in GFRP blades
- EOL pathway options are cement co-processing, mechanical recycling, or landfilling

Research Questions

- How do processing costs impact circularity in the wind blade supply chain?
- How does the supply chain transition towards circularity?
- How do circularity transitions affect supply chain environmental impacts?

Results

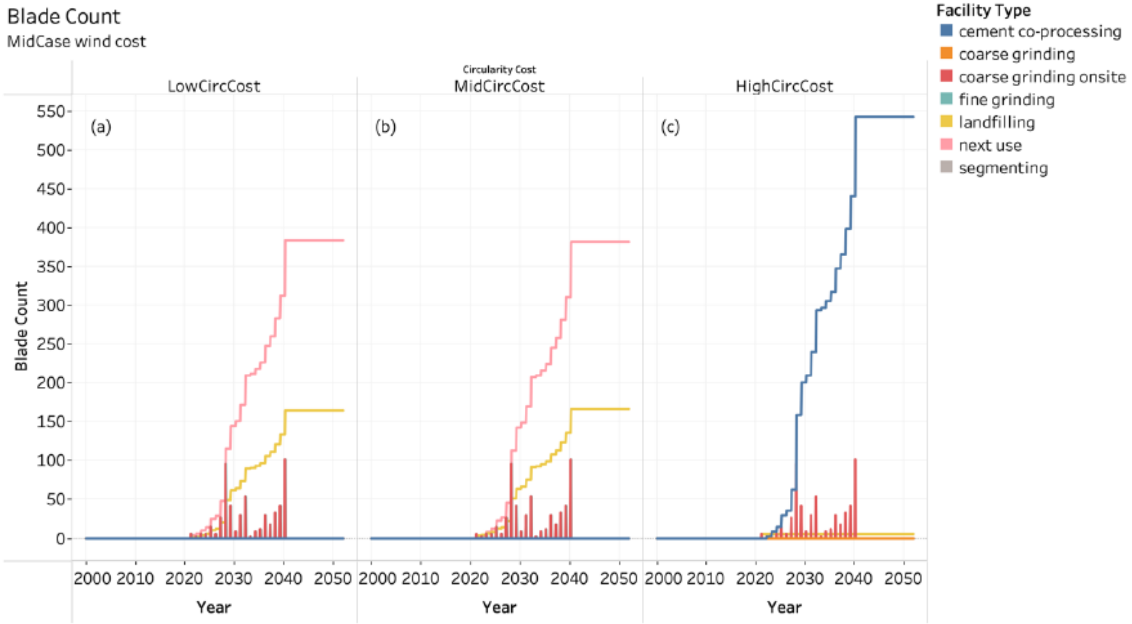
How do processing costs impact circularity transitions?

EOL processing costs do not appear to be a major barrier to implementing circular pathways.

- Under all three circularity cost scenarios, circular pathways were implemented instead of landfilling for most blades.

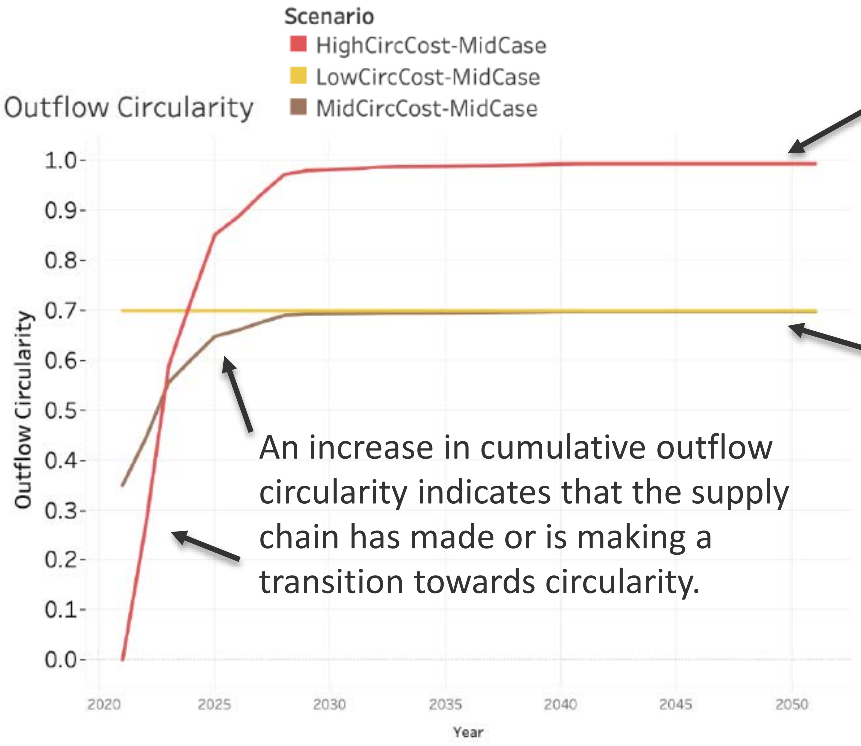
Transportation costs appear to have little to no effect on the total EOL pathway cost, *for this supply chain*.

Landfilling is not entirely avoided in two scenarios, due to material losses in the mechanical recycling pathway.



Results

How does the wind blade supply chain transition towards circularity?



An increase in cumulative outflow circularity indicates that the supply chain has made or is making a transition towards circularity.

Under high circularity costs, outflow circularity increases asymptotically to 1.0 due to implementation of the low-material-loss cement co-processing pathway.

Under the other two scenarios, the outflow circularity remains less than 1.0 due to significant material losses in the implemented pathway.

Outflow circularity = fraction of end-of-life materials that can be recirculated

Results

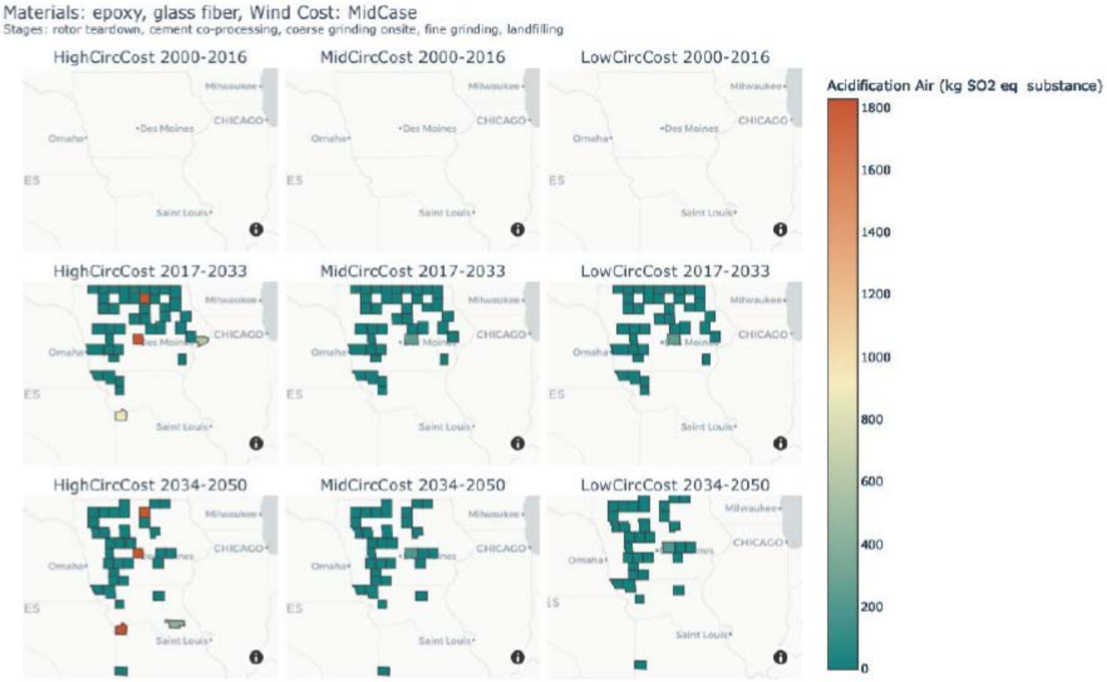
How do circularity transitions affect supply chain environmental impacts?

Analysis of environmental indicators:

- Life cycle impact assessment methodology = Tool for Reduction and Assessment of Chemicals and Other Environmental Impacts (TRACI 2.1) (Bare, 2011)
- Impacts are disaggregated by region, time period, component, materials, and process.

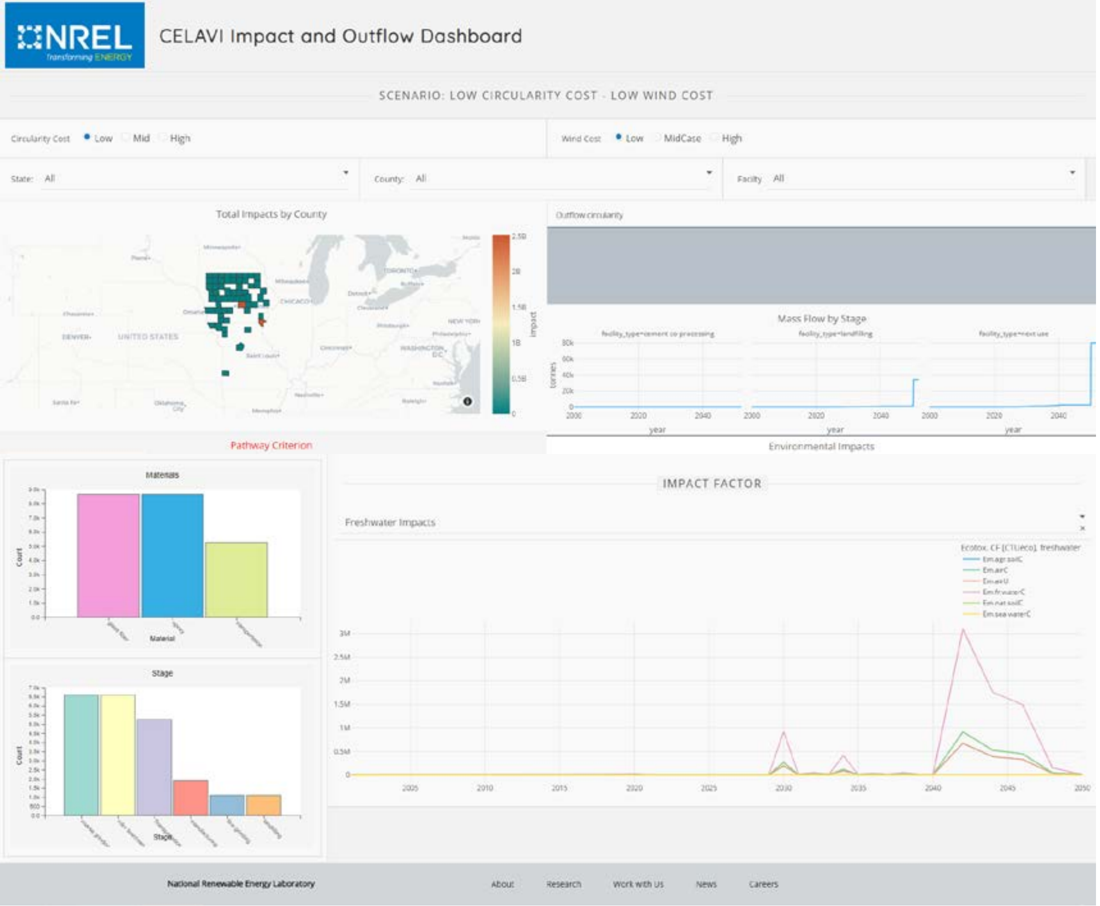
The cement coprocessing pathway results in the highest overall environmental impacts due to energy use and in-situ emissions, as well as hot spots where the cement plants are located.

The current study does not include the system expansion approach of consequential LCA (e.g., benefits from substituting materials in cement coprocessing are not included).



Results

Interactive visualization dashboard for decision support



CELAVI Impact and Outflow Dashboard

SCENARIO: LOW CIRCULARITY COST - LOW WIND COST

Circularity Cost ● Low ○ Mid ○ High

Wind Cost ● Low ○ MidCase ○ High

State: All

County: All

Facility All

Freshwater Impacts

- An interactive browser-based dashboard for visualizing key CELAVI outcomes is under development.
- Decision-makers and stakeholders will be able to access relevant results, apply filters, explore scenarios, and visualize the impact of uncertainty.
- Currently the dashboard is only available internally at NREL, but it will be made publicly available by the end of the project this fall.

Case Study – Lessons Learned

- The increase in global warming potential (GWP) when circularity is implemented is small (< 10%) relative to the total supply chain (including manufacturing) GWP.

- Environmental impacts from EOL will vary spatially and temporally during the circularity transition.

- How the blades are reduced in size before transportation has a large impact on EOL pathway costs, as does the recycling cost.

- Which circularity metrics are relevant and informative depends on the type of circularity implemented.
  - Open-loop, closed-loop, EOL materials used for energy generation, etc.

Ongoing and Future Work

Under Active Development

- Uncertainty analysis:
  - How are results affected when a parameter is removed?
  - How much can a parameter value vary from its baseline before affecting results?
  - How does uncertainty propagate when varying several parameters from their baseline?

Still to Explore

- Include more EOL technologies in existing case study.
- Include more wind turbine components and materials (e.g., permanent magnets and rare-earth elements)

Long-Term Vision

- Increase regional granularity of technologies and externalities.
- Integrate CELAVI with other models and tools:
  - Connect CELAVI to a larger-scale model such as BEIOM* for quantification of national-scale economic metrics.
  - Combine CELAVI and the CE ABM** to improve CE strategies adoption modeling.

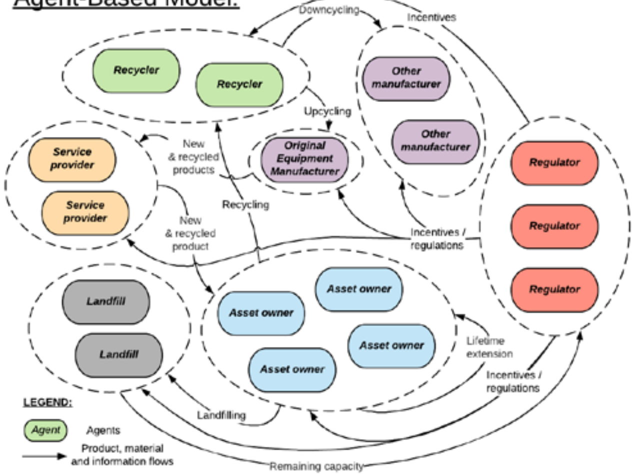
* BEIOM: Bio-based circular carbon economy Environmentally-extended Input-Output Model (Avelino et al., 2021)

** CE ABM: Circular Economy Agent-Based Model (Walzberg et al., 2021)

The CE ABM framework

Circular Economy Agent-Based Model (CE ABM) overview

Circular Economy Agent-Based Model:



Primary research question:

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?

INPUTS

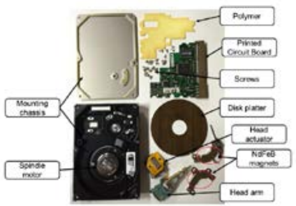
Recycling costs
Technology installed capacity
…
Distances to recycling sites

Circular Economy Agent-Based Model

OUTPUTS

Mass and value of recovered materials
Share of waste in each EOL pathway
Years to reach specific thresholds

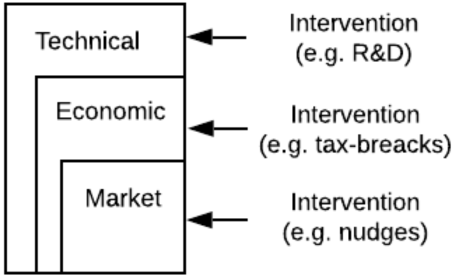
3 case studies:



Hard-disk drives

PV

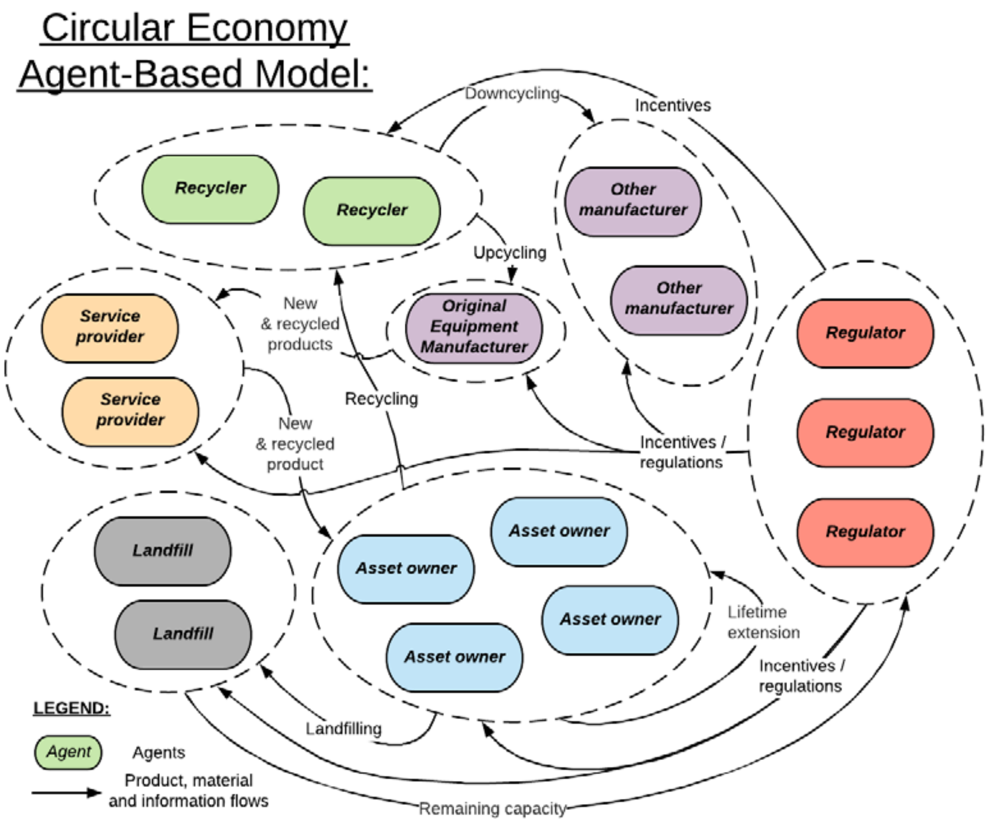
Wind



Material efficiency potentials

Image sources: NREL Image Gallery, München and Veit (2017)

CE ABM overview



- 6 types of agents: manufacturers, wind plant developers, wind plant owners, recyclers, regulators, landfills
- 3 EOL options: lifetime extension (i.e., repair), recycling (pyrolysis, grinding, co-processing), landfill
- 2 manufacturing options: thermoset blades, thermoplastic blades
- EOL option chosen according to an extended version of the Theory of Planned Behavior (TPB) (highest score):
- Model implementation:
  - Python (Git here)
  - Agent types are python classes (1 agent=1 class instance)
- Simulations:
  - Time step = 1 year
  - Studied period = 2020-2050
  - Scope: the United States

Example of agents' behavior rules

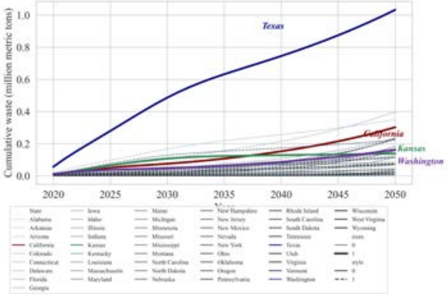
Details – asset owners:

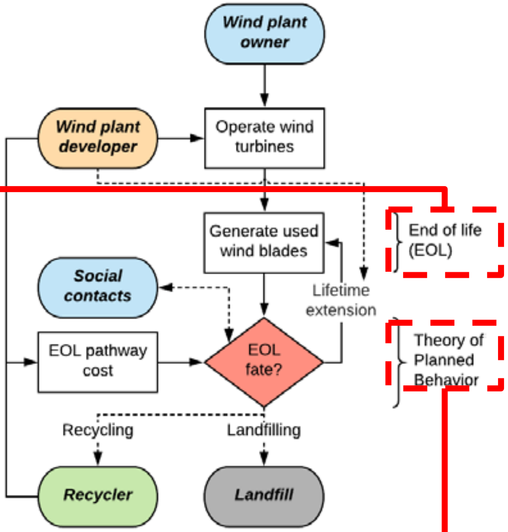
- The TPB is used to model the purchase decision (i.e., new versus used/refurbished assets)
- A Weibull function is used to generate the quantity of EOL assets at each time step
- The TPB is used to model the EOL management decision (i.e., repair, reuse, recycle, landfill, storage)

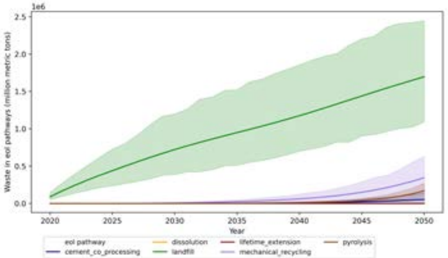
CE wind ABM example:

- 1320 wind plant owners (one for each wind plant project in the US) defined from the United States Wind Turbines Database (USWTDB)
- Texas wind plant projects generate most of the EOL wind blades

$$ELW_i^t = RPC_i^t \times \left(1 - e^{-(t/T)^{\alpha}}\right)^*$$







$$B_{ij}^t = w_{BI}\left(w_A A_{ij} + w_{SN} SN_{ij}^t + w_{dPBC} PBC_{ij}^t\right) + w_{iPBC} PBC_{ij}^t + w_P P_{ij}^t + w_{BA} BA_{ij}{}^{**}$$

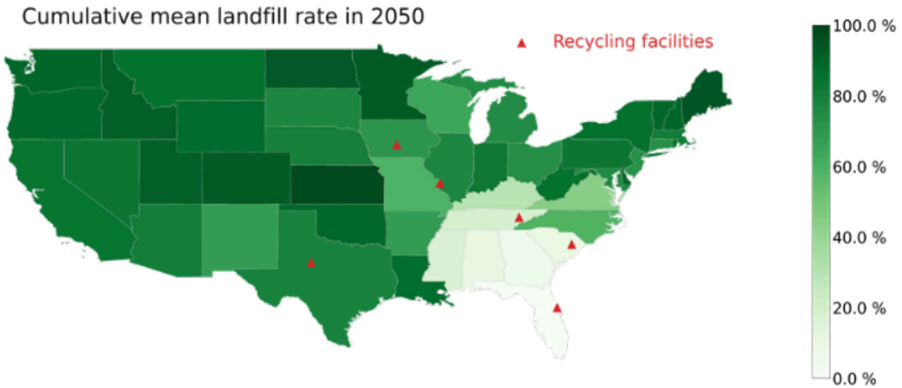
$^*ELW_i^t$: end of life waste of agent i at t; RPC_i^t: remaining wind power capacity of agent i at t; T: average lifetime; α Weibull shape factor

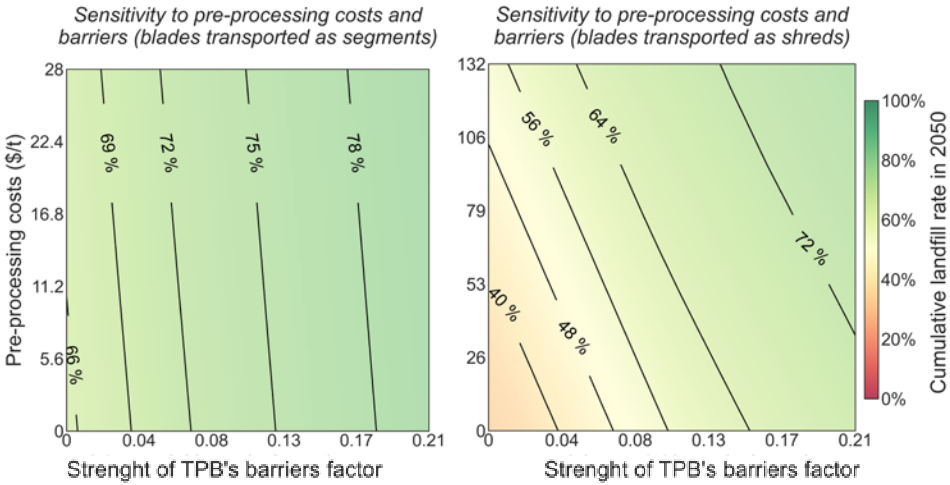
**Where at t, for each agent i and option j: BI = behavioral intention of performing the behavior; A = attitude toward the behavior; SN = subjective norms; PBC = perceive behavioral control over the behavior; P = pressures; BA = barriers; w_{BI}, w_A, w_{SN}, w_{dPBC}, w_{iPBC}, w_P, w_{BA} = regression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

Results

Key takeaways:

- States have different regulations regarding oversize/overweight road transportation
- Wind blades are considered construction & demolition waste or industrial waste depending on the state
- Transportation is costly, but shredding blades on-site may decrease transportation costs:
  - Cutting costs of \$28/metric ton and \$3.7–\$4.4/metric ton-mile for 40–45-meter blade segments
  - Shredding costs of \$116/metric ton and \$0.05–\$0.12/metric ton-mile for shredded blades
- Similar regulations to rubber tires could be applied (i.e., landfill ban on whole blades only or on whole and shredded blades depending on the state)





Frameworks comparison

	CELAVI	CE ABM
Ability to incorporate uncertainty	✓	✓
Computes circularity metrics and life cycle environmental impacts	✓	✗
Accounts for wind stakeholders' heterogeneity	✗	✓
Spatially resolved	✓	✓
Flexible enough to analyze different technologies	✓	✓
Detailed behavioral model of wind stakeholders	✗	✓
Provides results visualization	✓	✗

Combining the CE ABM with CELAVI

Combining the CE ABM with CELAVI

The Energy Act of 2020 Wind Recycling Language (section 3003 (A)):

- Research & development projects to create innovative and practical approaches to increase the reuse and recycling of wind energy technologies:
  - By minimizing potential environmental impacts from recovery and disposal processes.
  - By proposing strategies to increase consumer acceptance and participation in recycling.
- Gives special considerations to projects that aim at improving the recovery of critical materials.

Critical material definition in the Energy Act:

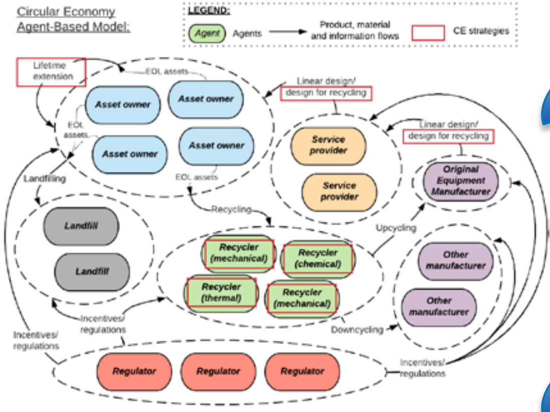
- Any non-fuel mineral, element, substance, or material that the Secretary of Energy determines:
  - Has a high risk of a supply chain disruption.
  - Serves an essential function in 1 or more energy technologies, including technologies that produce, transmit, store, and conserve energy,

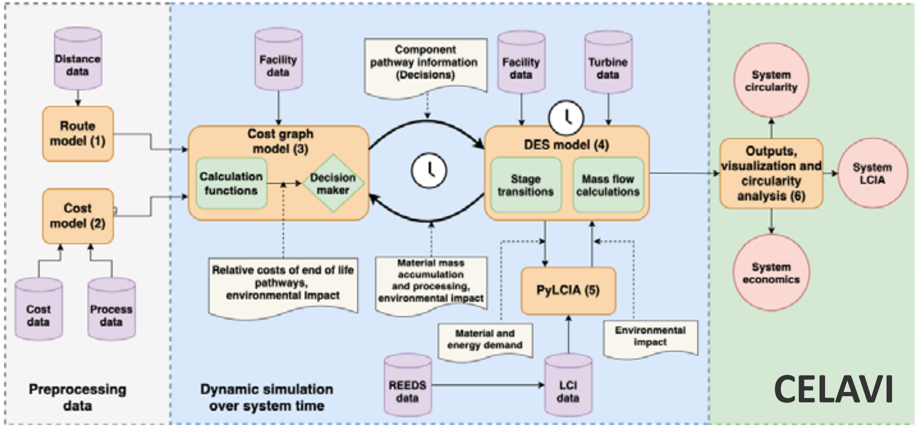
  Or a critical mineral (as defined in the DOI List of Critical Minerals).

For wind turbines, critical materials are: aluminum, boron, carbon fiber, dysprosium, electrical steel, lithium, neodymium, nickel, praseodymium, terbium, and zinc.

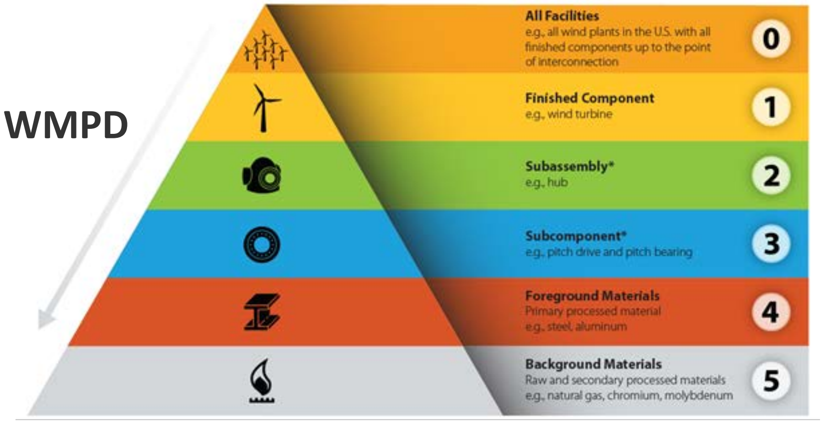
Combining the CE ABM with CELAVI

CE ABM





WMPD



Using CELAVI for the WETO recycling program:

- “Proposing strategies to increase consumer participation in recycling” → CE ABM
- “Minimizing potential environmental impacts from recovery and disposal processes” → PyLCIA or eventually the Lifecycle Analysis Integration into Scalable Open-source Numerical models (LiAISON) framework
- “Improving the recovery of critical materials” → wind material property database (WMPD)

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CELAVI Code Repository:
https://github.com/NREL/celavi/

Thank You!

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LiAISON overview

The Life cycle Analysis Integration into Scalable Open-source Numerical models (LiAISON) framework combines:

- An Integrated Assessment Model (IAM)
- An open source LCA python package
- Shared Socioeconomic Pathway scenarios

To compute the environmental impacts linked to different transition scenarios.