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Closing the Loop: End-of-life considerations and material circularity in modular residential construction

September 24, 2024

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PNNL-SA-203571

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LCA at PNNL

PNNL LCA website, more posted soon:

Focus: Data-driven sustainability for buildings and infrastructure by applying existing or improved Life Cycle Assessment (LCA) approaches to address lack of **high-quality data and accounting methods for both products and buildings**

Enhancing sustainability data and reporting by facilitating access to high-quality data, feeding this data into the Federal Commons for setting baselines and targets, and leveraging industry-average product data for Whole Building Life Cycle Assessment (WBLCA).

- Partnership and industry collaboration (e.g., 17 orgs in focus group and more who have tested a template, ASHRAE, AHRI, IES, Building Re-Use products, and more),
- Developed unique LCA (life cycle inventory/life cycle impact analysis) template for luminaires and rooftop units,
- Collaborated with industry on first LCA rules for luminaires in North America,
- Addressed data gap (power supplies),
- Identified recommended practices for WBLCA, with focus on circularity and mechanical & electrical systems.

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The Problem

- The building sector contributes 37% of global emissions[1] and comprises a significant amount of landfill waste
- In the U.S., residential building energy use alone accounts for 15% of greenhouse gas emissions[2]
- Construction industry is slow to innovate
- Recent changing attitudes about decarbonization offer opportunity for market transformation and a shift to a more circular economy

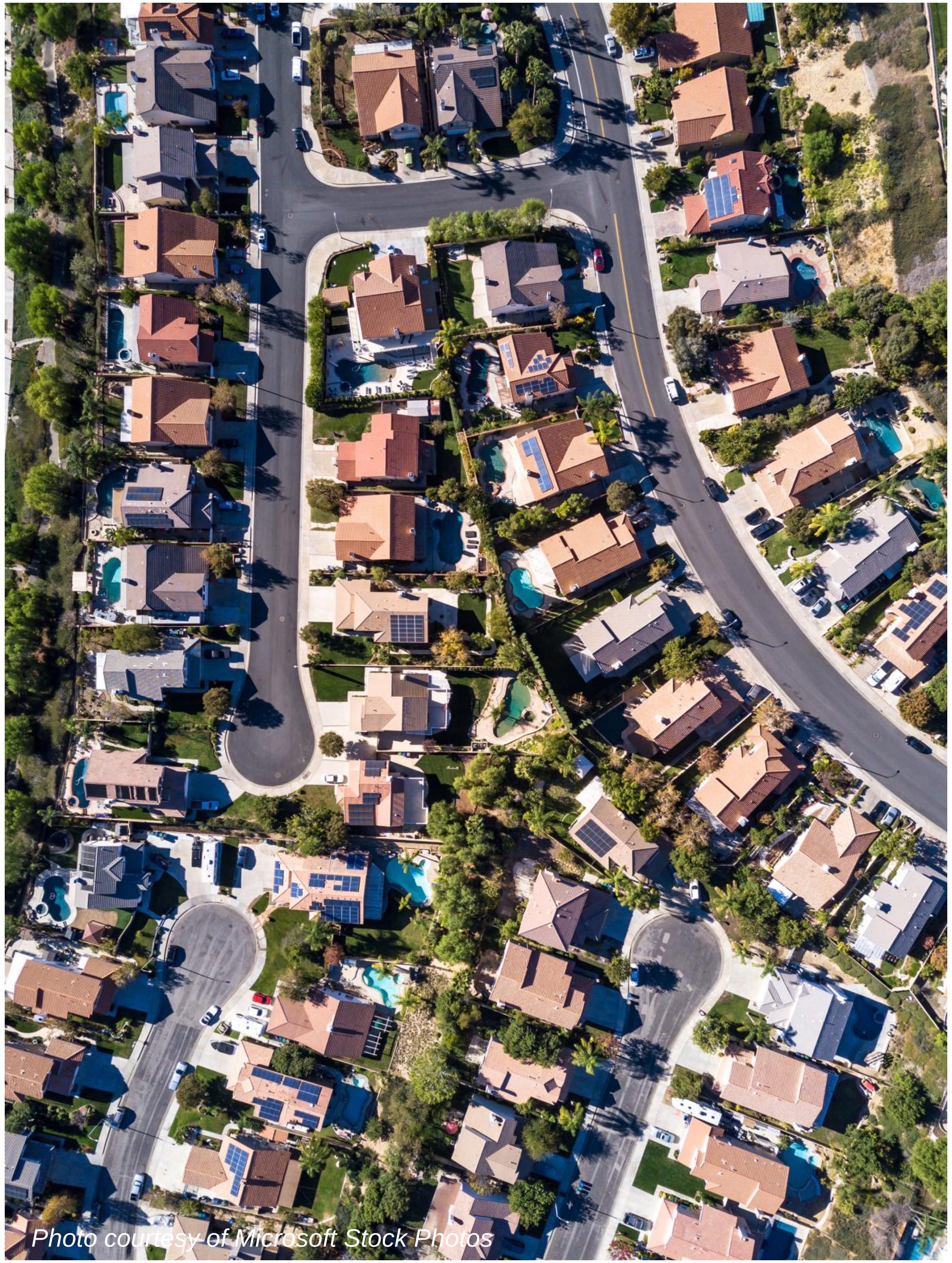
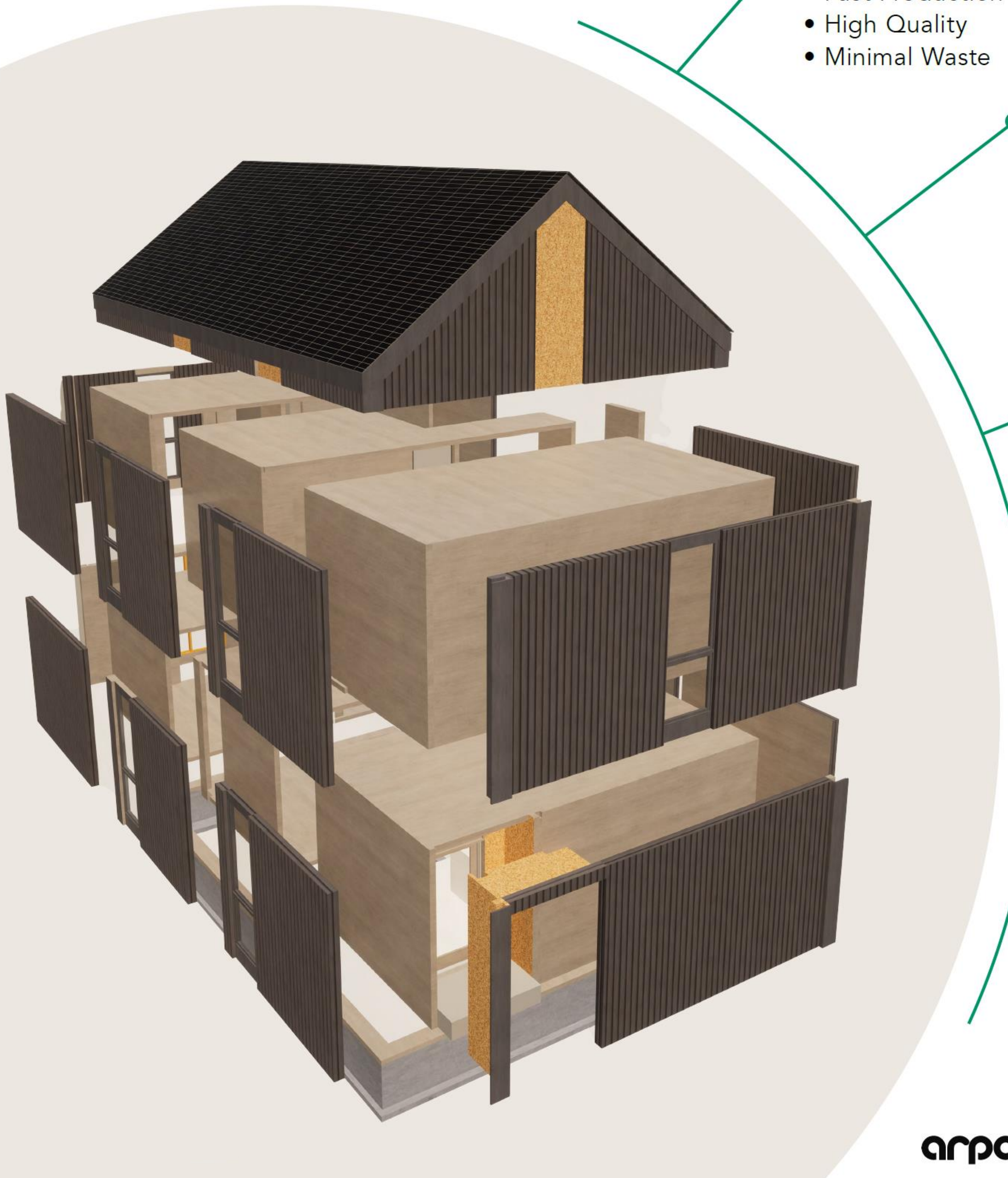


Photo courtesy of Microsoft Stock Photos

[1] https://www.unep.org/resources/report/building-materials-and-climate-constructing-new-future
[2] https://www.energy.gov/eere/buildings/us-residential-building-stock-decarbonization-analysis

Circular Home Overview



Offsite modular construction
- Fast Production
- High Quality
- Minimal Waste

Optimized for
- Sustainability
- Resilience
- Durability
- Life-stages
- Adaptability
- Long use-life

Low embodied carbon and net zero operational carbon
- Plant-based products
- Minimal plastic and concrete
- Climate-tuned envelope
- Efficient equipment
- All-electric systems
- On-site renewables

Value retention for Iterative reuse
- Modules
- Sub-assemblies
- Components
- Materials

Non-destructive connectors add value by improving
- Building Performance
- Fabrication speed
- Ease of assembly/disassembly

Minimize embodied carbon through bio-based design

Minimize operational carbon through energy efficient building performance

Reduce waste and extend useful building life through circularity (designed for disassembly and reassembly)

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Circular Home Renderings

Images courtesy of Green Canopy NODE

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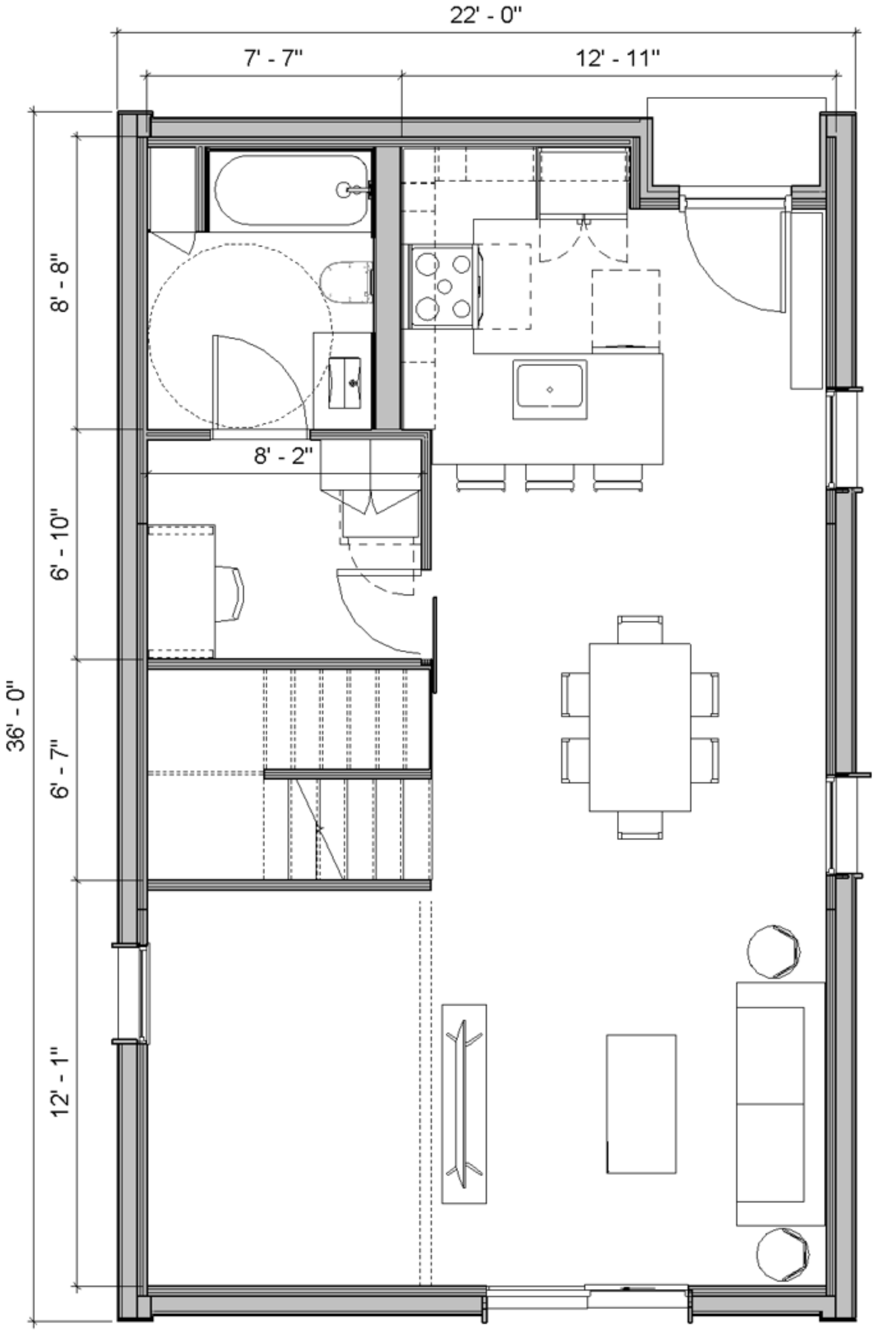
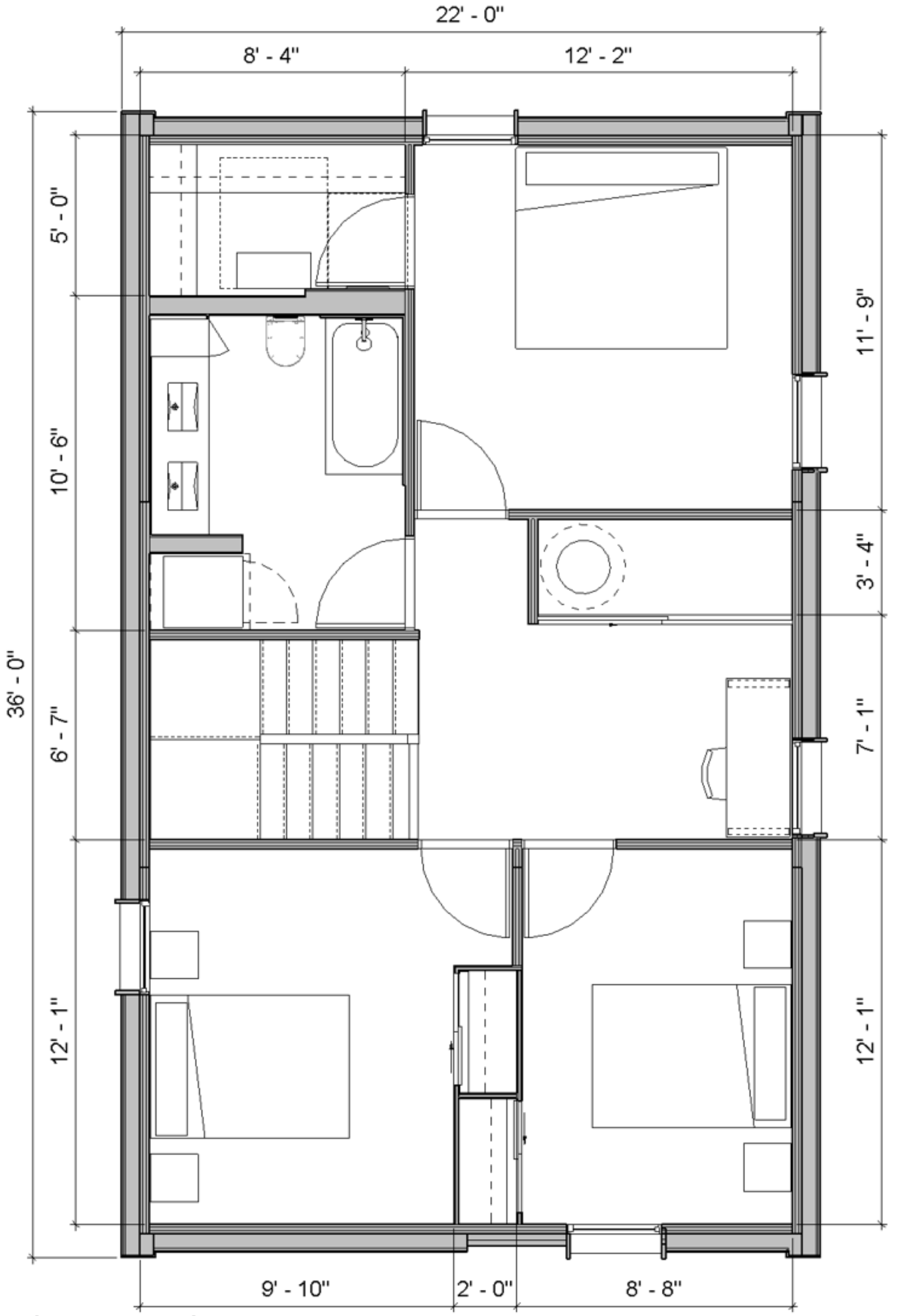
Circular Home Floor Plans

- 1,430 SF
- Configurable for Full Accessibility
- 3 Bed (4th Configurable)
- 2 Bath
- Duplex Configuration Available

Level 1



Level 2



Images courtesy of Green Canopy NODE

LCA Overview

	Circular Home Prototype	Traditional Baseline
Materials	CLT structure with non-destructive connectors; Bio-based replacements for insulation, finishes, and accessories	Wood stud framing with standard fasteners; Incumbent materials and products to meet code minimum requirements
Methods	Factory-assembled modules transported to site; intentionally designed for disassembly and re-use	Site-built by a variety of trades, composed of hundreds of individual elements into a permanent whole

Overarching goal: carbon-negative cradle to grave

Anticipated Results: Comparison of Circular Home Prototype to Traditional Baseline

LCA		
	Global Warming Potential (kgCO_2eq)	Smog Formation Potential (kgO_3eq)
	Acidification Potential (kgSO_2eq)	Primary Energy Demand (MJ)
	Eutrophication Potential (kgNeq)	Non-renewable Energy Demand (MJ)
	Ozone Depletion Potential (CFC-11eq)	Renewable Energy Demand (MJ)

For whole building and for component/ material breakdown

10 R-strategies for Circularity

Circular Home Strategy:

- Prioritize design-phase circular thinking
- Maximize circularity of materials
- Prioritize deconstruction/disassembly throughout design process

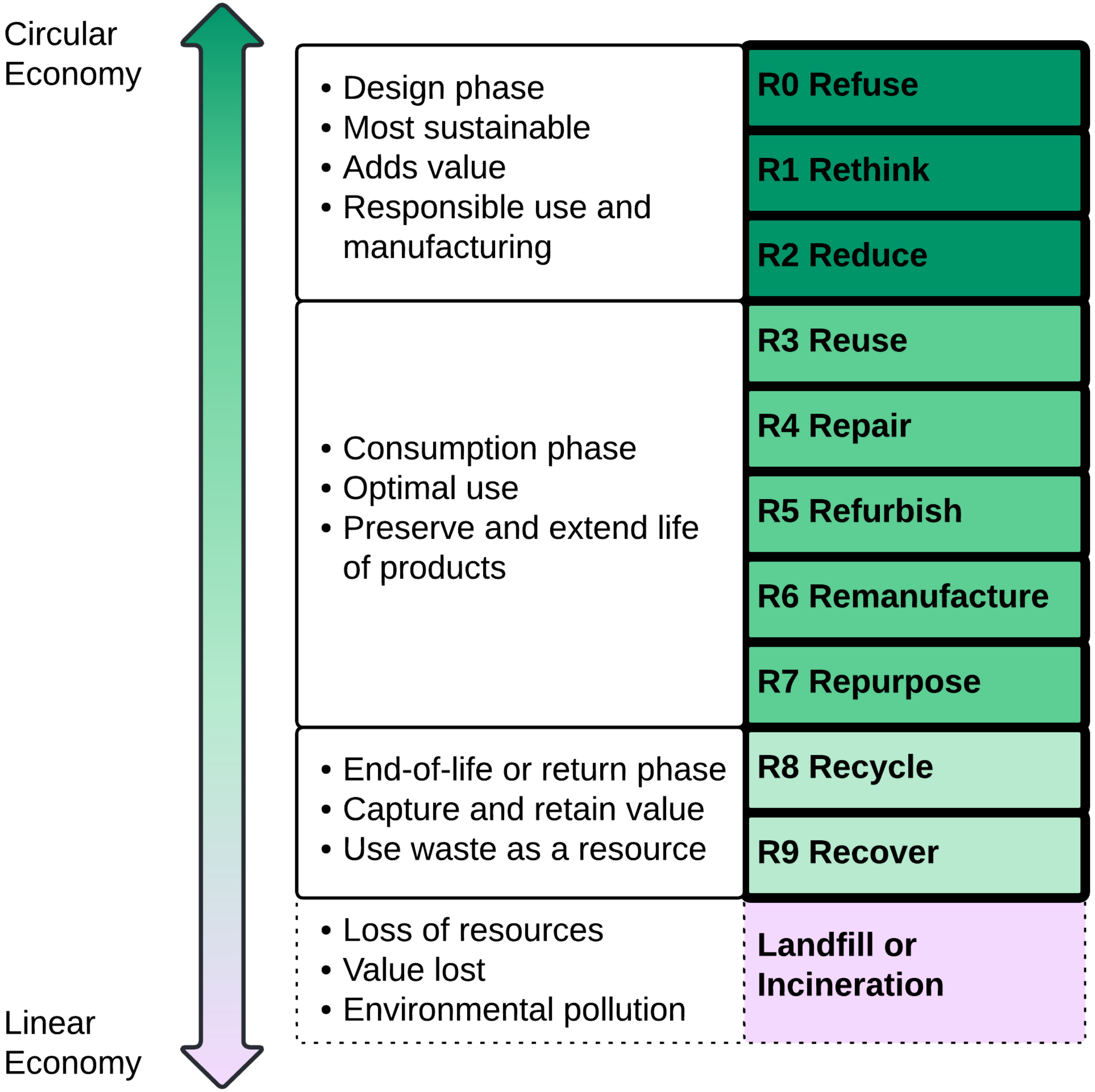


Figure adapted from https://www.circularise.com/blogs/r-strategies-for-a-circular-economy

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- R0 Refuse
- R1 Rethink
- R2 Reduce
- R3 Reuse
- R4 Repair
- R5 Refurbish
- R6 Remanufacture
- R7 Repurpose
- R8 Recycle
- R9 Recover
- Landfill or Incineration

Circularity by Component

	Material	Mass (kg)	% of building (mass)	Building-level Re-use in present form	Building-level Re-use with additional processing	Material level Re-use	Downcycling Re-use	Waste
Ceilings	Cross laminated timber (CLT)	5427	7.5%	99%			1%	
	Wall covering, cork	76	0.1%		[illegible]%			
Doors (11 count)	Door frame, wood	43	0.1%		[illegible]8%		13%	
	Door, exterior, wood, solid core	97	0.1%	100[illegible]				
	Door, interior, wood, hollow core, flush	1610	2.2%	[illegible]%				
Floors	Cross laminated timber (CLT)	6020	8.3%	99%			1%	
	Rubber underlayment	492	0.7[illegible]	95%				
	Plywood, interior grade	2801	[illegible]%	90%			10%	
Roofs	Cross laminated timber (CLT)	3900	[illegible]%	[illegible]%			1%	
	Cellulose Blown Insulation	776	1[illegible]	90%				
	Metal roofing panels, formed	5[illegible]	0.7[illegible]	70%	30%			
	Polyethelene sheet vapor barrier (HDPE)	2[illegible]	0.0%				100%	
Stairs and Railings	Hardwood Veneer	34[illegible]	0.5%			20%	80%	
Structure	Cast-in-place structural concrete	168[illegible]	[illegible]%		100%			
	Foam glass gravel	525[illegible]	7.2[illegible]	90%				10%
	Glass fiber board insulation	98	0.1%	50%	50%			
Walls	Cross laminated timber (CLT)	13037	17.9%	99%			1%	
	Decorative high pressure lamina[illegible]PL)	640	0.9%	40%			60%	
	Wood fiber ins[illegible]	[illegible]	8.0%		100%			
	Polyethel[illegible] sheet vapor b[illegible]er (HD[illegible]	54	0.1%				50%	50%
	Wall co[illegible]ng, cork	1378	1.9%		100%			
	Wood sid[illegible]	4295	5.9%	40%			60%	
	Fiberglass s[illegible]ound	193	0.3%				80%	20%
	MEP Wall	616	0.8%					
Windows (8 count)	Glazing, triple p[illegible]IGU	1504	2.1%		88%		13%	
	Window frame, wo[illegible]	150	0.2%		88%		13%	
Renewables	PV Panels	378	0.5%				100%	
	PV Battery	195	0.3%				95%	5%
	Subtotal	72827	100.0%					
	% of Building Circularity (Mass)			55.8%	35.5%	1.1%	6.7%	0.9%

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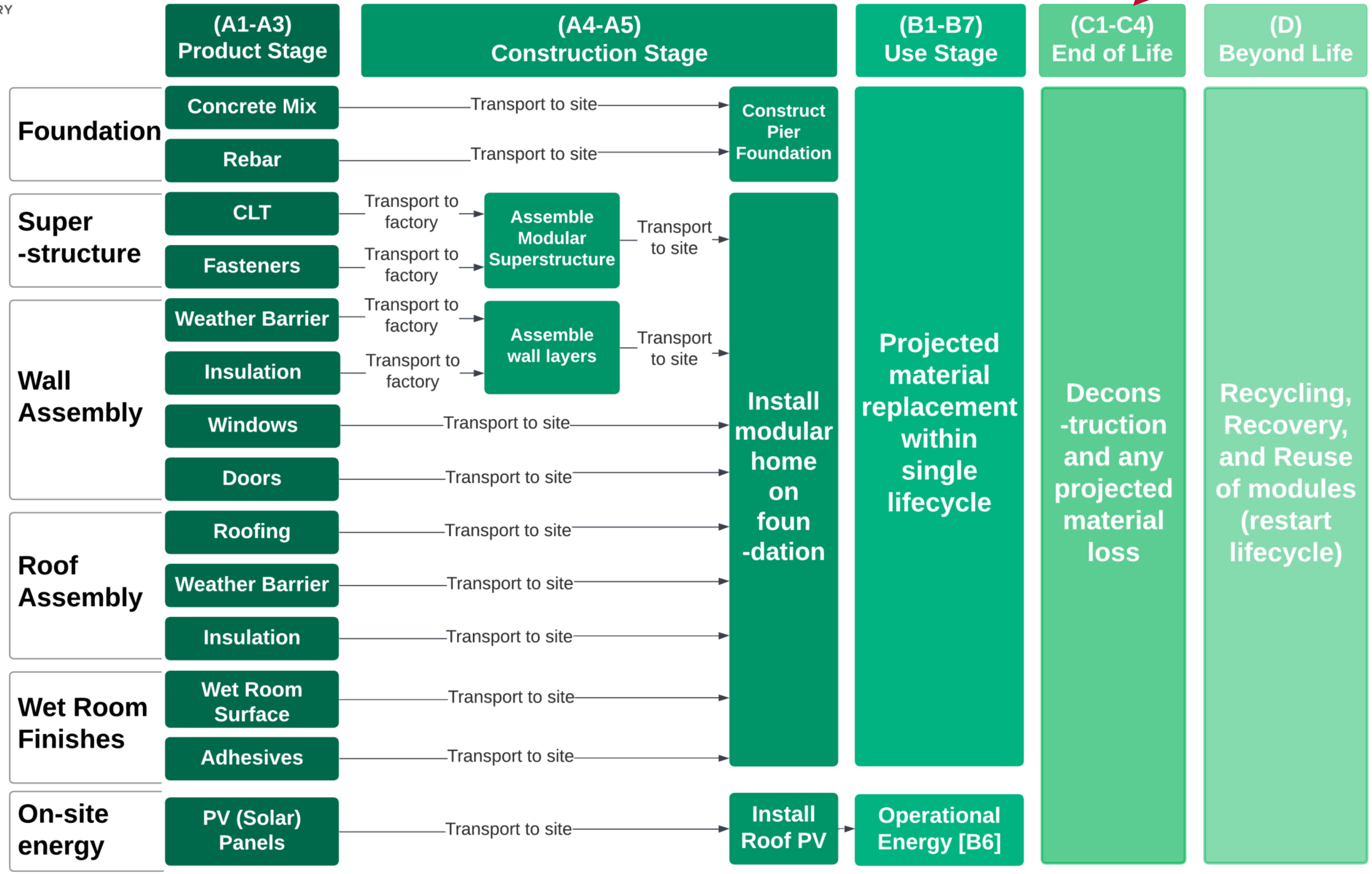
Scope of Circular Home LCA

Selected LCA software has unchangeable defaults for end of life



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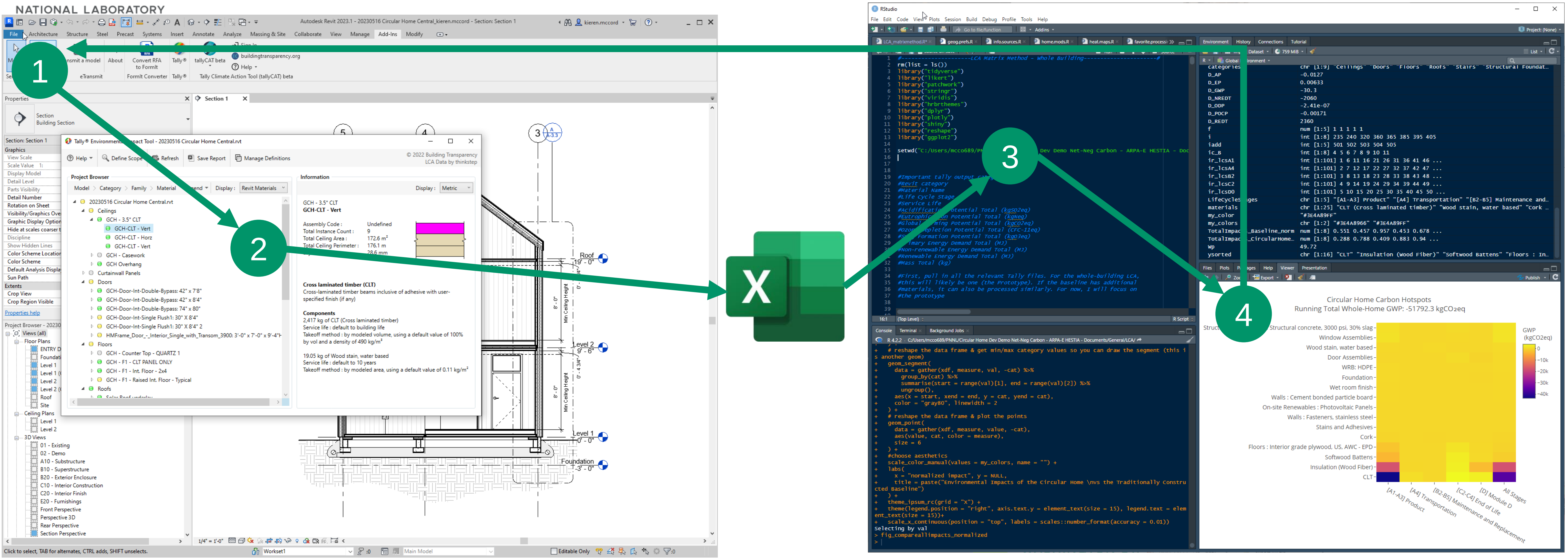
LCA Calculation Process

Necessary to supplement software limitations:



1. Receive circular home design model (Revit)
2. tallyLCA plugin for available materials/ processes
3. Import tallyLCA spreadsheet to R and add missing flows
4. Review heat map for initial results/impacts, inform design

Post-software modifications

- Building materials unavailable in software
- End-of-life re-use percentages
- Grid mix projections for operational impacts
  - How will the operational impacts change over time as the grid mix changes?

Current U.S. Grid Mix (Renewables Only)

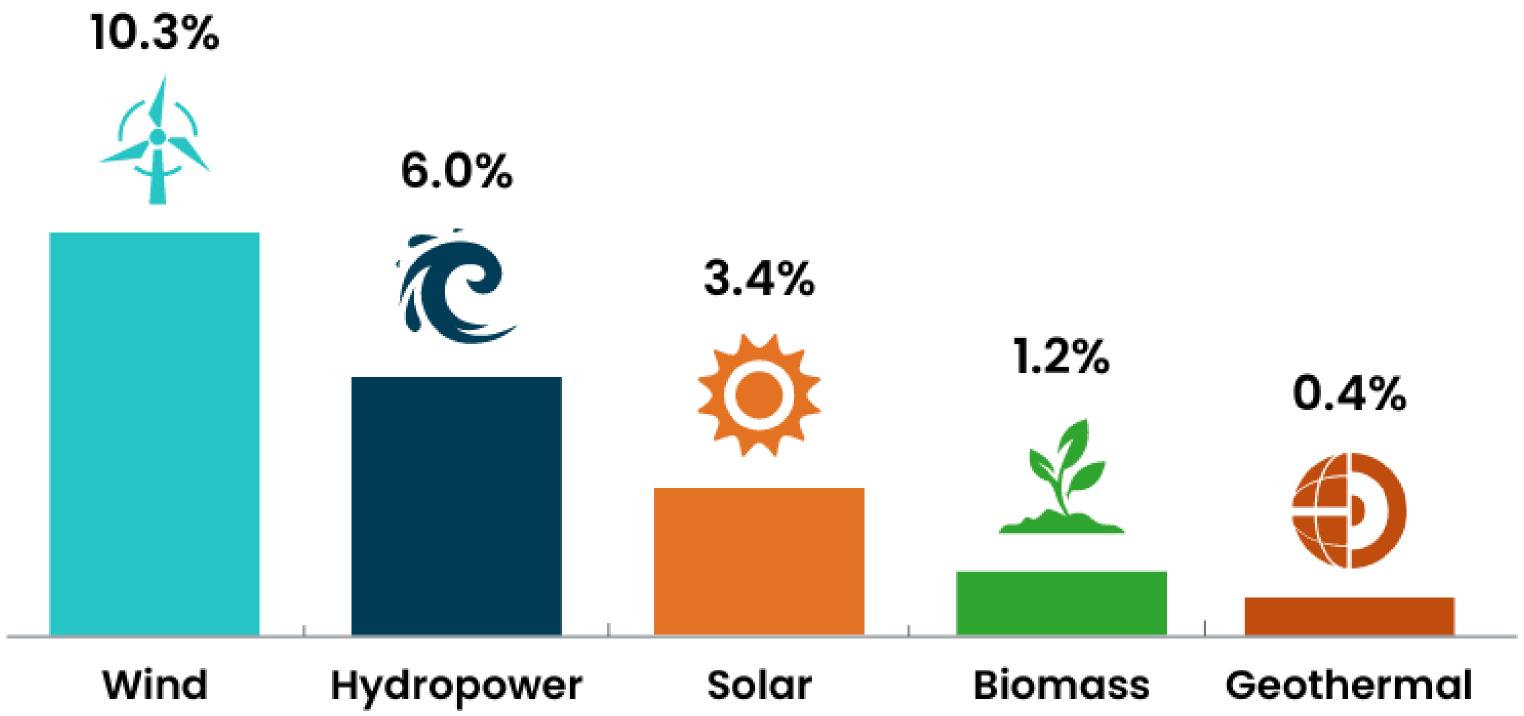
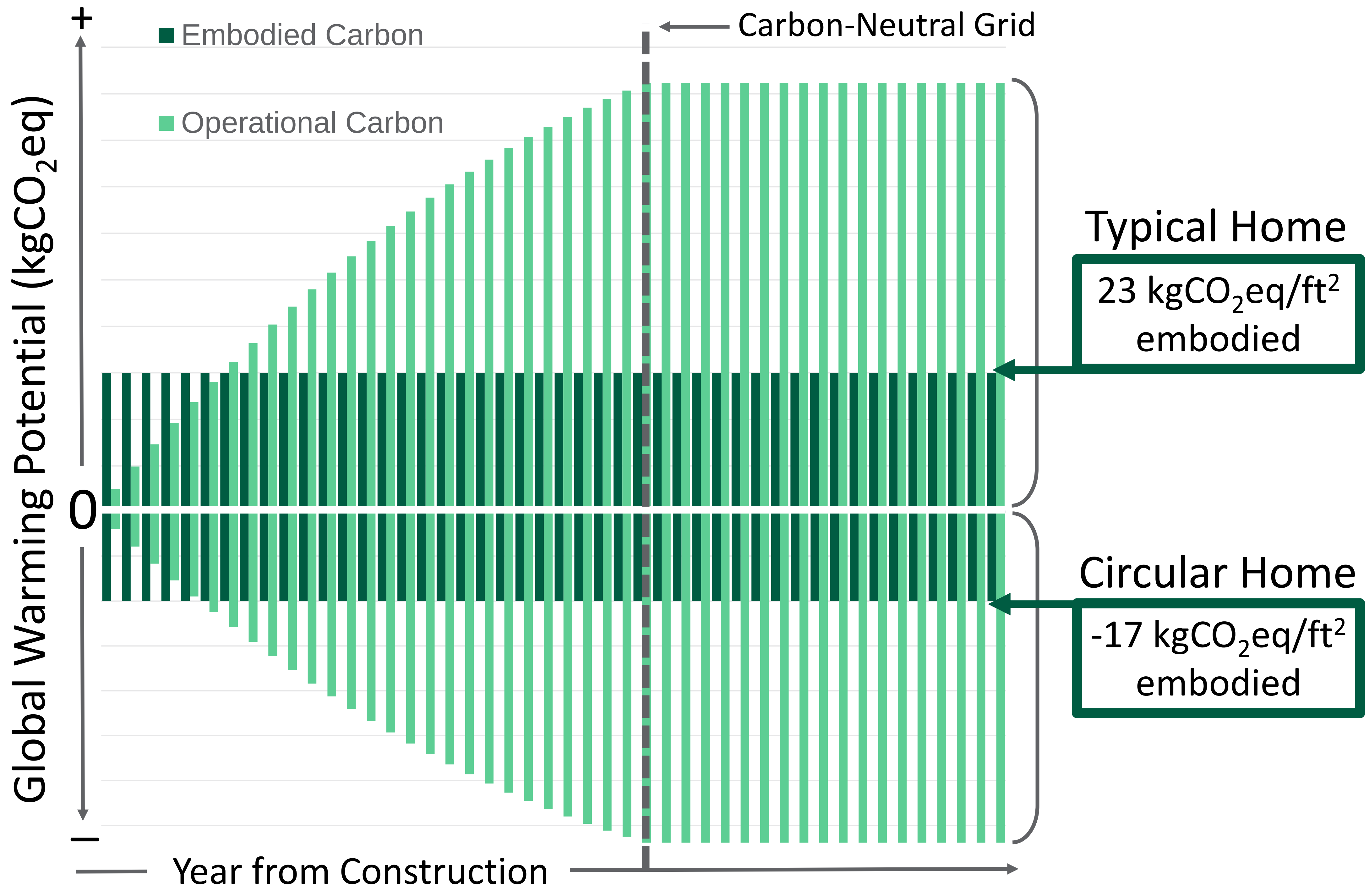


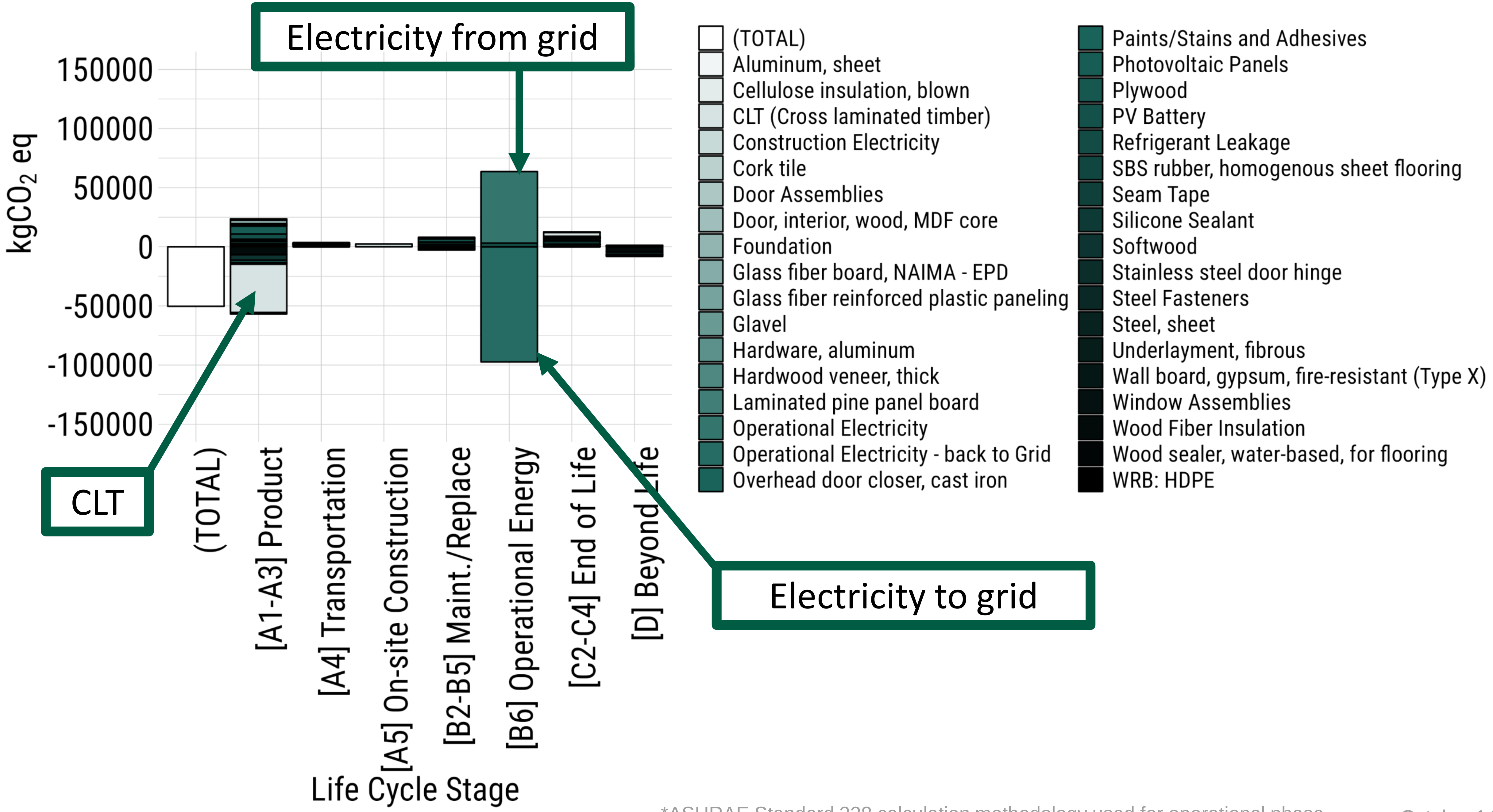
Image courtesy of https://www.energy.gov/eere/renewable-energy.

Simulation: cumulative impacts over time

"While building operational emissions can be reduced by improving energy efficiency and sourcing carbon-free electricity, embodied carbon is a large "burp" of emissions associated with building construction and renovation that cannot be improved over time. As global construction ramps up, urgent action to reduce these emissions is needed to meet climate goals over the next decade."
(https://rmi.org/embodied-carbon-cities-policy-toolkit/)



Circular Home Preliminary Results



*ASHRAE Standard 228 calculation methodology used for operational phase

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Future Work

- Finalize and publish LCA findings

- Goal: Build circular home prototype
  - Monitor during construction/operation for:
    - ✓ Actual material usage/waste
    - ✓ Transportation
    - ✓ Construction energy usage
    - ✓ Site energy usage

Photo courtesy of Green Canopy NODE and Mercer Mass Timber

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Thank you

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