



A Critical Review of the Circular Economy for Lithium-Ion Batteries and Photovoltaic Modules: Status, Challenges, and Opportunities

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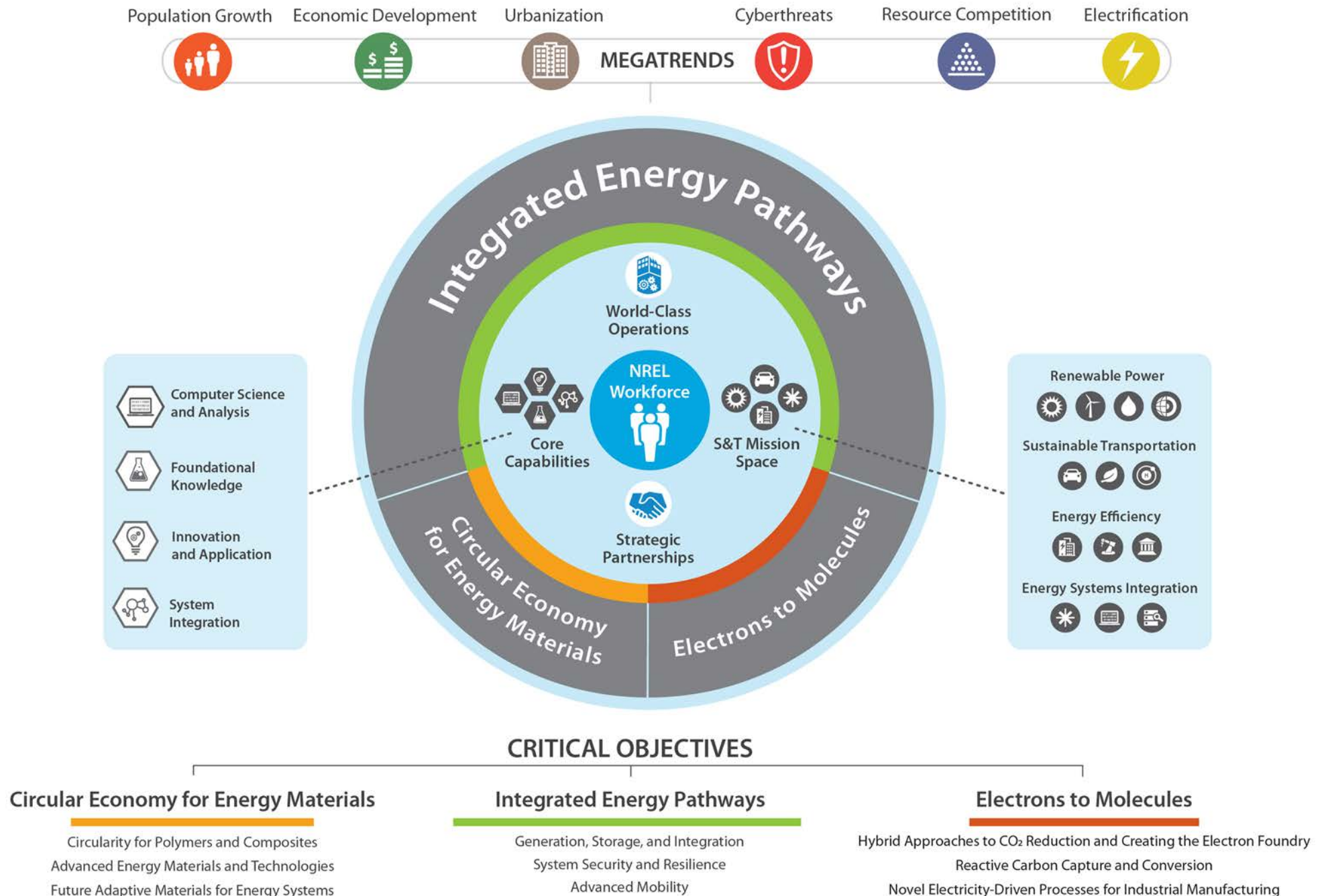
Undergraduate interns

2022 A&WMA
Critical Review

Air & Waste Management Association Annual Conference
June 30, 2022

NREL at a Glance

- 3000 people
- Golden, CO main campus
- Only DOE national lab with circular economy as top 3 objective



Outline

- 1 Our five conclusions**
- 2 What is circular economy (CE)?**
- 3 Why study photovoltaics (PV) and lithium-ion batteries (LIB)?**
- 4 Goal of this critical review**
- 5 Method: A different approach**
- 6 A systems diagram for PV CE (and parallel for LIB)**
- 7 Our five conclusions**
- 8 Our assessment of the status of CE for PV and LIB**

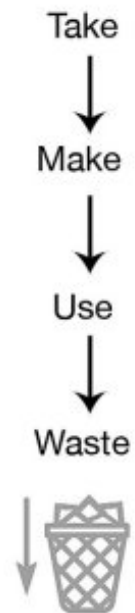
Five Conclusions (Common for PV and LIB)

1. Expand research beyond recycling
2. Support technology deployment with economic, environmental, and policy analysis
3. Leverage digital information systems
4. Improve recycling technologies
5. Study and design CE-related aspects of LIB and PV markets

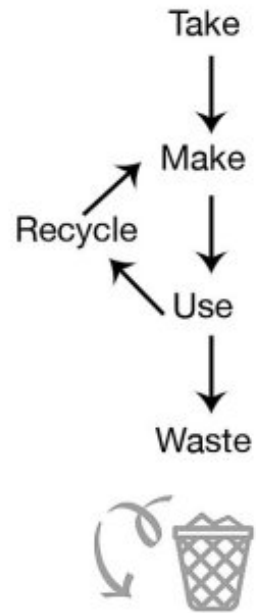
What is a Circular Economy?

A *circular economy* shifts from a take-make-waste linear economic model to one that retains the value of materials and products as long as possible, recovering materials at end of life to recirculate back into the economy.

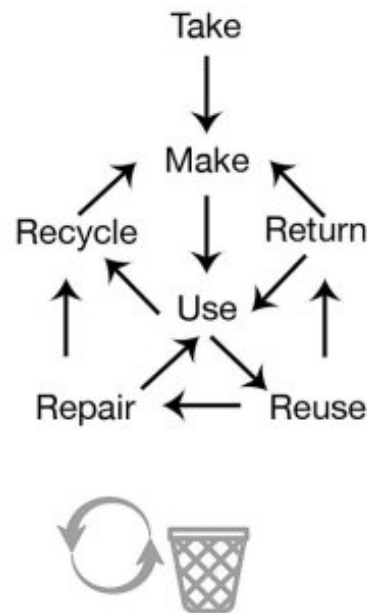
LINEAR ECONOMY



RECYCLING ECONOMY



CIRCULAR ECONOMY



- *Defined* as opposed to our current linear economy
- Goes farther than a recycling-only focus
 - The recycling economy is the current focus of research, investment, and policy
 - Fits easiest into our current linear system.
- Relates to the waste management side of A&WMA
 - Relates indirectly to air.

Expanding on the Elementary School Mantra: The 10 Rs

- Prioritized from top to bottom
 - Logic: the more you change what’s already manufactured, the more value you lose and greater effort/cost/carbon.
 - If you do not use materials in the first place, all the better.
- Some variability in R strategy definitions
 - A manufacturer or consumer perspective can be used for the lower-numbered R strategies.
 - Literature largely focuses on the manufacturer perspective and thus is the focus of our review.
- Application of the terms can vary
 - For example, refurbish, repair and remanufacture are often used synonymously.
 - “Reuse” of batteries is often misused when repurpose is meant (e.g., car to stationary battery storage).
 - For consistency, we enforce our definitions to sometimes change the author-identified R strategy.

Circular Economy



Linear Economy

| CE Strategy | |
|---|--------------------|
| Smarter product use and manufacture. Parts of these strategies contribute to Design for Circularity | R0 – Refuse |
| | R1 – Rethink |
| | R2 – Reduce |
| Extend lifespan of product and its parts | R3 – Reuse |
| | R4 – Repair |
| | R5 – Refurbish |
| | R6 – Remanufacture |
| | R7 – Repurpose |
| Useful application of materials | R8 – Recycle |
| | R9 – Recover |

Source: Adapted from Potting et al. 2017, Reike, Vermeulen, and Witjes 2018; Morseletto 2020

Some Other Points about CE and the Scope of Our Review

1. Profit maximization motivates strategies that also have circularity benefits.
 - Reducing materials per unit product (dematerialization)
 - Increasing manufacturing or product efficiency
 - When not done explicitly for a CE purpose, we exclude research on these strategies, yet the CE benefits are real.
2. Intrinsic versus extrinsic circularity
 - The Ellen MacArthur Foundation (Ellen MacArthur Foundation, 2022) states, “[a CE] is underpinned by a transition to renewable energy.”
 - So, any renewable energy technology inherently improves circularity, and any strategy to increase renewable deployment likewise → **extrinsic**.
 - We focus on **intrinsic** circularity, or improving circularity of the product itself, not the system in which it is used.

A CE Should Not Be A Goal In and of Itself

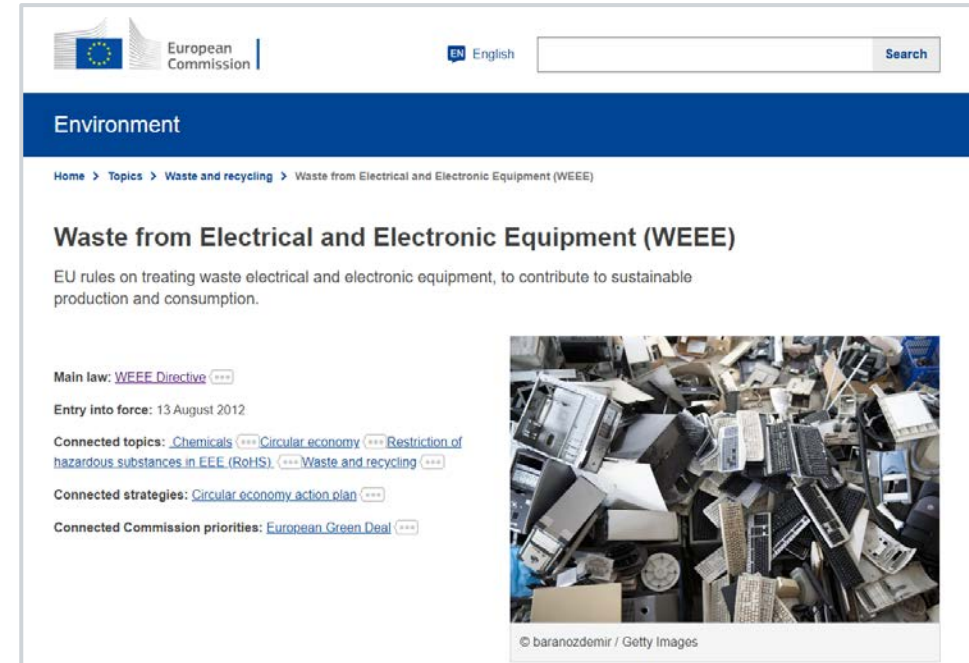
- We view a CE as a means to achieve other societal goals.
 - Improvement to environmental quality
 - Responsible consumption and production (United Nations Sustainable Development Goal #12)
 - Long-term security, reliability and resilience of industrial supply chains
 - Decarbonization
 - Addressing historical environmental inequities from resource extraction through waste management.
- However, there are times when higher material circularity has trade-offs such as higher cost or worse environmental performance.
 - It is necessary to holistically evaluate CE strategies from a systems perspective to mitigate these trade-offs.



CE is Not New: Success Stories

- Industry
 - **99%** lead-acid battery recycling rate (SmithBucklin Statistics Group 2019)
 - **95%** automobile recycling rate, plus reuse and remanufacture of engines and parts (Aguilar Esteva et al. 2021)
 - **75%** of all aluminum ever manufactured still in use (Kvande 2014)

→ Combination of economics and human behavior, sometimes with policy, have led to widespread adoption.
- Policy
 - European Union Waste Electrical and Electronic Equipment (WEEE) Directive
 - China's CE Promotion Law.



European Commission

EN English

Search

Environment

Home > Topics > Waste and recycling > Waste from Electrical and Electronic Equipment (WEEE)

Waste from Electrical and Electronic Equipment (WEEE)

EU rules on treating waste electrical and electronic equipment, to contribute to sustainable production and consumption.


Main law: [WEEE Directive](#)

Entry into force: 13 August 2012

Connected topics: [Chemicals](#) [Circular economy](#) [Restriction of hazardous substances in EEE \(RoHS\)](#) [Waste and recycling](#)

Connected strategies: [Circular economy action plan](#)

Connected Commission priorities: [European Green Deal](#)



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Circular Economy Promotion Law

Source: Shanghai Cooperation Organization Environmental Information Sharing Platform

Order of the President of the People's Republic of China No.4

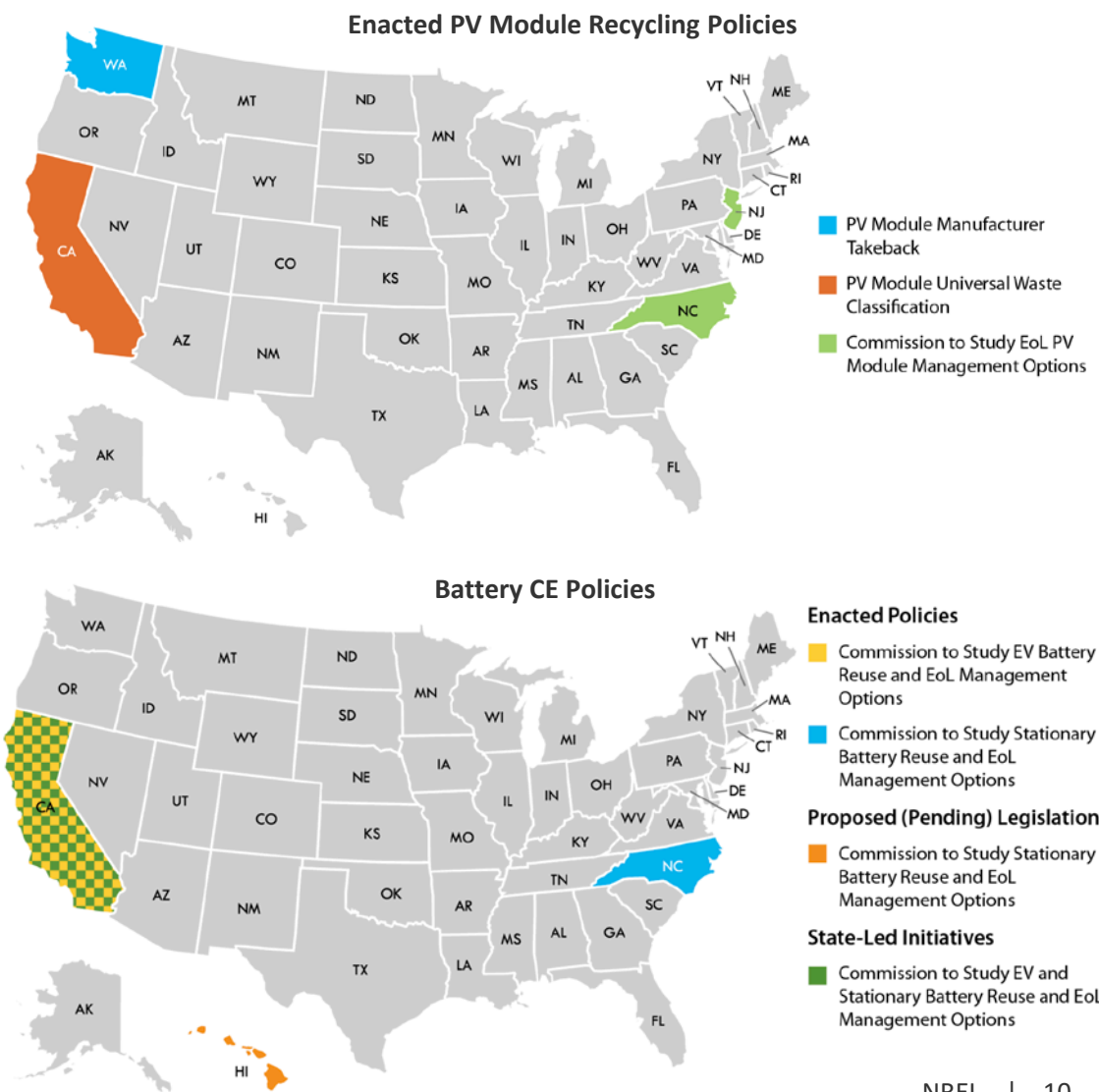
The Circular Economy Promotion Law of the People's Republic of China passed at the fourth meeting of the Standing Committee of the 11th National People's Congress of the People's Republic of China on August 29, 2008 is hereby promulgated for implementation as of January 1, 2009.

Hu Jintao, President of the People's Republic of China

August 29, 2008

But CE is Relatively New for PV and LIB, With Impetus Growing

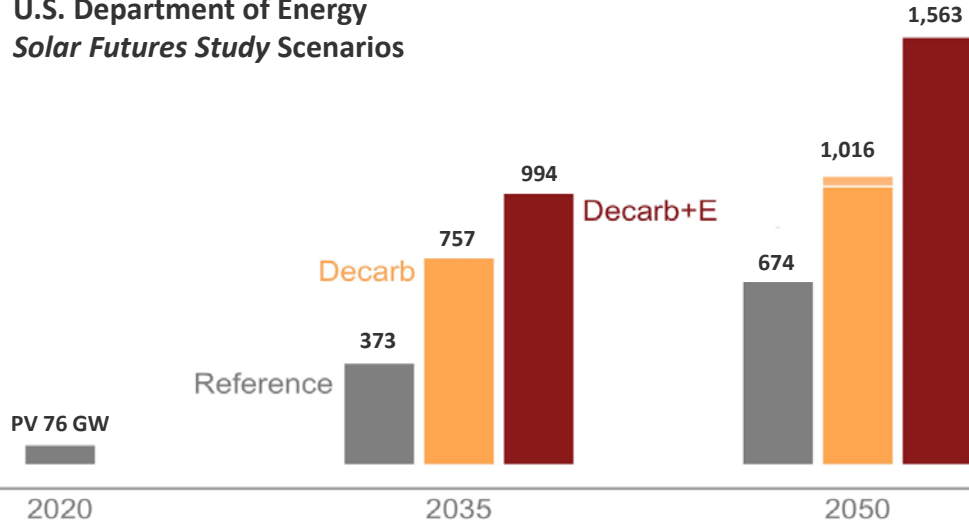
- Though regulations are used in some countries, in the United States and most other countries, nonregulatory approaches are more typical.
 - Research and development.
- There is growing call for a transition to a CE from nongovernmental organizations, industry, and to some extent governments. Why?
 - Address global supply chain disruptions and increase domestic supply chain resiliency
 - Concern about continuing growth in demand for materials
 - Social issues such as child or forced labor in extractive industries.
- PV and LIB industries/government are responding.
 - Recycling is gaining traction.
 - Defense Production Act.



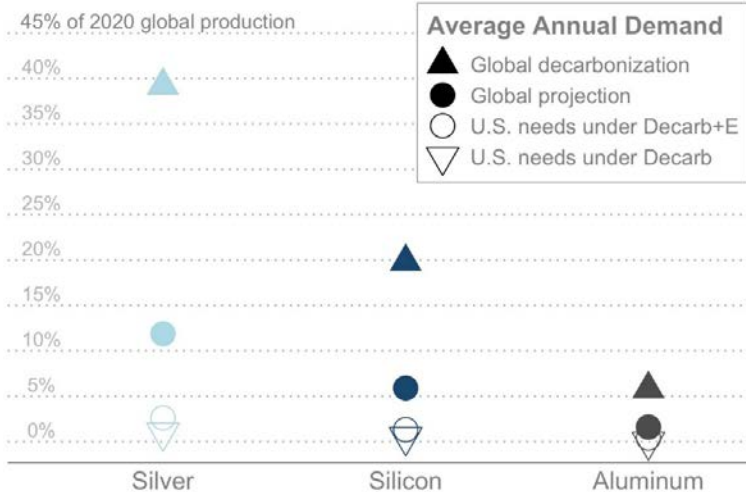
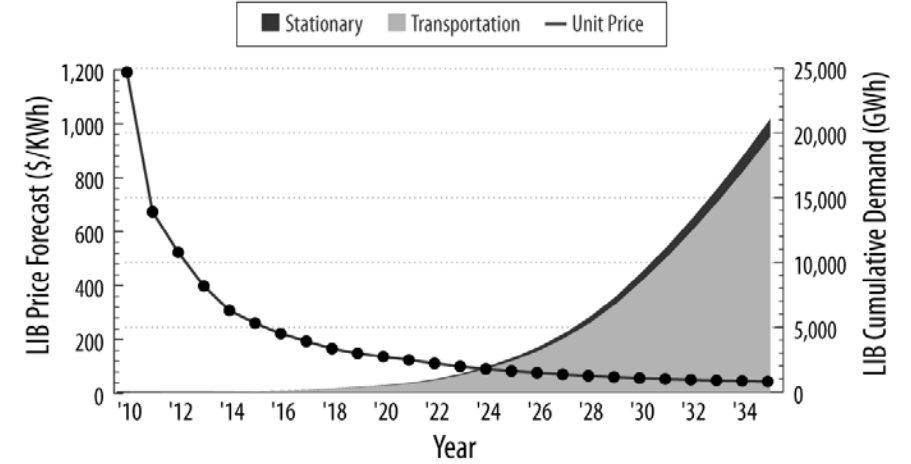
Why Focus on PV and LIB?

PV

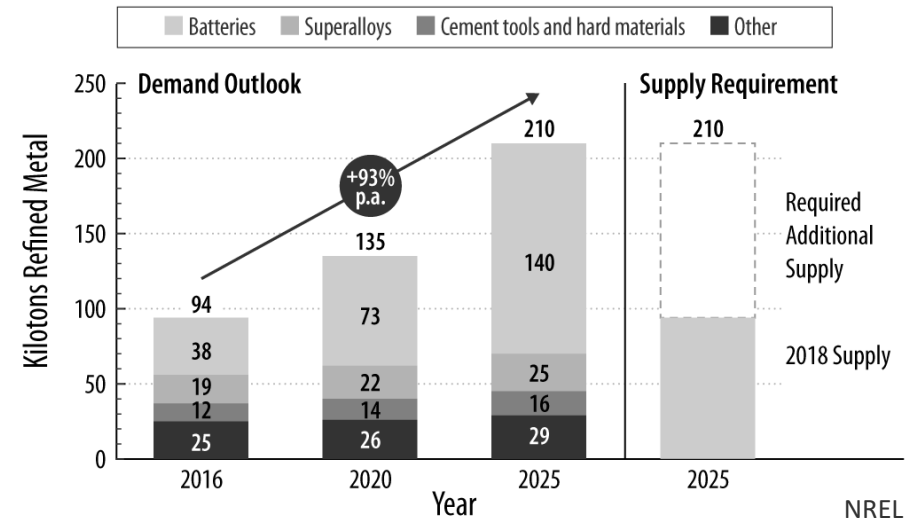
U.S. Department of Energy
Solar Futures Study Scenarios



LIB

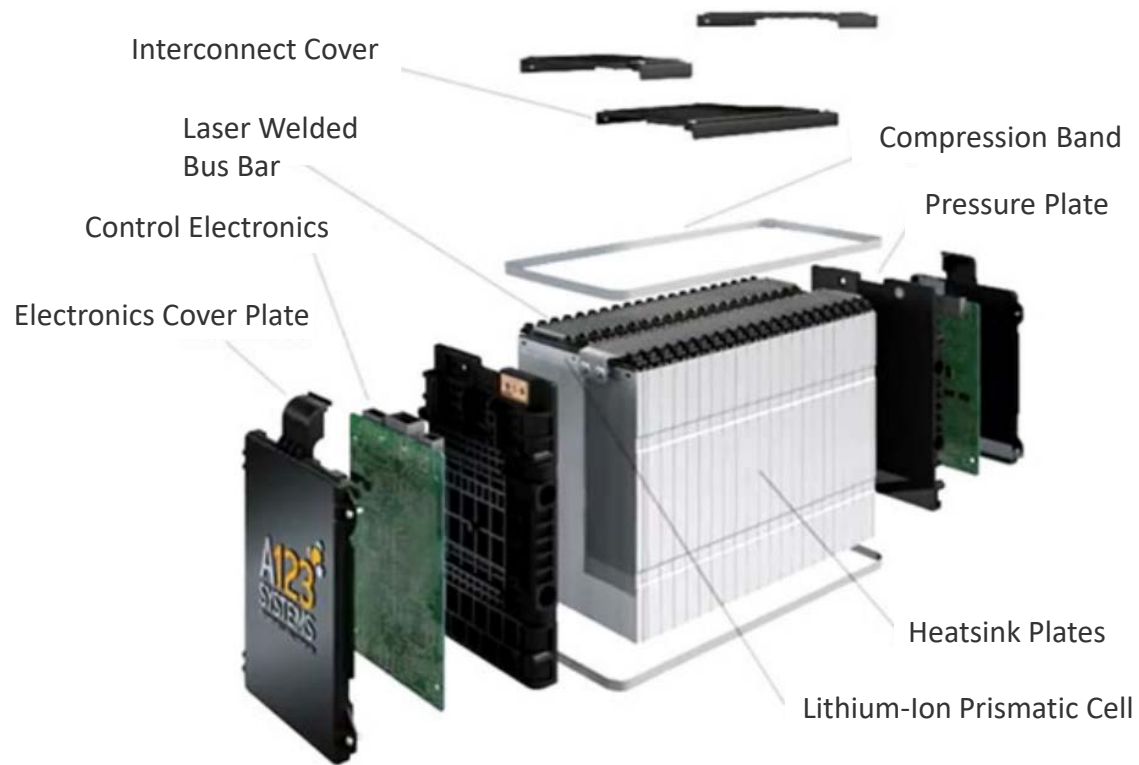


Cobalt

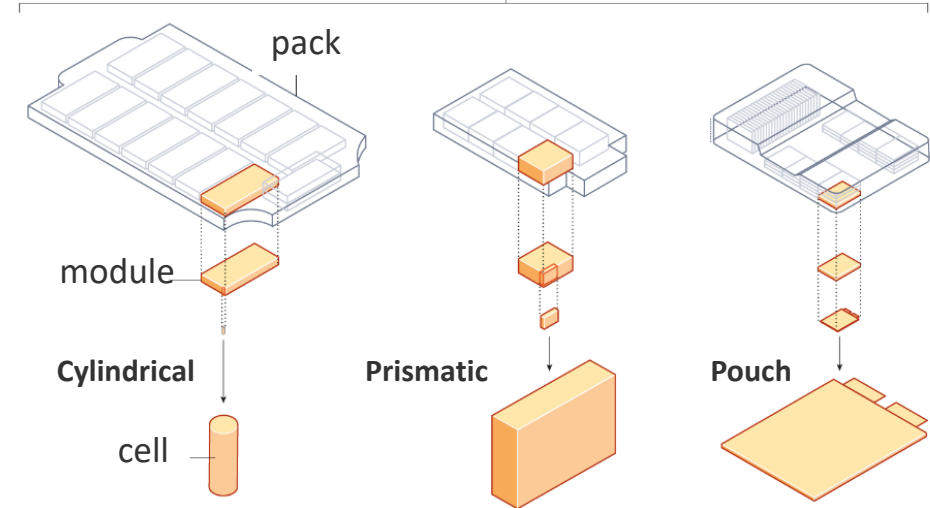


LIB Design

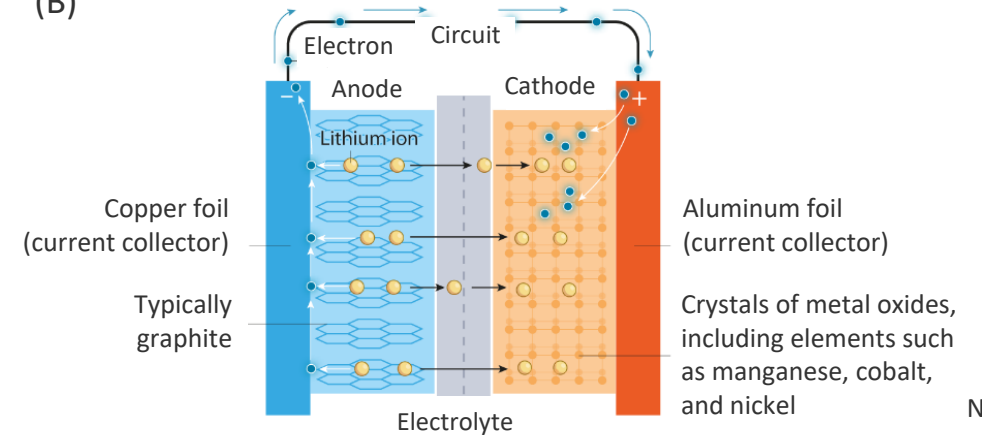
EV Battery Schematic



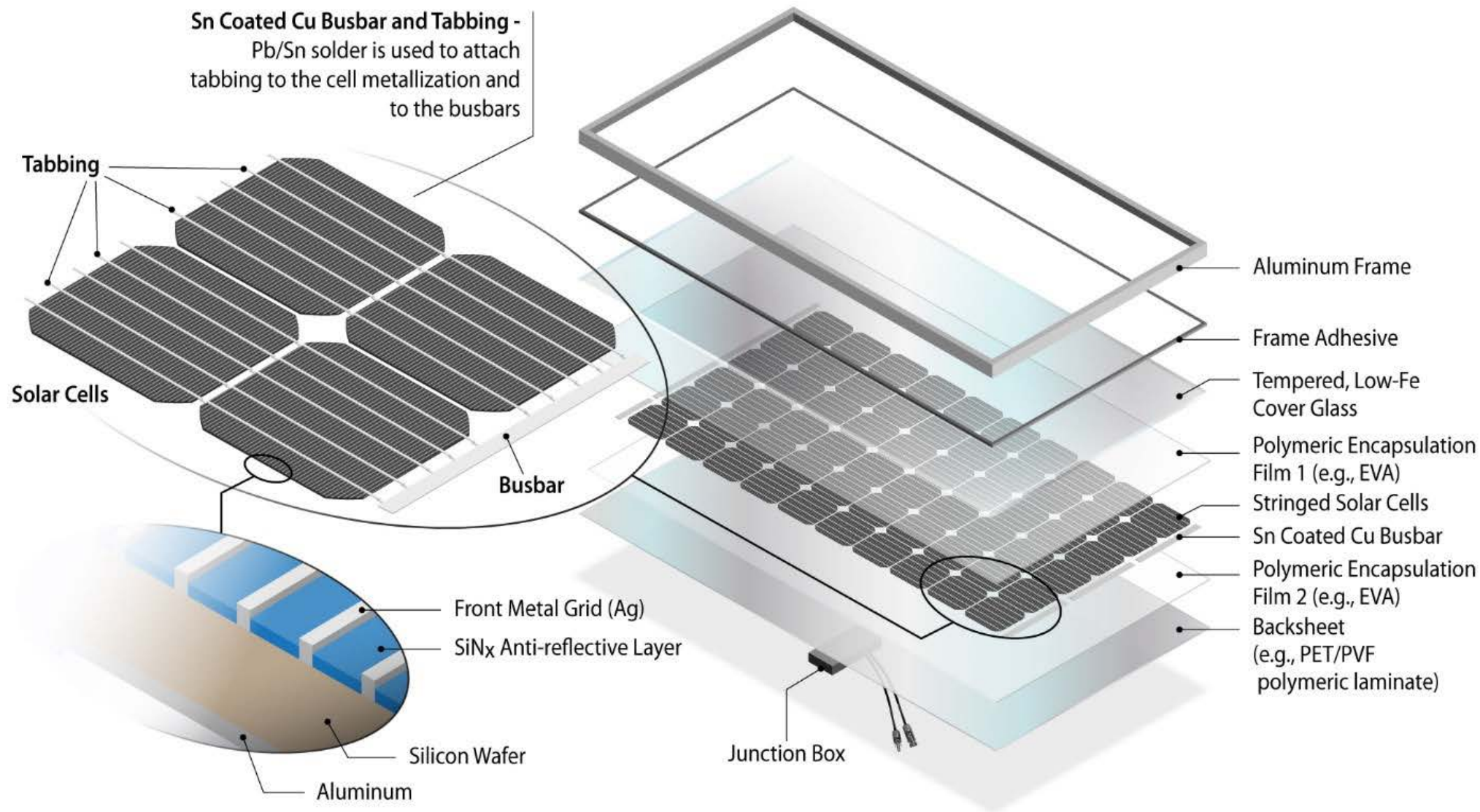
(A)



(B)



PV Module Design (silicon)



Different Approach Than Other PV/LIB CE Reviews and Prior A&WMA Critical Reviews

- Primary difference is use of *systematic review* procedures and reporting guidelines
- Based on advances initiated in the biomedical sciences to support meta-analyses of clinical trials
- Led by Cochrane Collaborative
 - Cochrane Handbook – systematic review methods
 - PRISMA – Preferred Reporting Items for Systematic Reviews
 - Endorsed by 187 journals as well as several societies of science and medical editors.
- No prior PV or LIB CE review, nor any A&WMA Critical Review of the last 20 years, has followed systematic review procedures
- Also, we are first to review
 - all 10 R strategies,
 - all 3 life cycle stages (manufacturing, use and end of life), and
 - both material *and* digital strategies.

Benefits of Systematic Reviews

- Systematic reviews aren't the only way to review literature
- Benefits
 - Comprehensively summarize state of the literature, identify trends, and document prevalence
 - Collect maximal information with minimal bias,
 - Allow consistent intercomparison and
 - Ensure transparency and reproducibility.
- Achieved by establishing search terms, inclusion/exclusion criteria, and literature classification schemes up front so they can be objectively applied
 - Check objectivity and consistency with independent second review for subset of publications
 - Our review found an error rate of just 1.4% with independent second review of 8% of publications passing our screens.

Literature Classification

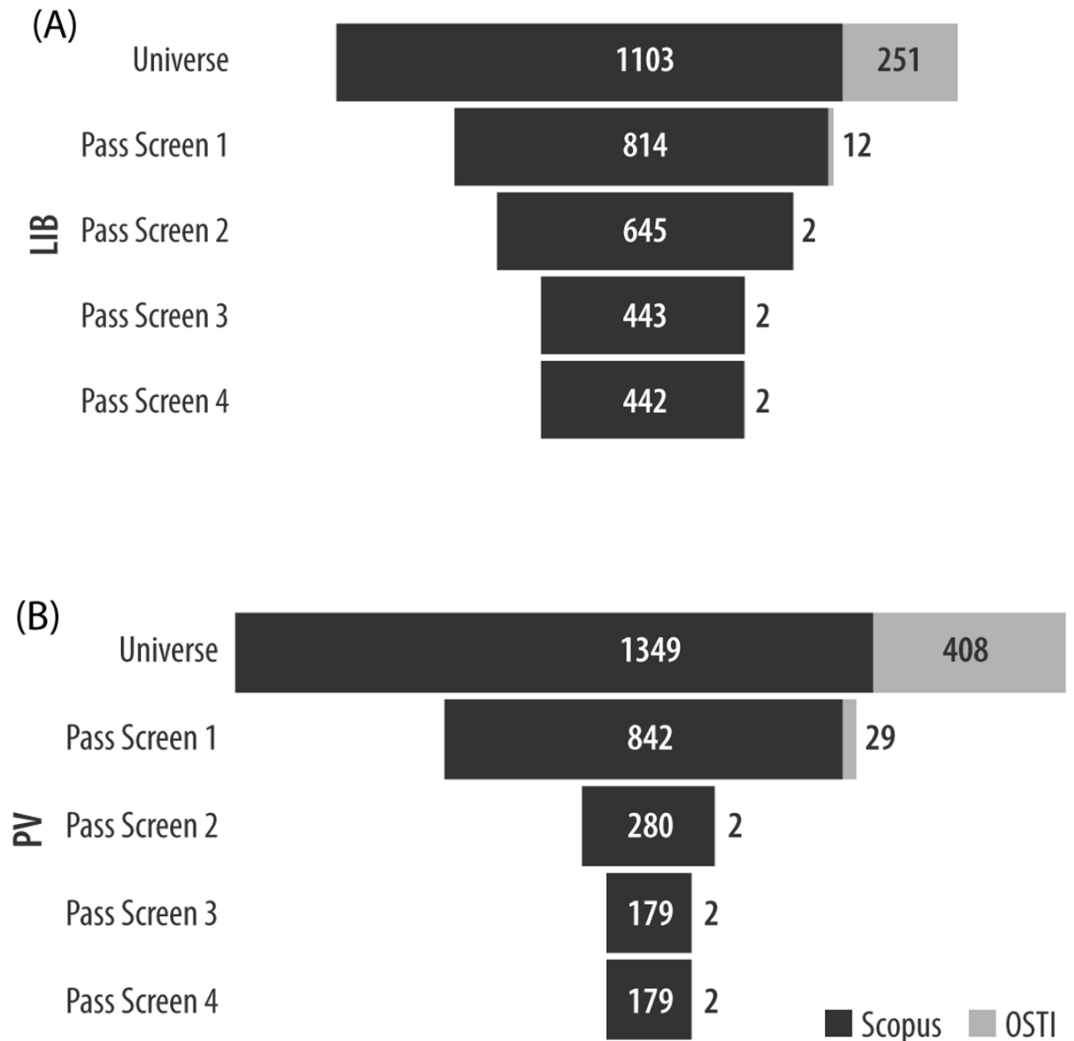
- **70 standard classifications**, for example:
 - R strategy investigated
 - Life cycle phase
 - Study type
 - Indicators
 - Scale of analysis
 - PV/LIB specific ones, such as
 - PV technology
 - LIB cathode chemistry.
- Created **43,820 potential data points** for analysis

Digital Pathways

- CE literature focuses on material (physical) pathways
- Many of these pathways are enabled, enhanced or accelerated by digital approaches such as:
 - Machine learning/artificial intelligence
 - Automation
 - Digital product labeling or monitoring
 - Alternative business models.
- Not many publications on these yet, so we document industrial activity as reported on websites or news articles

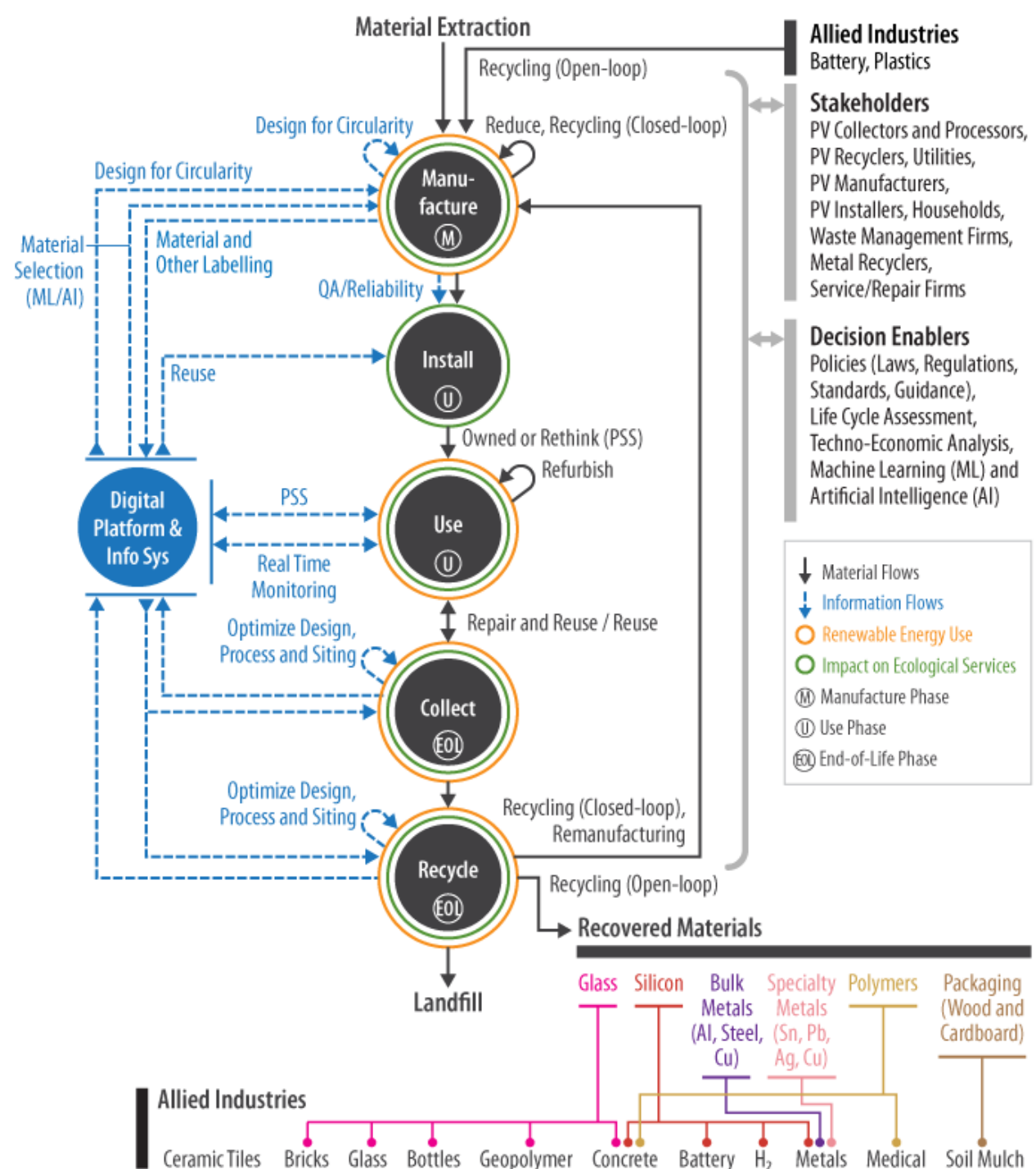
Literature Screening

- **3,111** publications in total reviewed
 - Another difference with prior reviews which did not evaluate as much literature.
- **LIB:** Out of 444 publications passing all screens
 - 332 original research publications and
 - 112 reviews.
- **PV:** Out of 181 publications passing all screens
 - 160 original research publications and
 - 21 reviews.



CE Systems Diagram: PV

- Our Critical Review produced comprehensive CE systems diagrams for PV and LIB for material and information (digital) flows
- They provide a concise, visual summary of the CE pathways that exist, plus other important relationships



Material Extraction



↓ Material Flows

Ⓜ Manufacture Phase
Ⓤ Use Phase
ⓔⓞⓁ End-of-Life Phase

Material Extraction



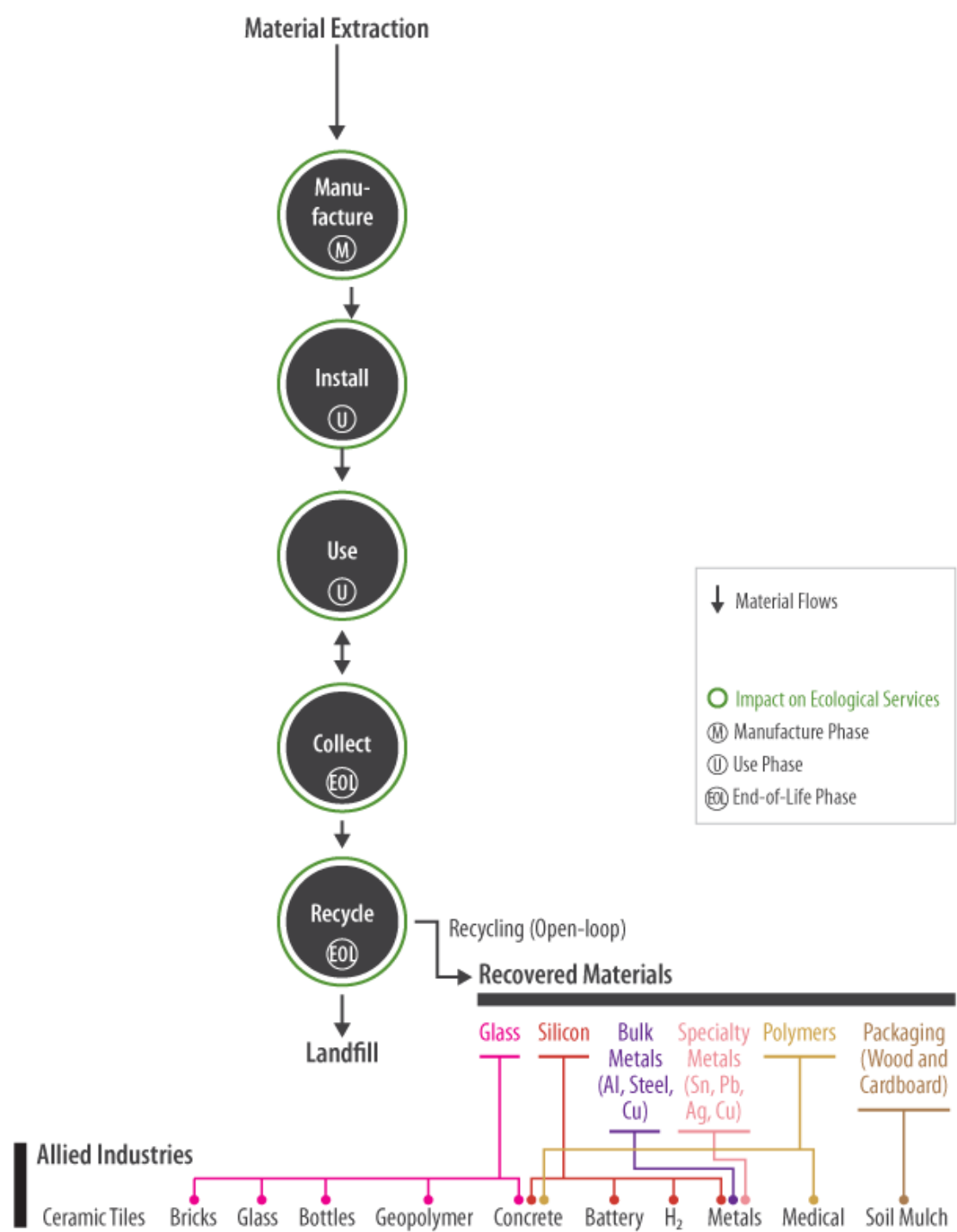
↓ Material Flows

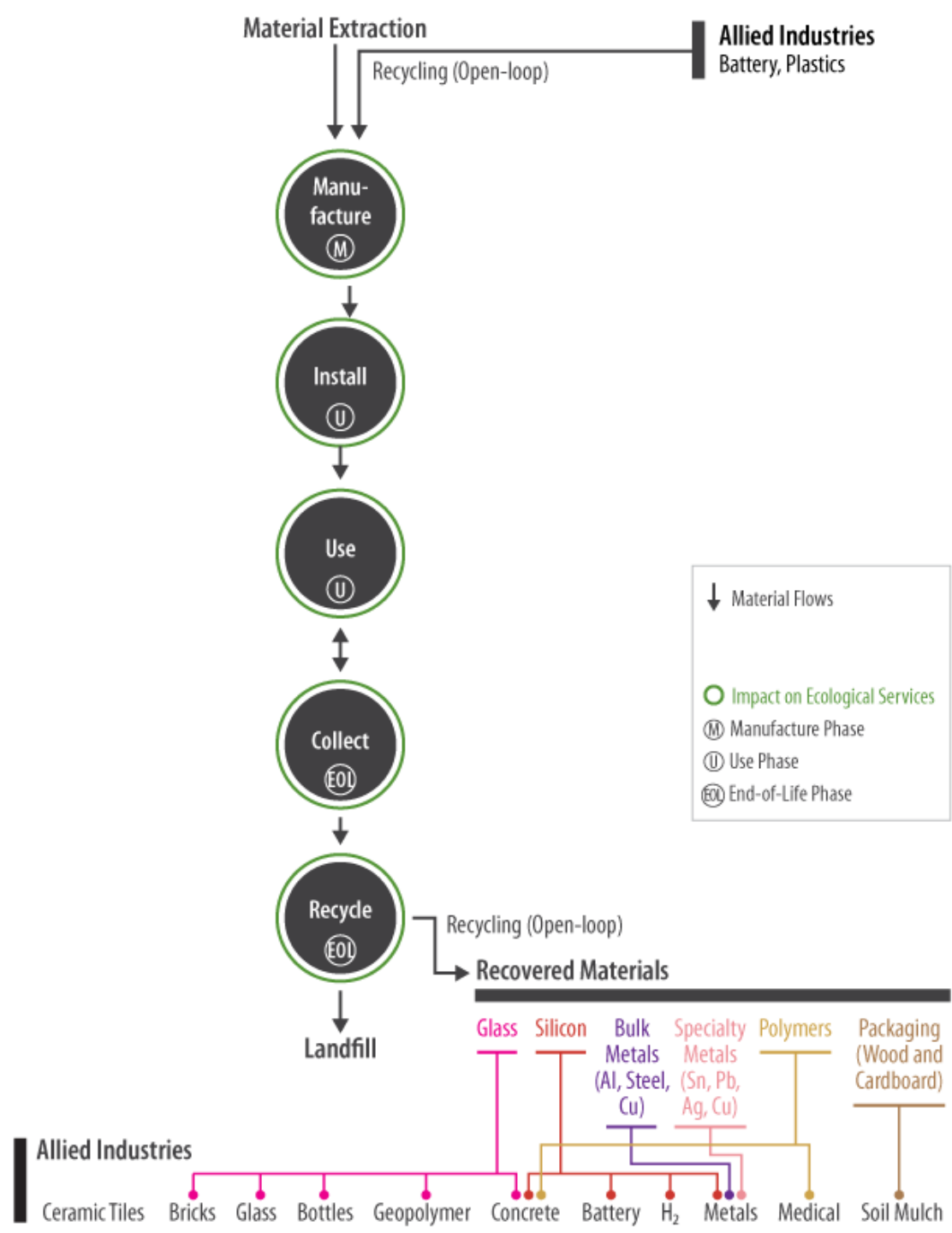
○ Impact on Ecological Services

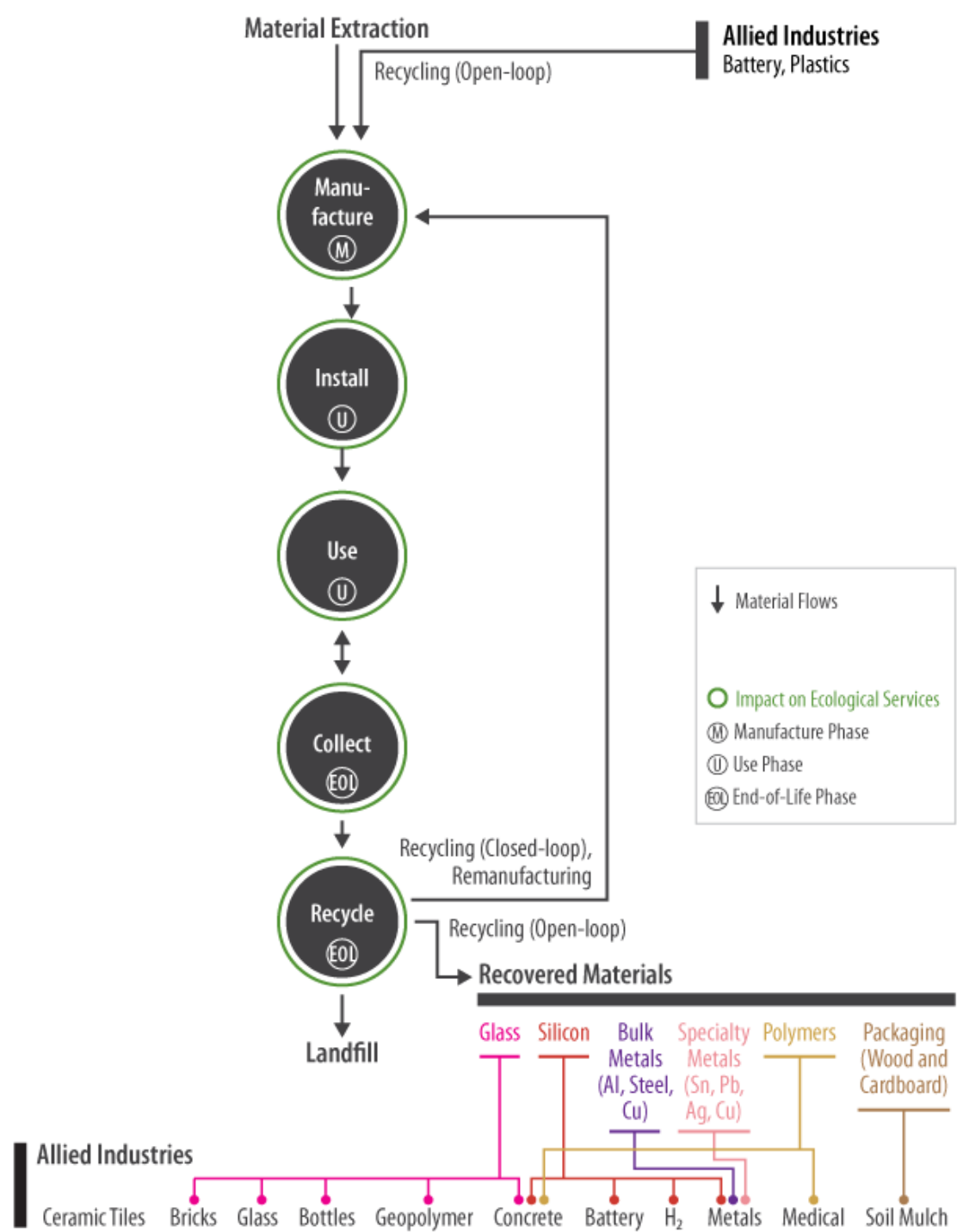
Ⓜ Manufacture Phase

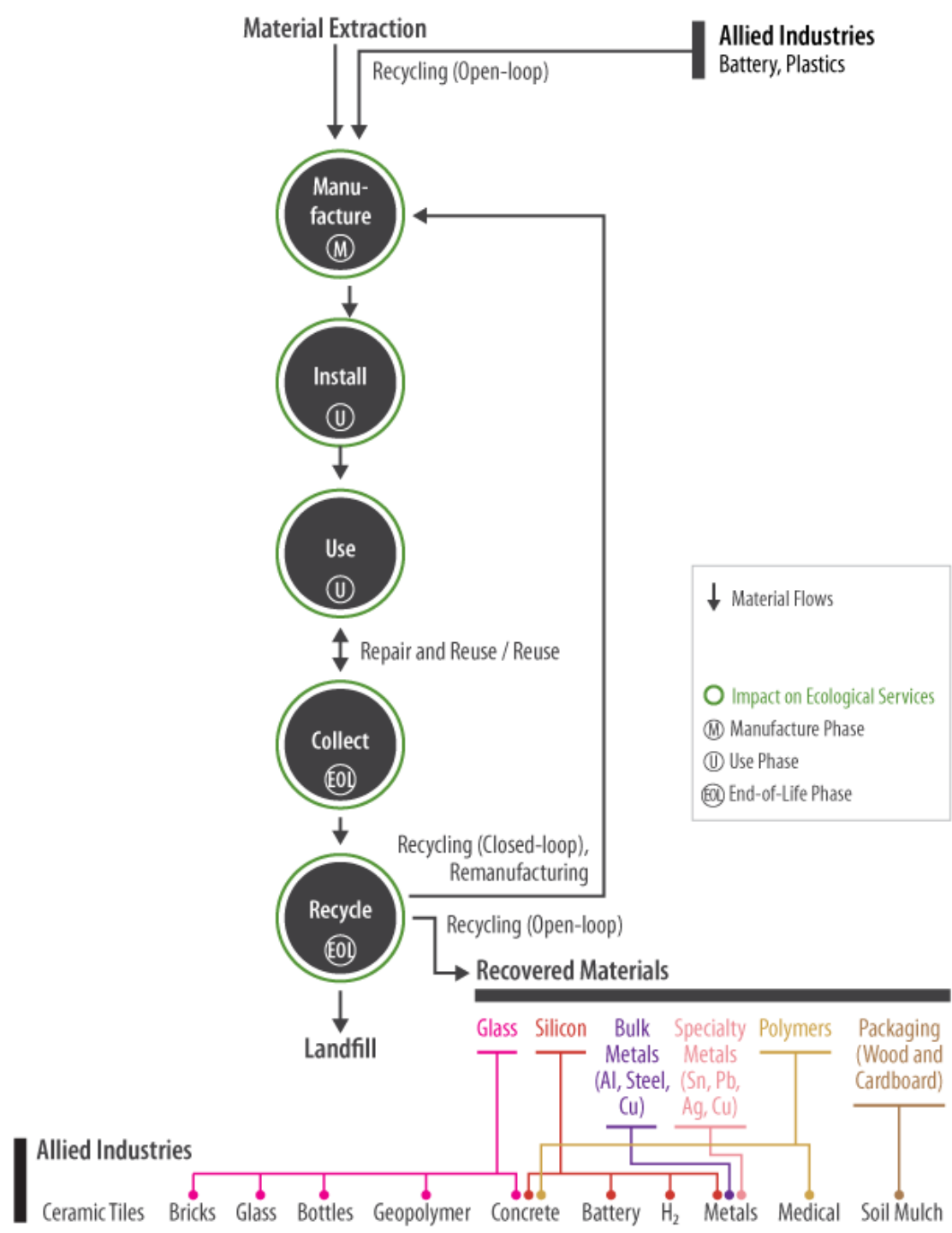
Ⓤ Use Phase

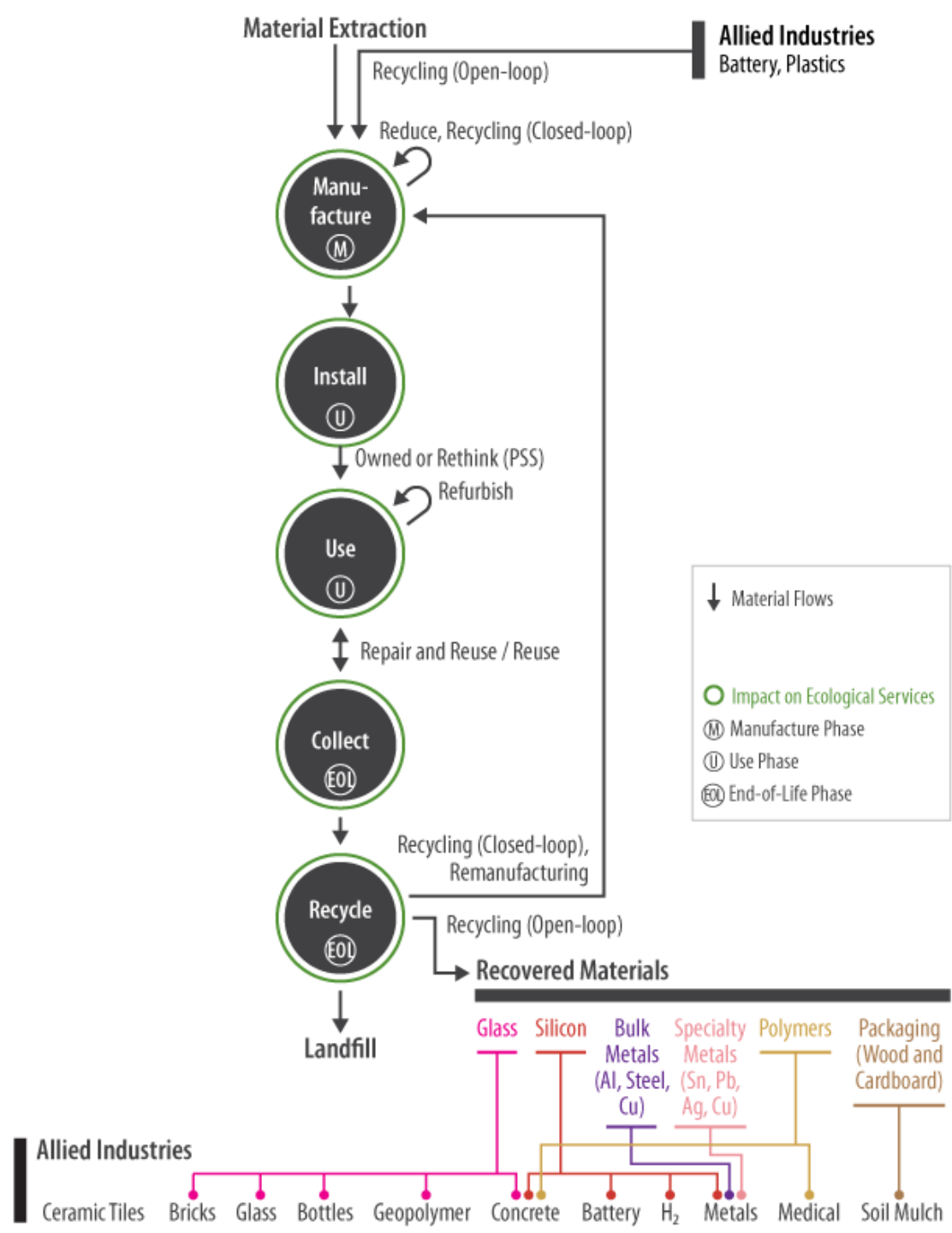
ⓔⓞⓁ End-of-Life Phase

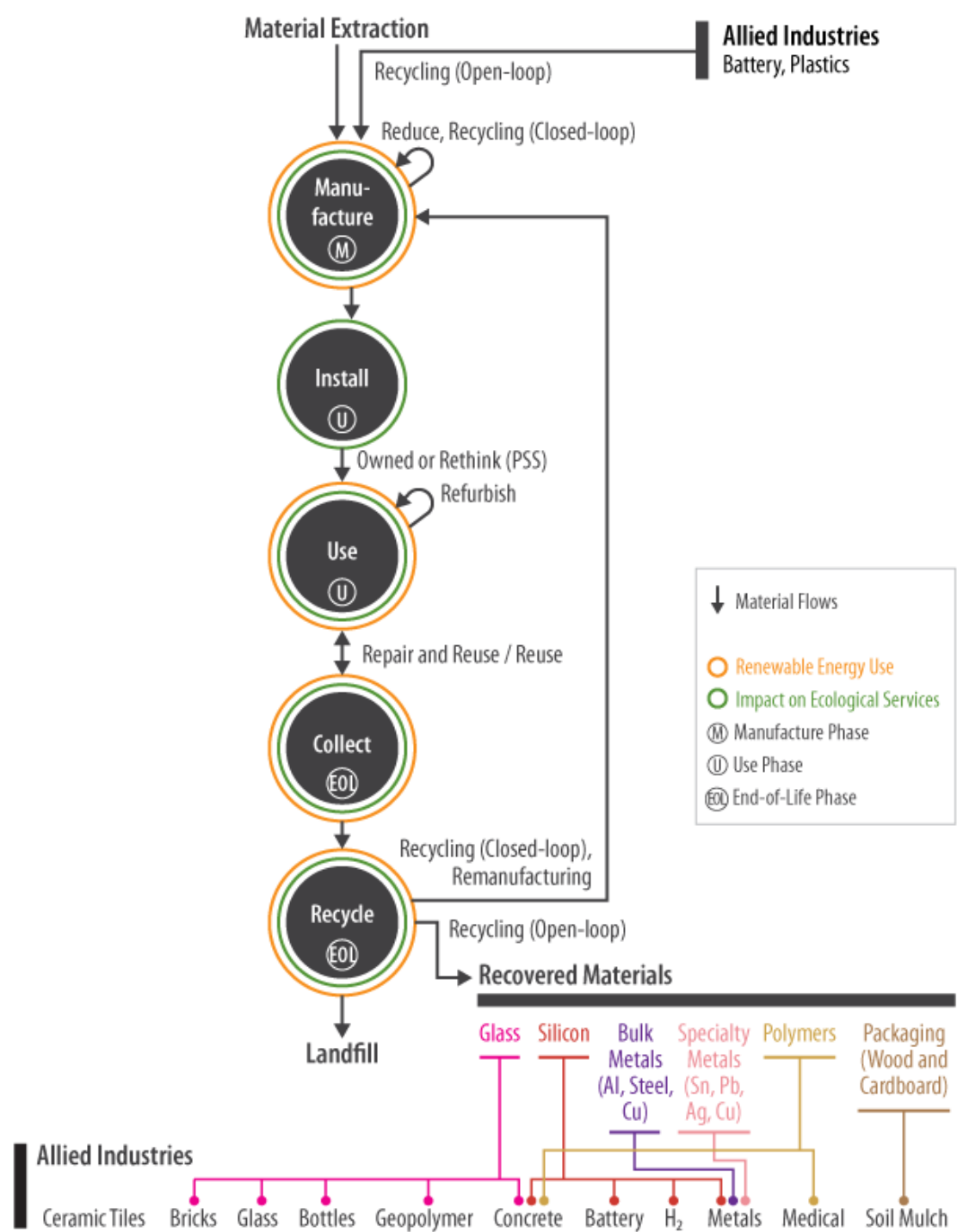


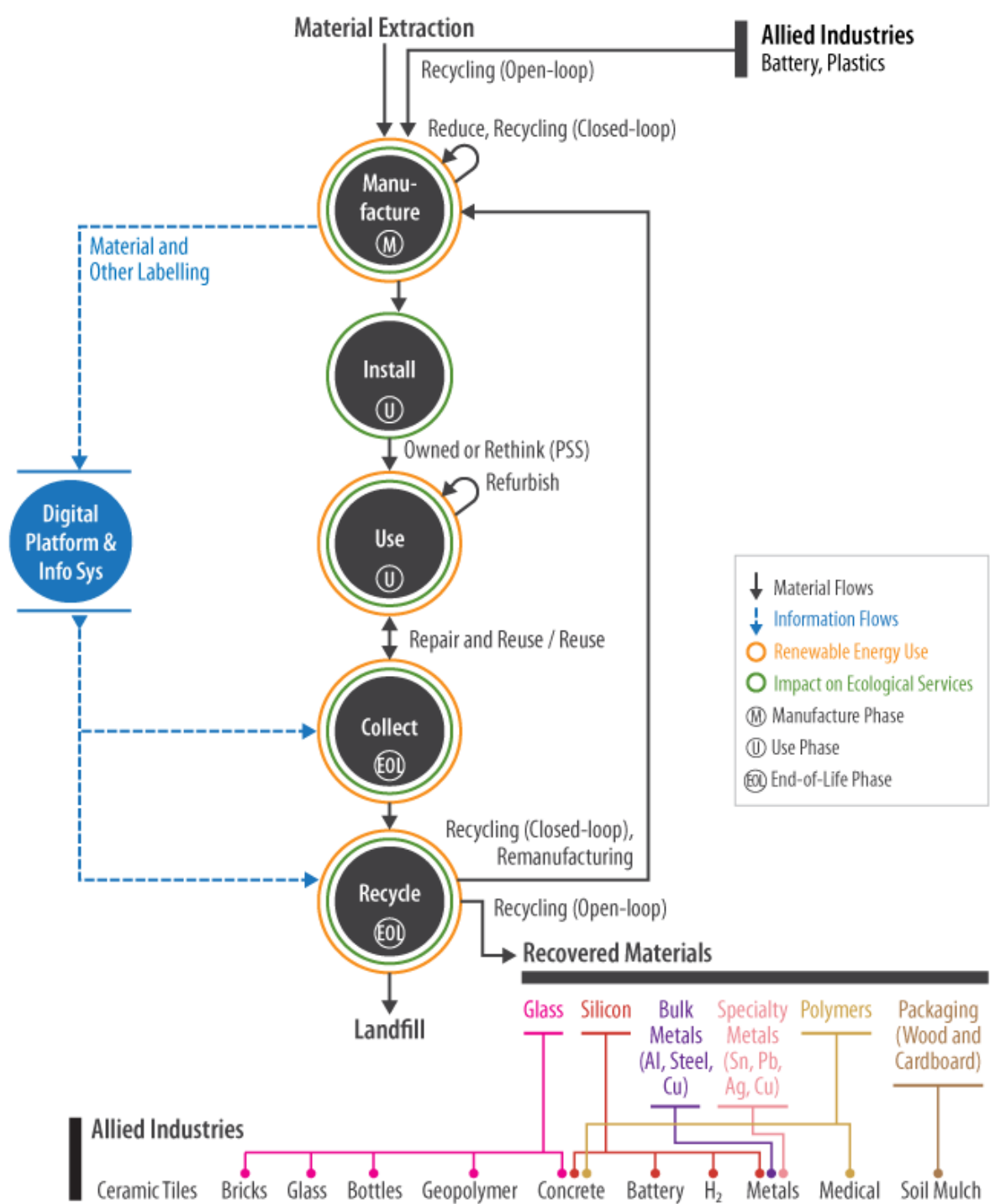


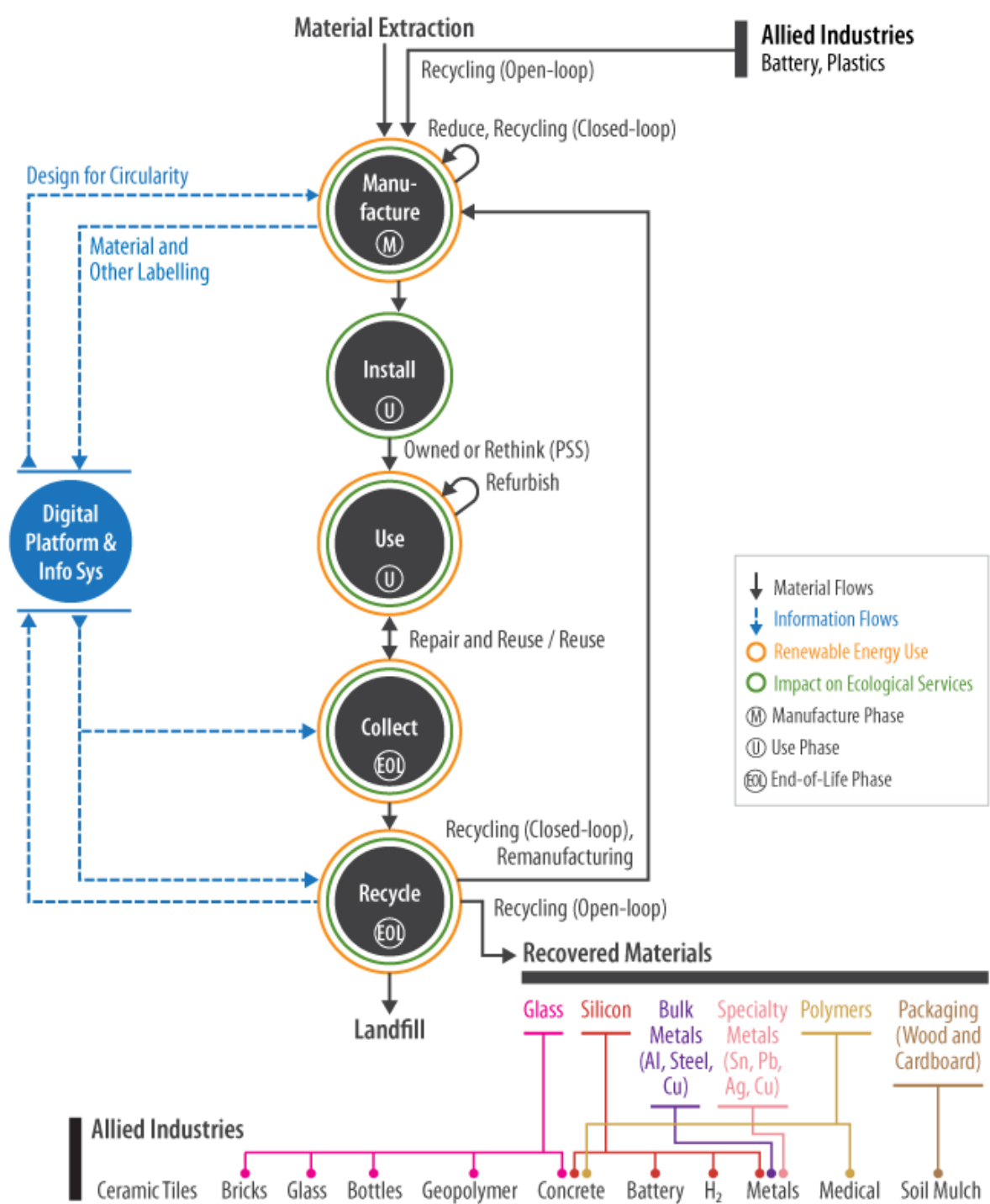


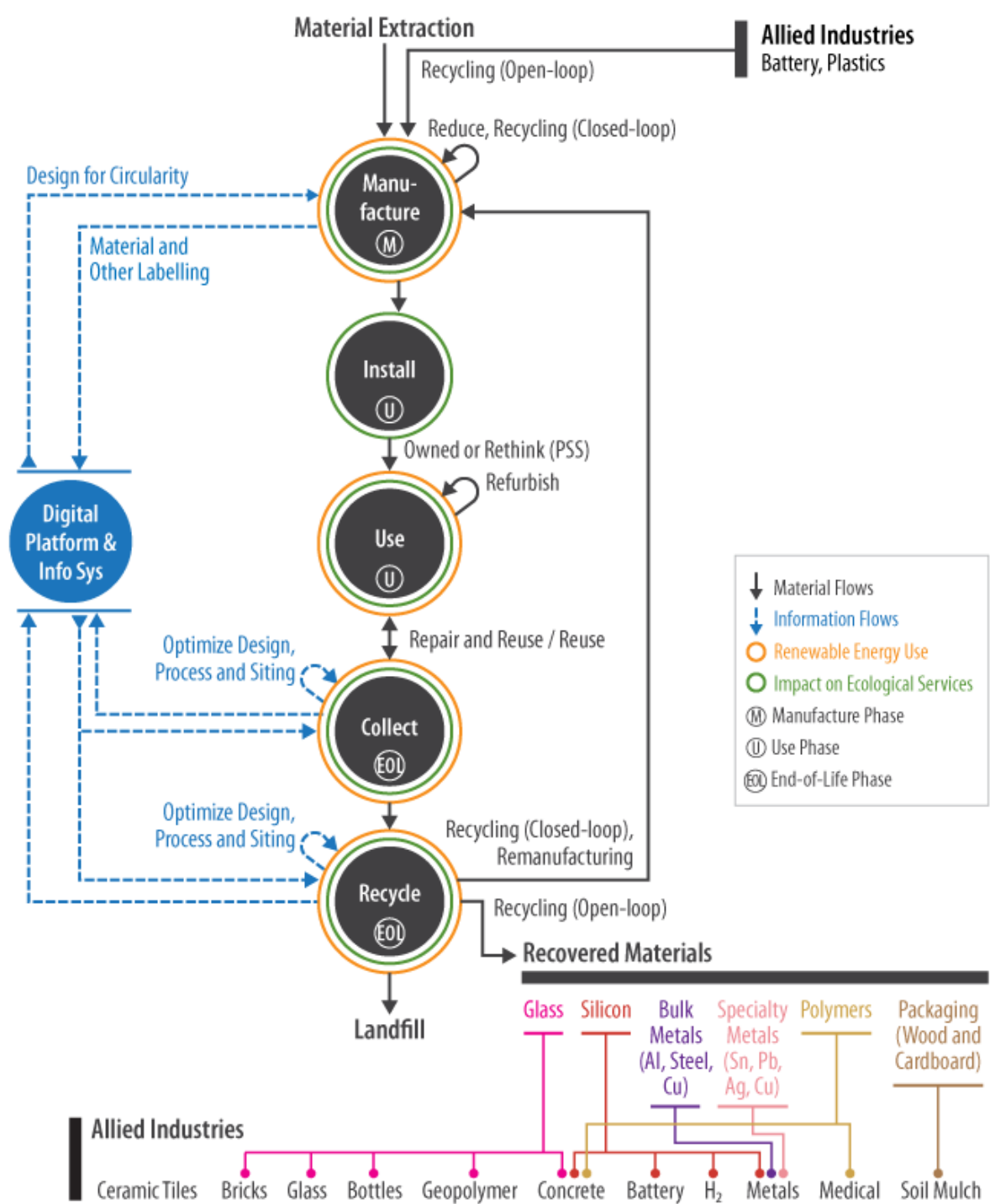


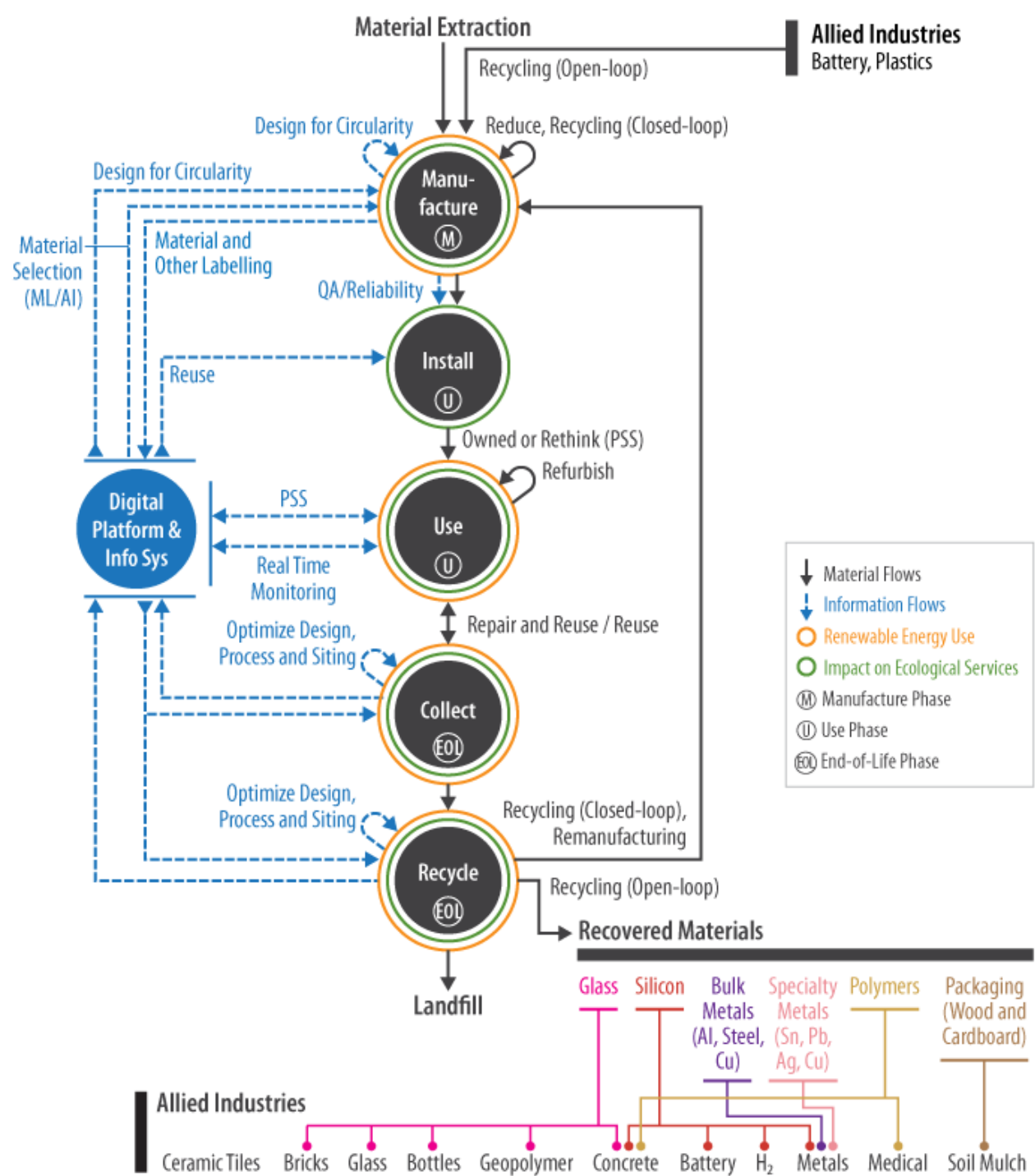


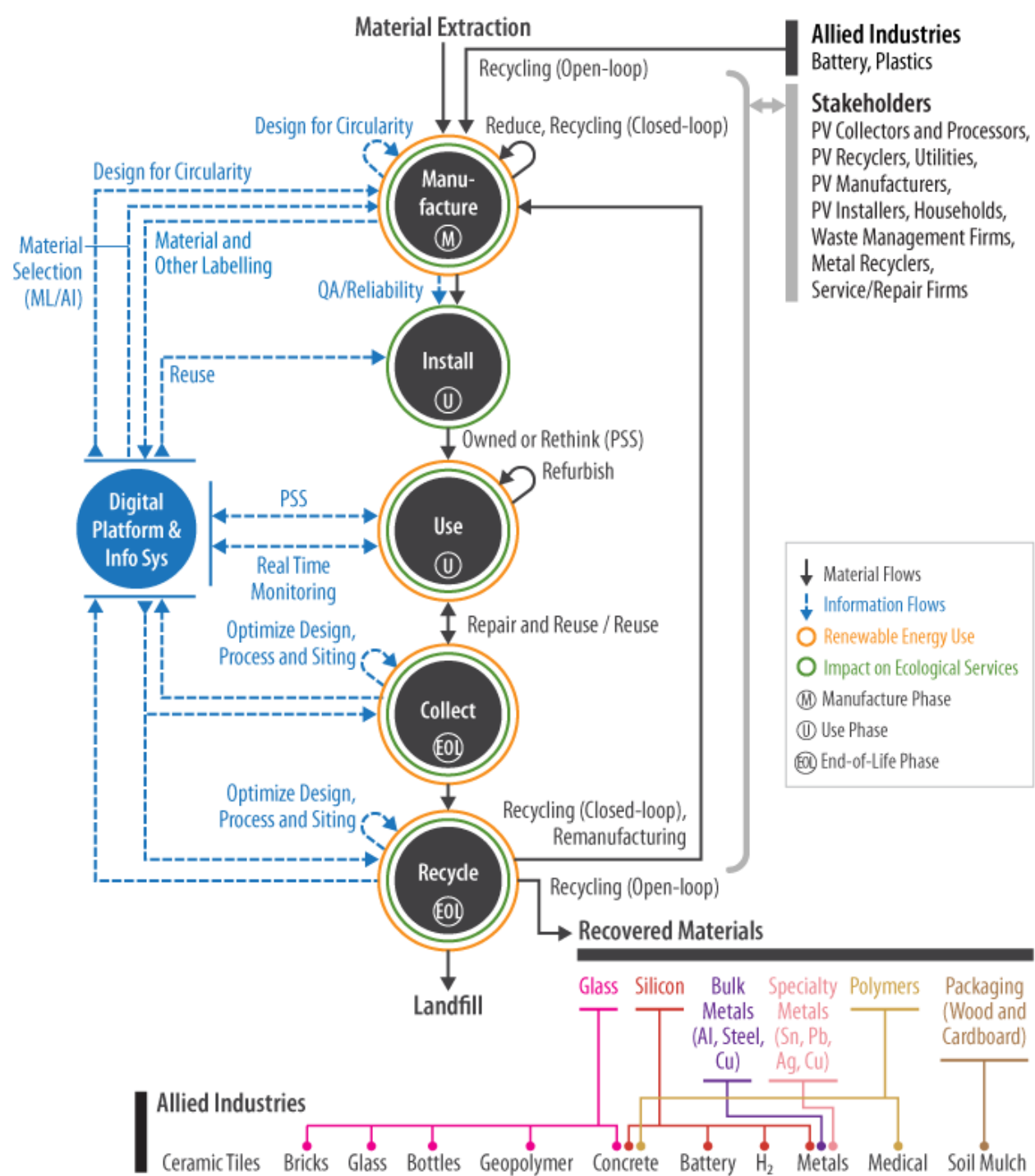


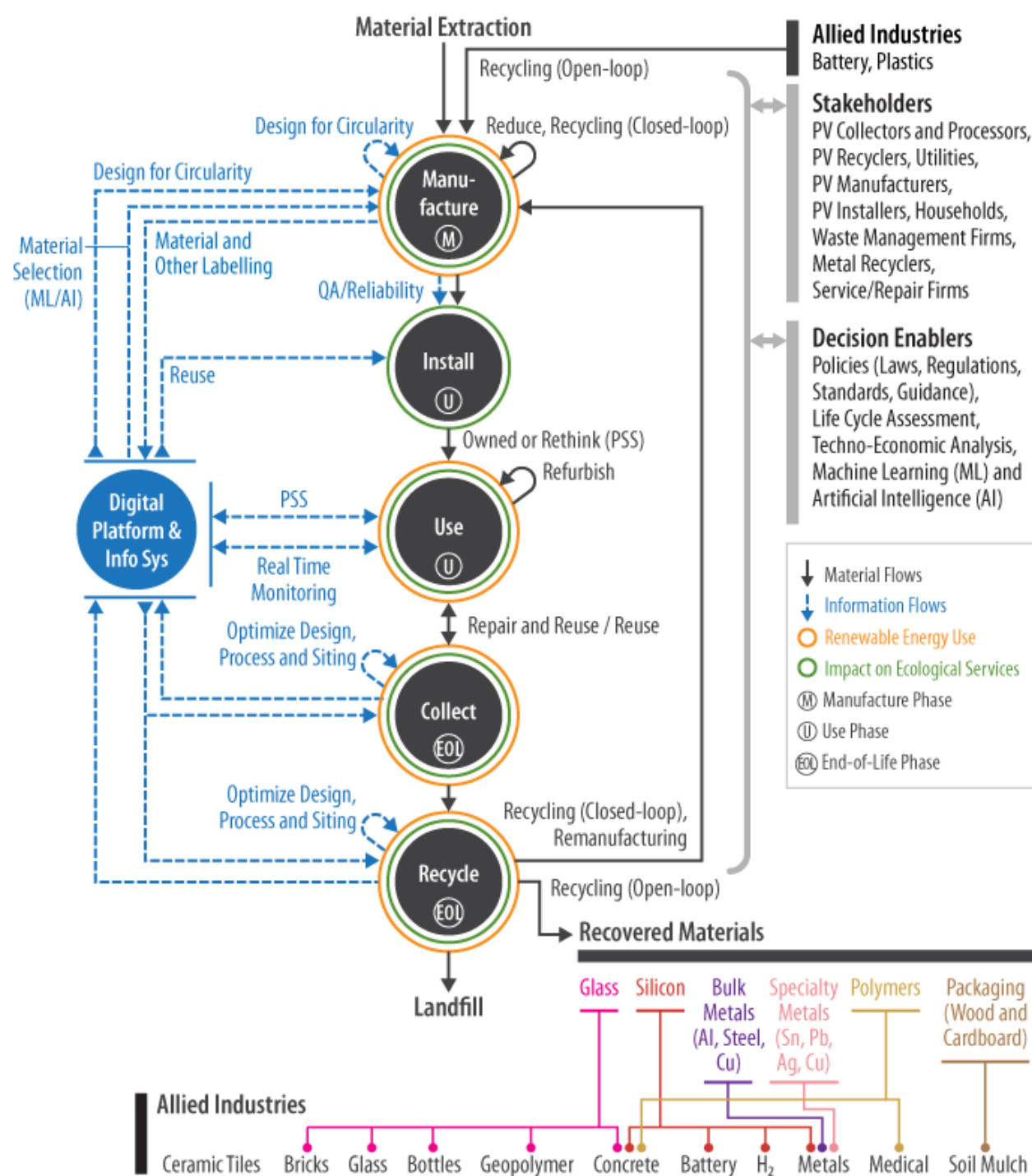






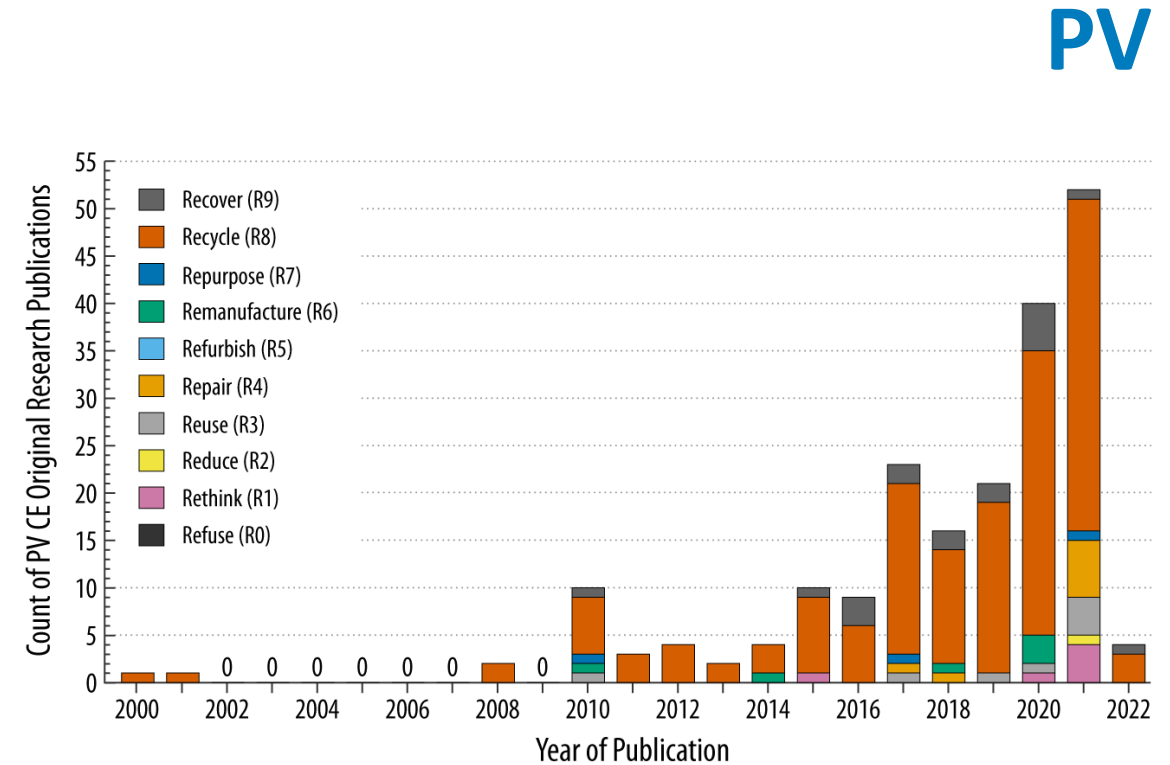
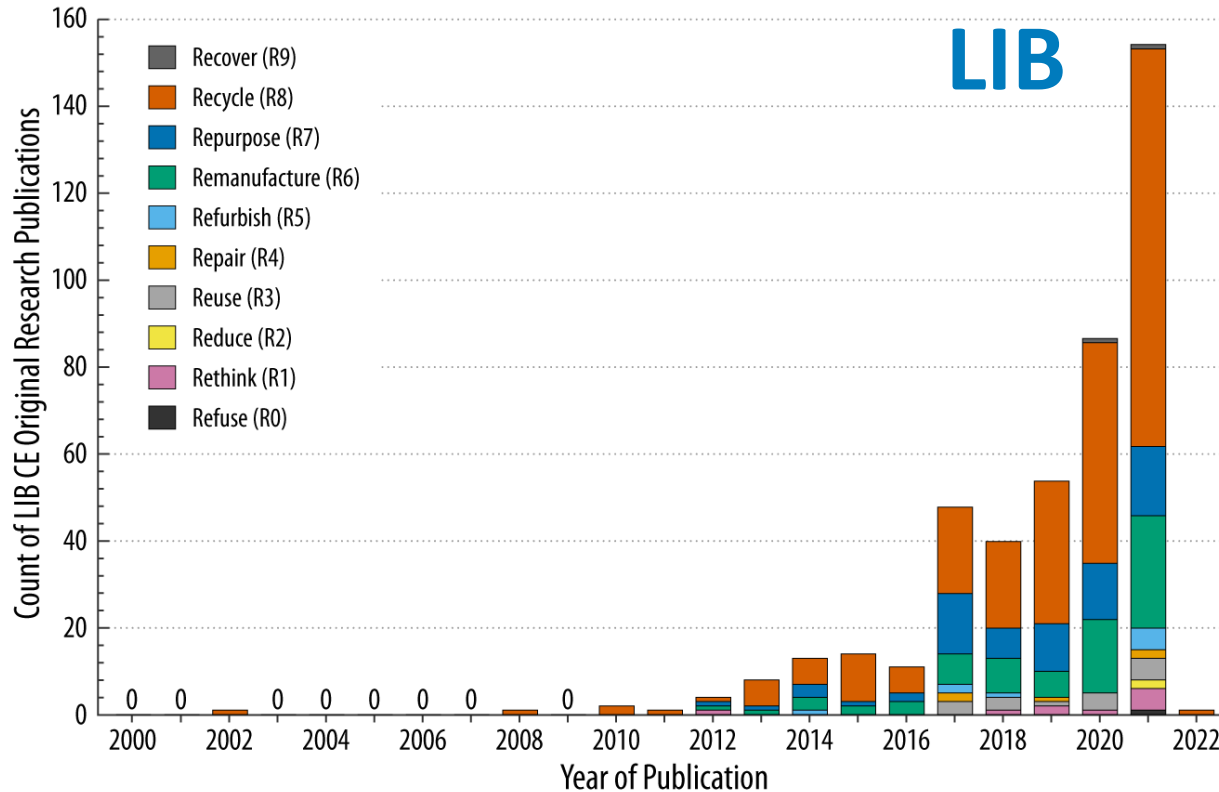






LIB and PV CE Literature Trends

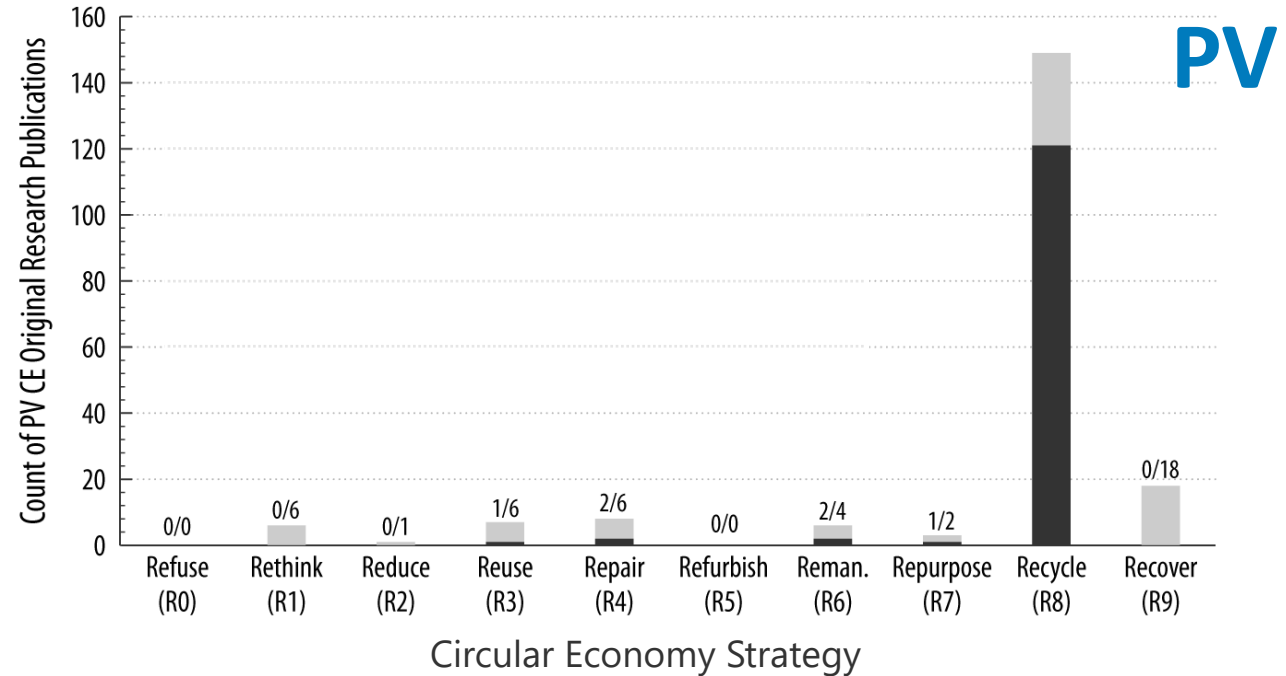
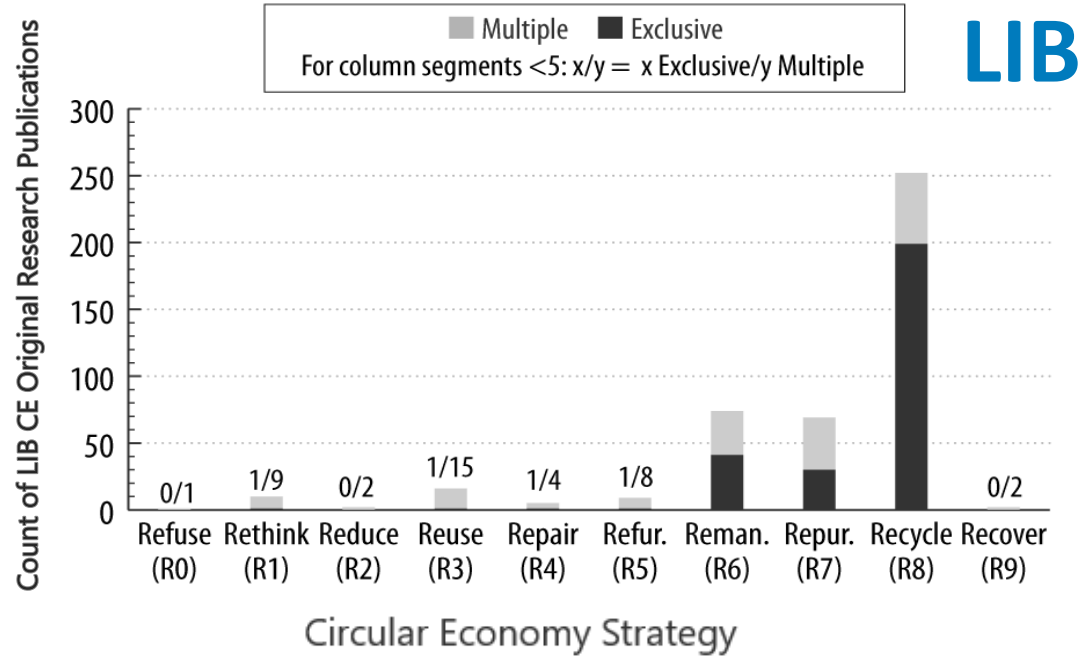
Note different scales



- First evidence of CE literature for PV and LIB in ~2000
 - Not until ~2017 does interest grow.
- Recycling by far largest single R strategy
 - Other R strategies appear more substantially in ~2017 for LIB and 2021 for PV.

Conclusion #1: Expand Research Beyond Recycling

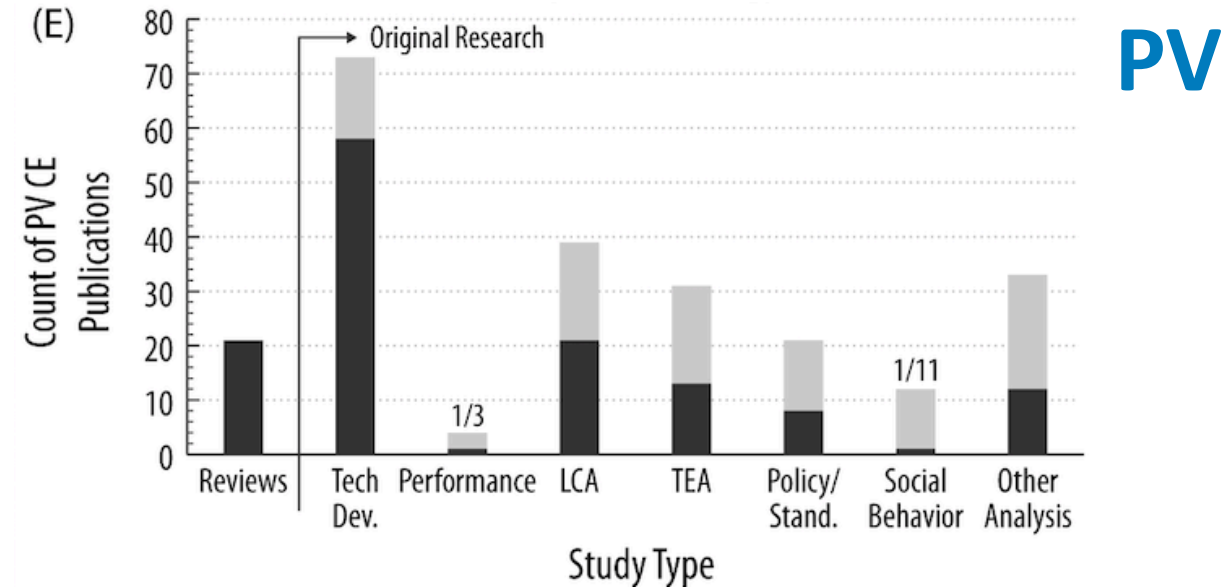
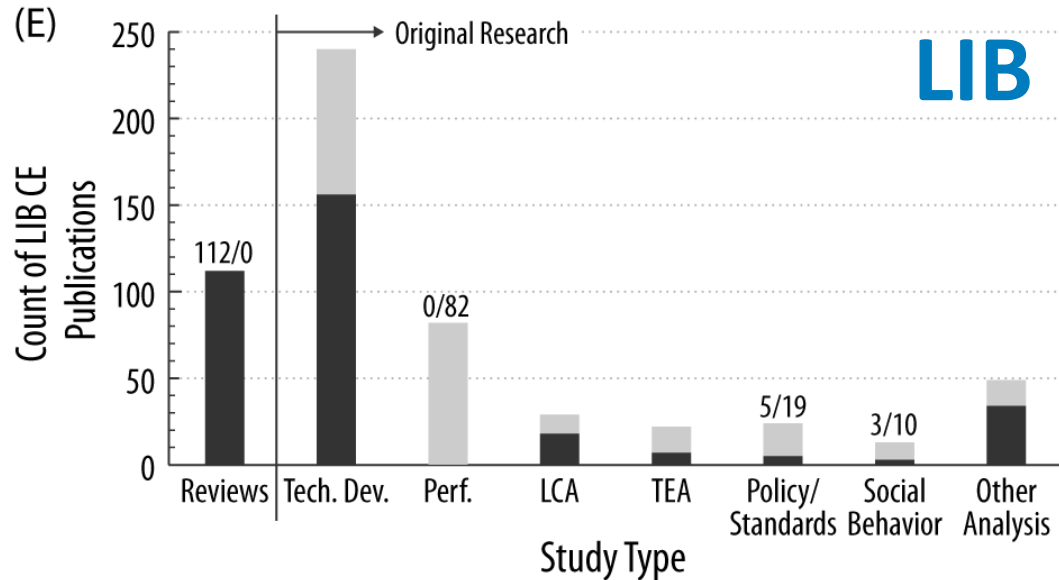
Note different scales



- Recycling is an important CE strategy and is a backstop to avoid landfilling after other strategies have been exhausted.
- Yet, other CE strategies are preferred over recycling, and have been shown to:
 - Retain a greater proportion of the value of the original products
 - Provide greater environmental and economic benefits.

Conclusion #2: Support Technology Deployment with Economic, Environmental and Policy Analysis

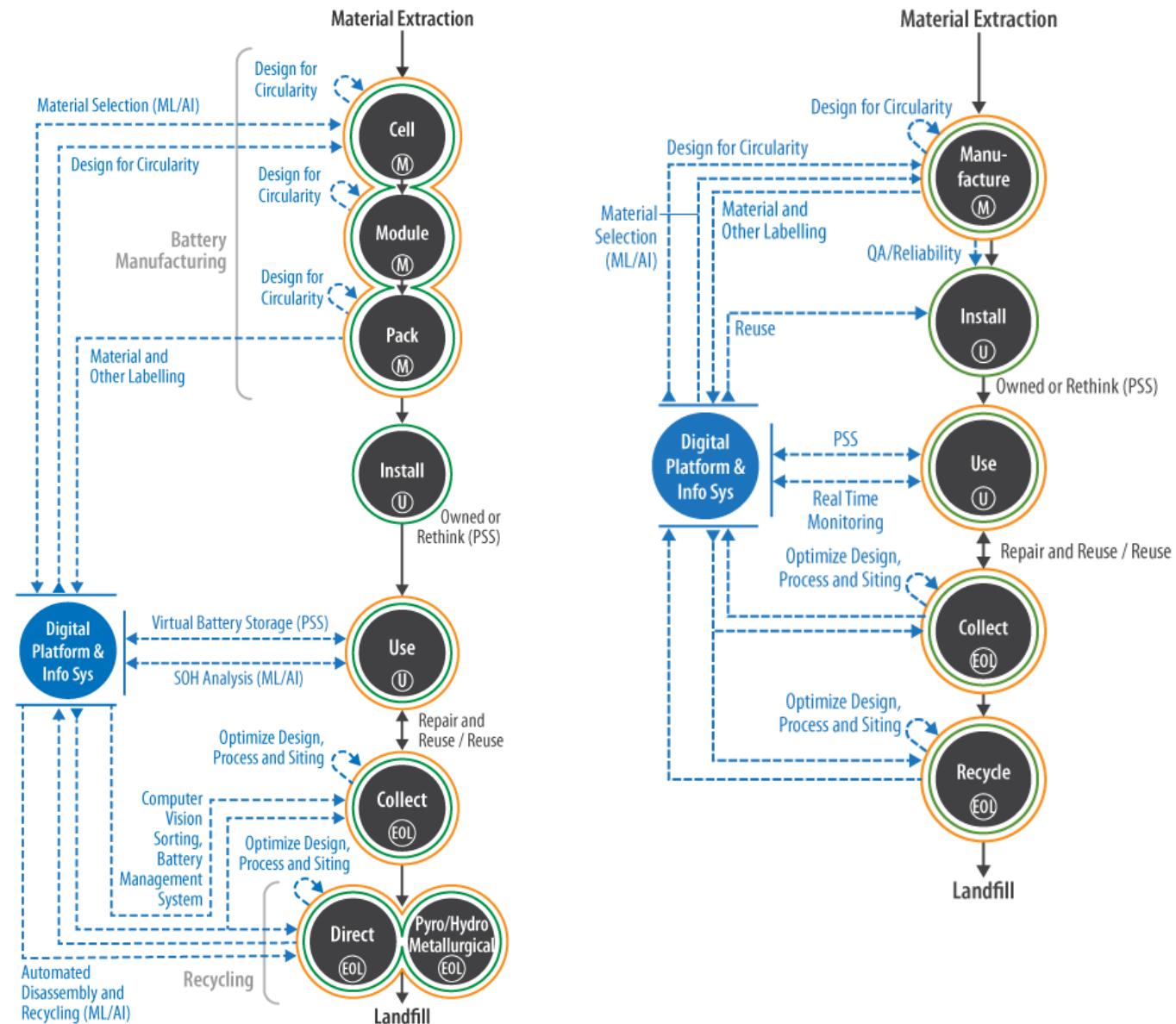
Note different scales



- All other studies combined account for less than those for technology development.
- Yet, **prevalence of adoption** determines whether and to what degree circular economy succeeds in providing benefits.
- Especially in unregulated jurisdictions, adoption requires favorable economics; behavioral factors are also important.
- If a chief motivation to pursue CE is for environmental benefits, then these benefits must be proven and documented.
- Finally, even for unregulated markets, policies and regulations play a critical role in shaping the marketplace.

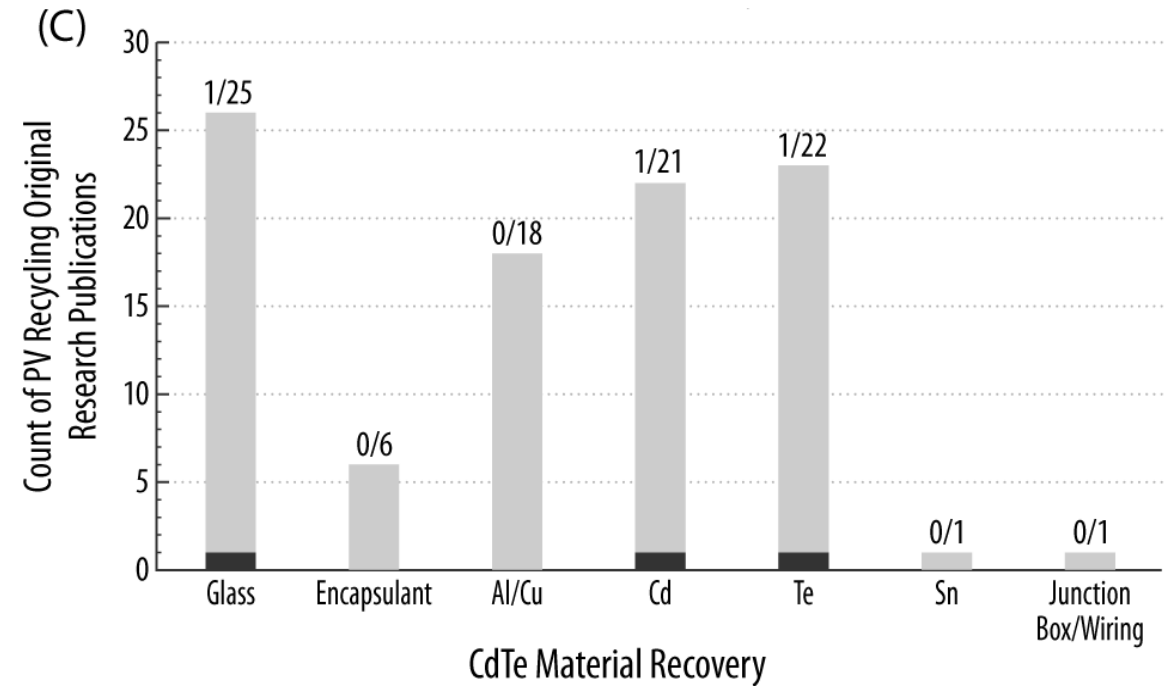
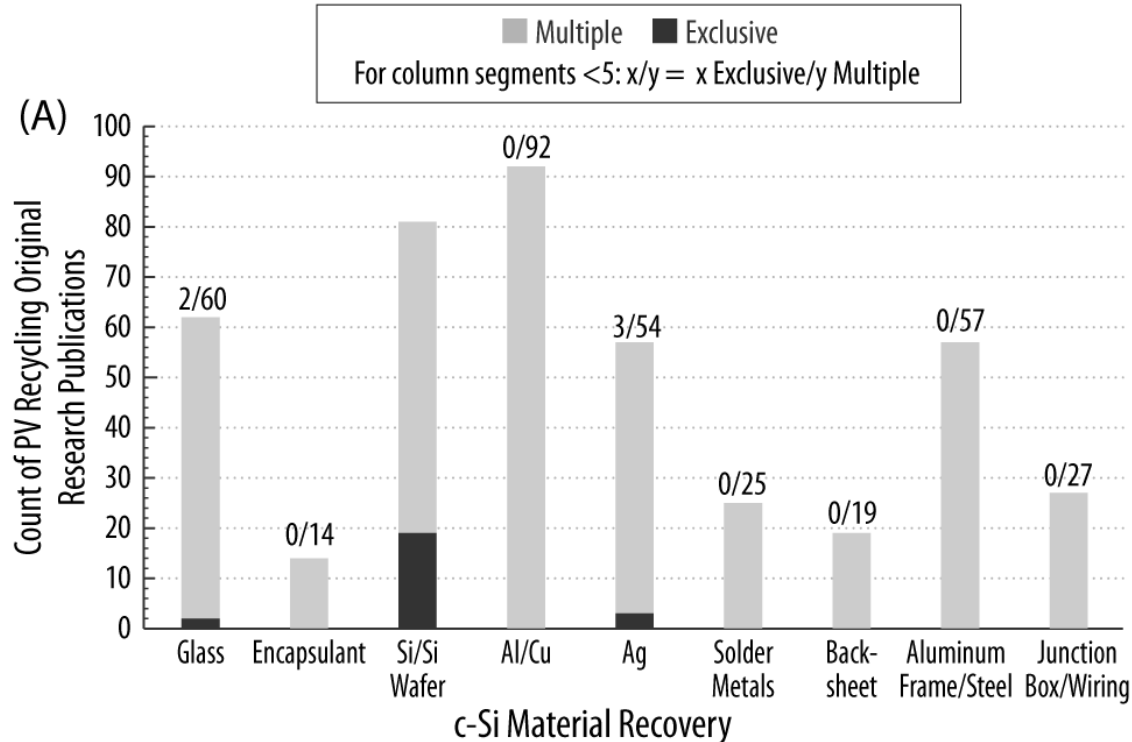
Conclusion #3: Leverage Digital Information Systems

- Digital platforms and information systems can be leveraged to implement and improve CE strategies across all three life cycle stages.
- We find that digital pathways deserve more attention to explore their technical potential, benefits and trade-offs.



Conclusion #4: Improve Recycling Technologies

Note different scales



- Lack of integrated recycling processes that can recover all constituent materials
- Cost remains the greatest challenge for increased recycling in countries that have not mandated recycling
- Research has focused more on lab-scale applications and will need to account for potential challenges that emerge in the transition to commercial scale.

Conclusion #5: Study and Design CE-related Aspects of LIB and PV Markets

- Data will need to be collected at regular intervals on both the markets for LIB and PV, and their developing CE markets
 - How many firms offer this service
 - Locations for collection and recycling
 - Their capacity
 - Annual mass recycled
 - Recycling process
 - End markets
 - Etc.
- Also
 - Publicly available projections of decommissioned PV modules or LIBs that incorporate all factors leading to end of life (e.g., failure modes, performance degradation, extreme weather events, economic alternatives such as repowering)
 - At decision-relevant geographic scales (sub-state) and temporal frequency.

Assessment of the Status of CE for PV and LIB

Have we achieved a circular economy for LIB and PV yet?

Not yet.

Are PV and LIB moving toward a CE?

Yes. Benefits of the journey to a CE for PV and LIB can be realized along the way.

Is academic research the only area of activity in CE for PV and LIB?

No.

A more circular economy can help the world reduce impacts of technology transitions.

We hope our review and recommendations can provide **some guidance towards achieving this goal.**

A Personal Note

- The A&WMA helped me get through grad school with multiple scholarships:
 - Milton Feldstein Award for Air Quality Engineering, 2003
 - 1st place, (National) Graduate Scholarship, 2003
 - Golden West Section Scholarship, 2002
- I am honored to give something back to an organization that supported me at a critical time early in my career.
- I hope this also lends support for AWMA leadership and members to continue to support students, and for students to continue to support AWMA

Discussion

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NREL/PR-6A20-83294

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