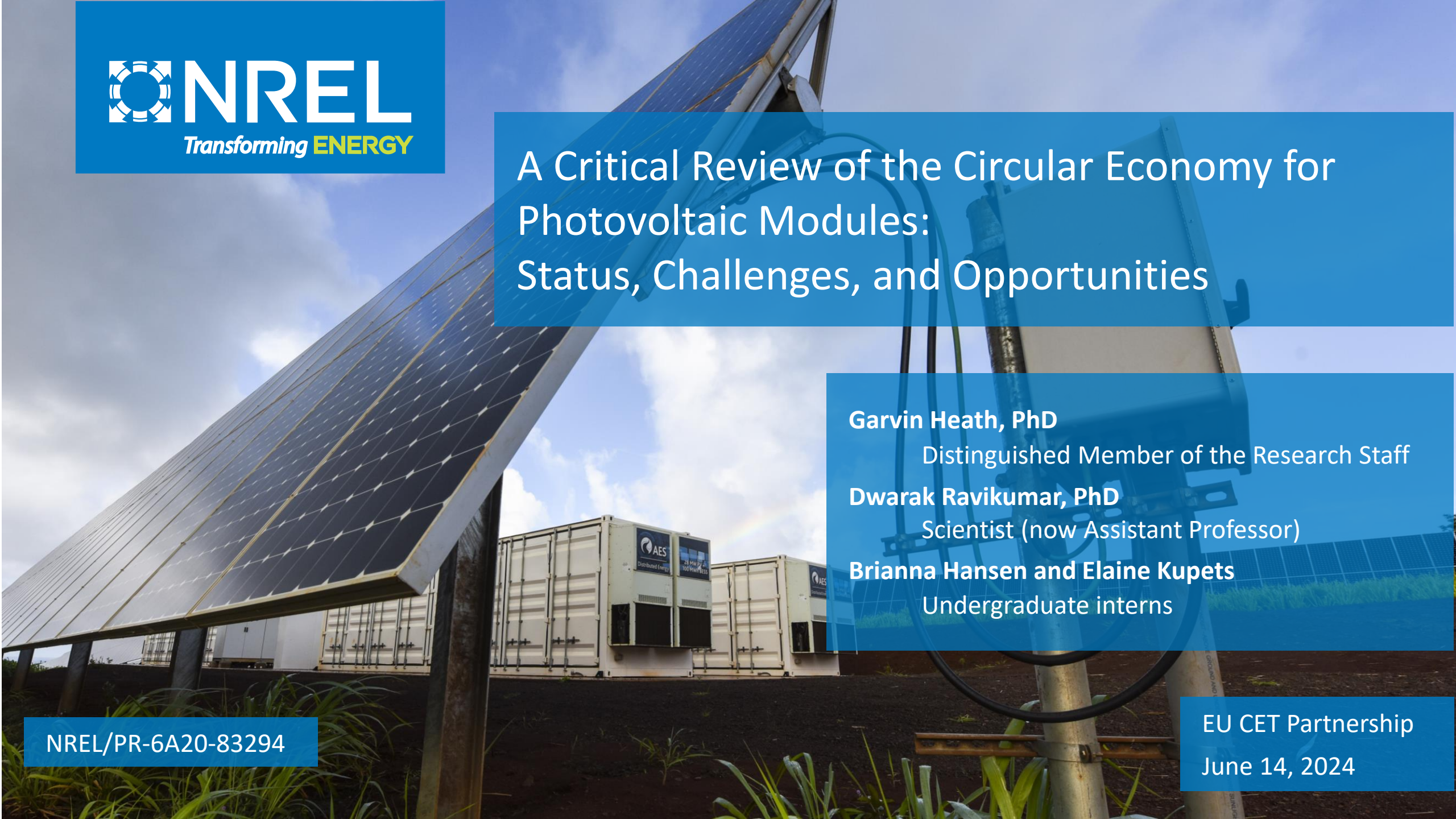

A Critical Review of the Circular Economy for Photovoltaic Modules: Status, Challenges, and Opportunities

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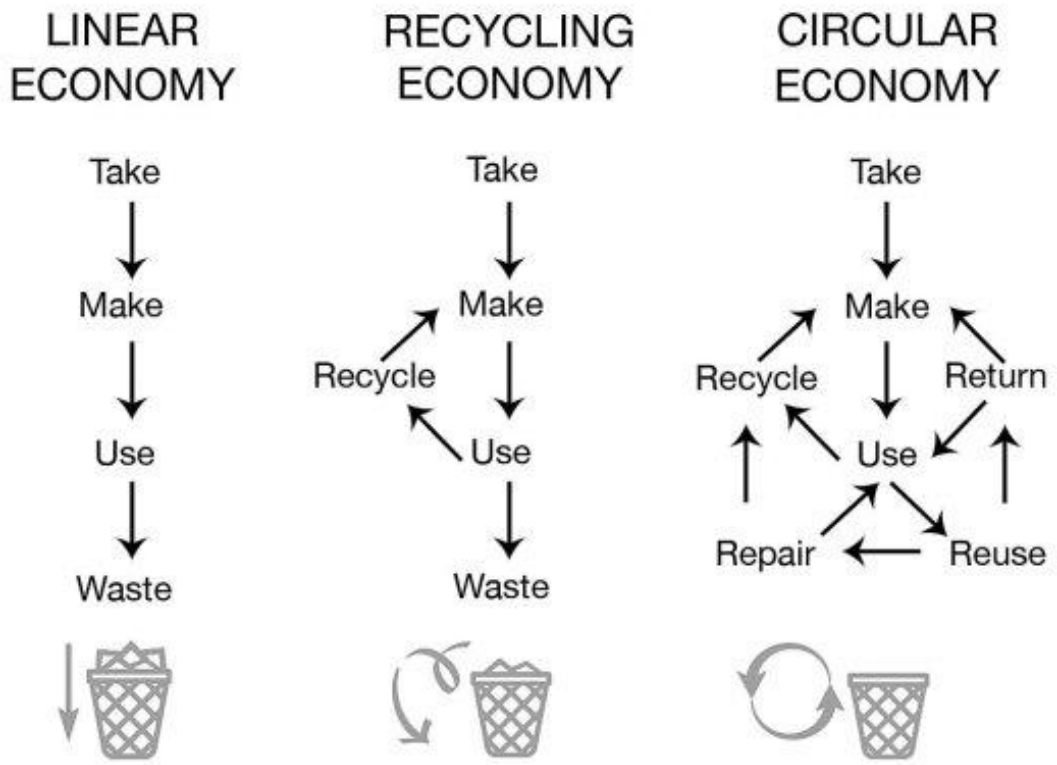
What is a **Circular Economy?**

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.

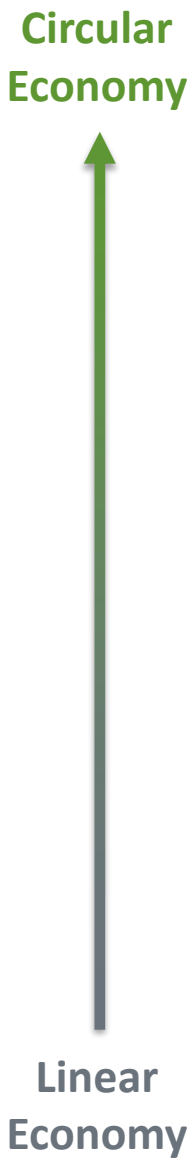


- Defined as opposed to our current linear economy
- Goes farther than recycling only
  - The recycling economy is the current focus of research, investment, and policy
  - Fits easiest into our current linear system.

Image source: https://rfittingroom.com/circular-vs-linear-economy/

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.
  - For consistency, we enforce our definitions to sometimes change the author-identified R strategy.



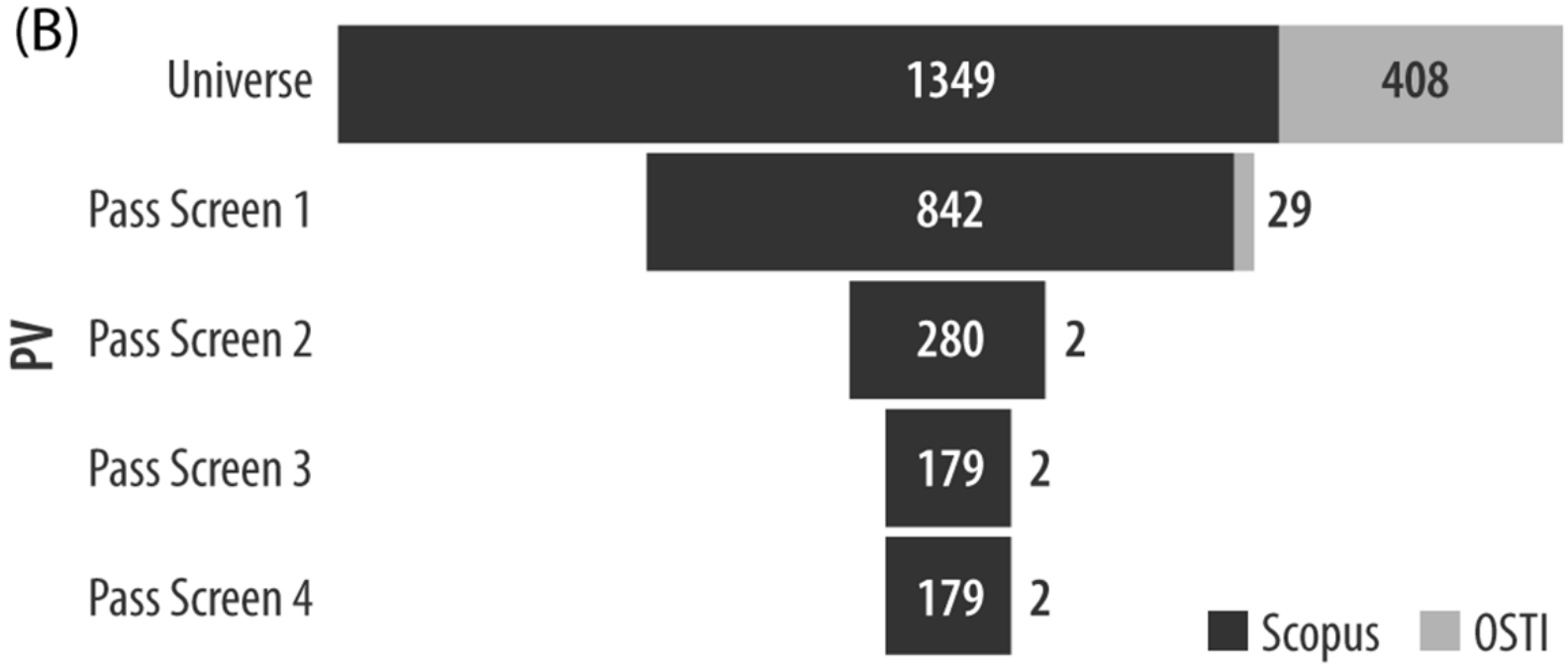
CE Strategy	
Smarter product use and manufacture. Parts of these strategies contribute to Design for Circularity	R0 – **Refuse**
	R1 – **Rethink**
	R2 – **Reduce**
Extend lifespan of product and its parts	R3 – **Reuse**
	R4 – **Repair**
	R5 – **Refurbish**
	R6 – **Remanufacture**
	R7 – **Repurpose**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

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

Different Approach Than Other PV CE 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 CE review 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.

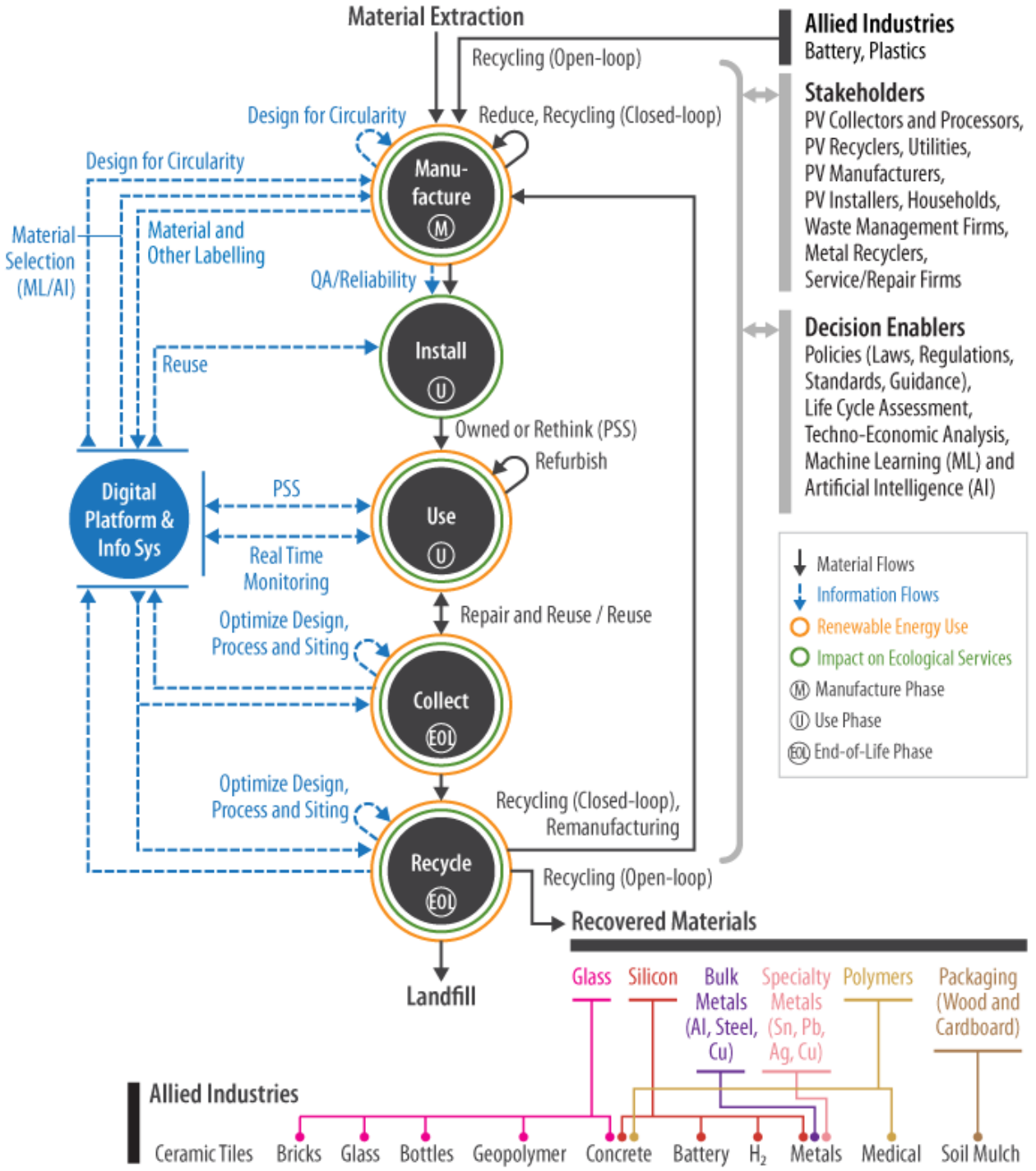
Literature Screening



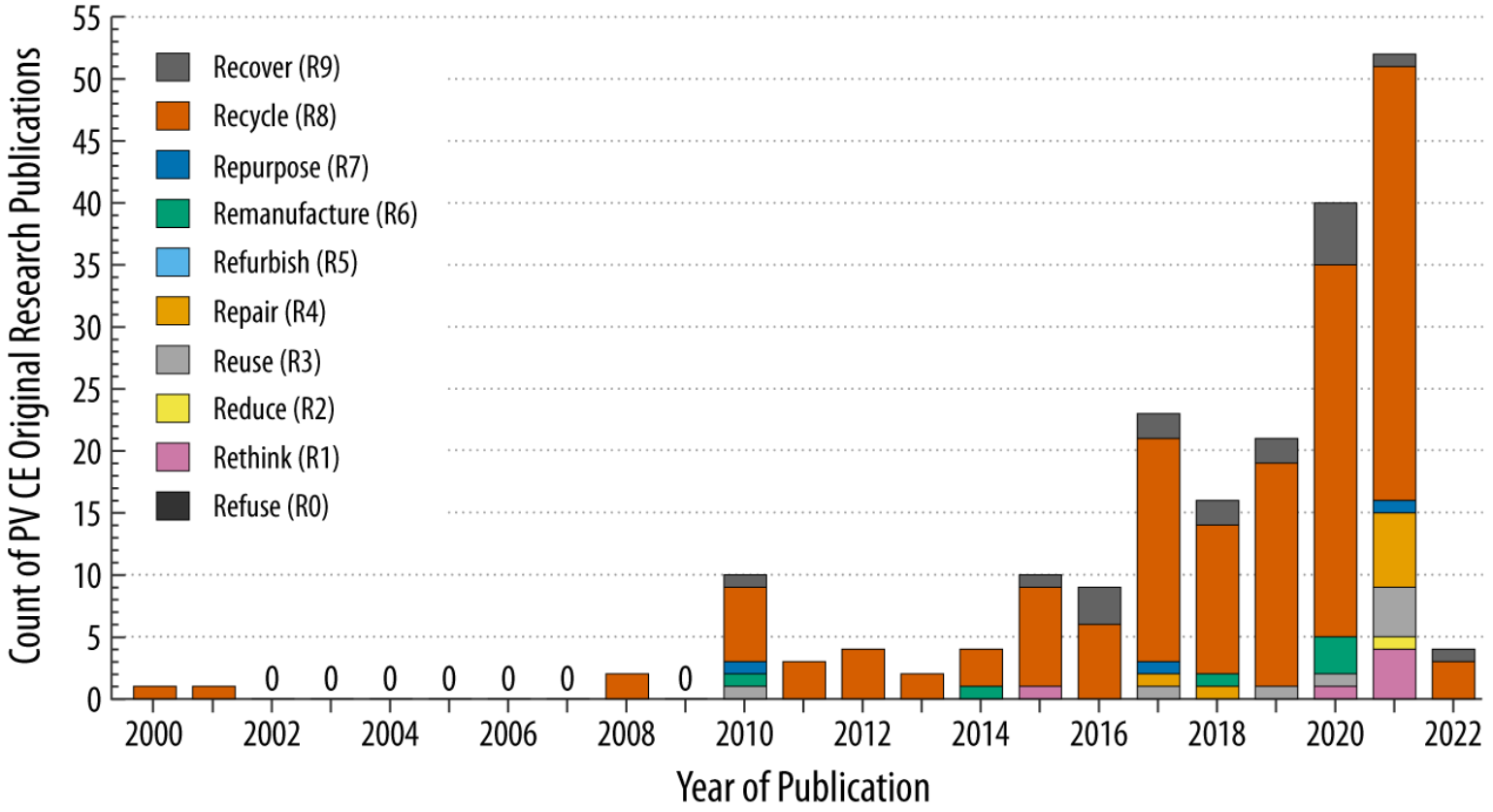
- **1,757** publications in total reviewed
  - Another difference with prior reviews which did not evaluate as much literature.
- Out of 181 publications passing all screens
  - 160 original research publications and
  - 21 reviews.

PV CE Systems Diagram

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

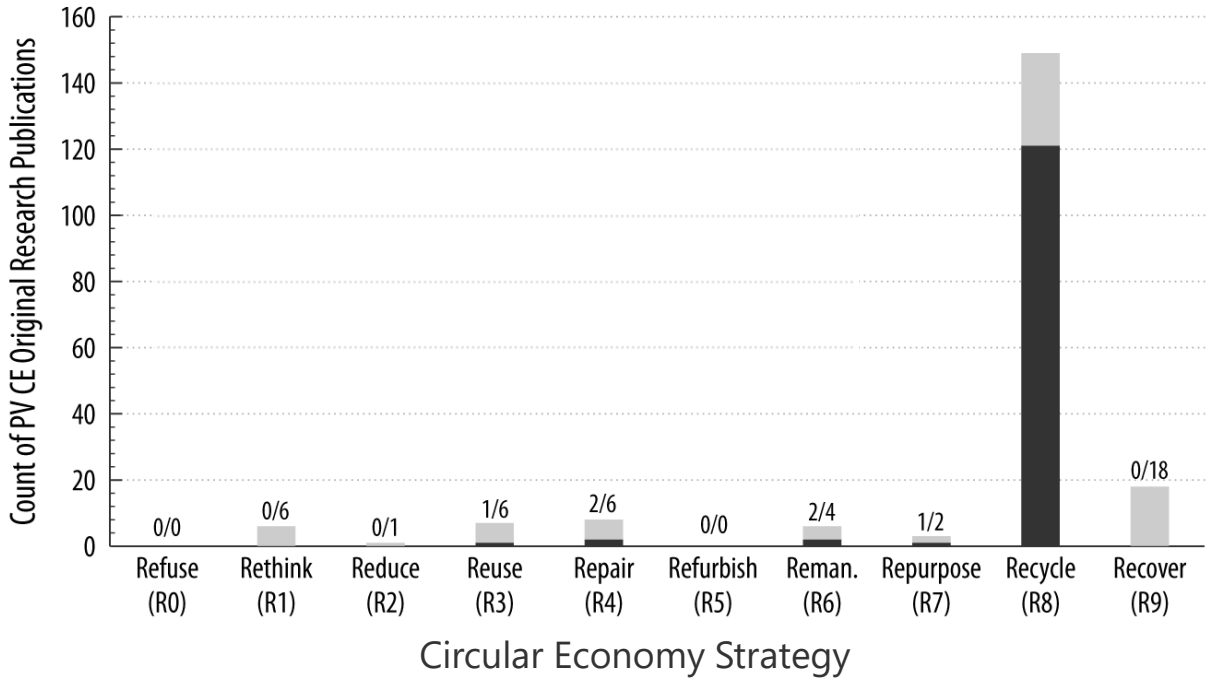


PV CE Literature Trends



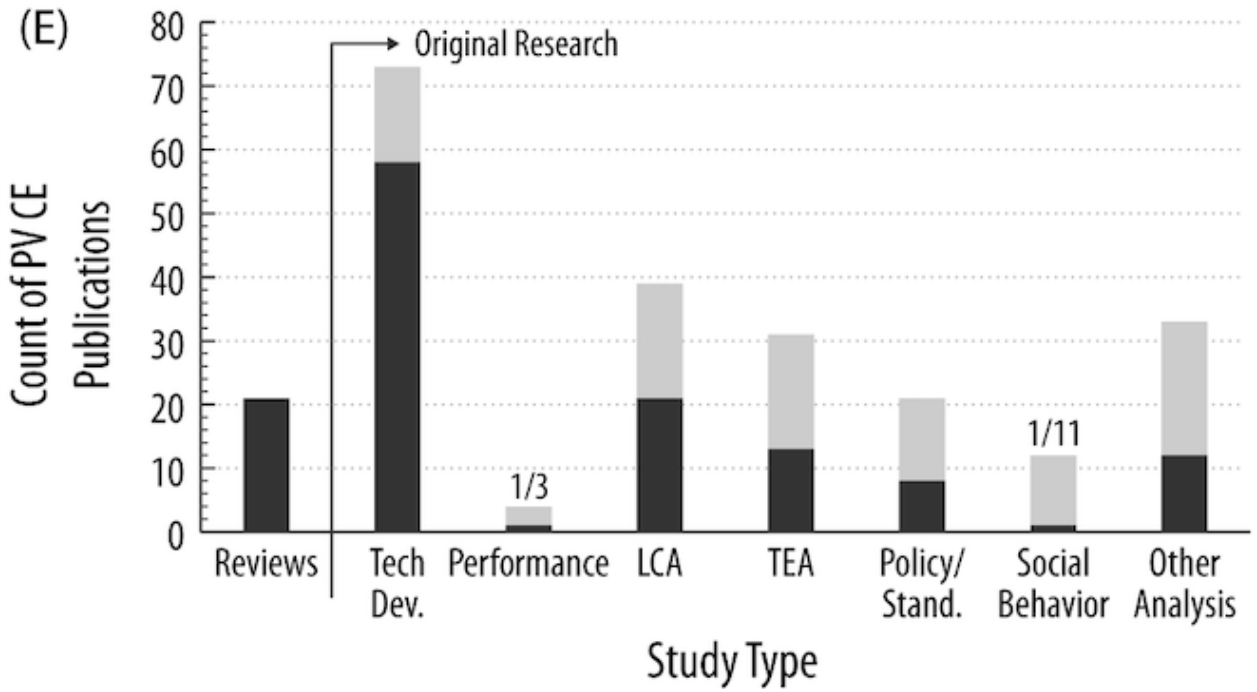
- First evidence of CE literature for PV in ~2000
  - Not until ~2017 does interest grow.
- Recycling by far largest single R strategy
  - Other R strategies appear more substantially in 2021 for PV.

Conclusion #1: Expand Research Beyond Recycling



- 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.

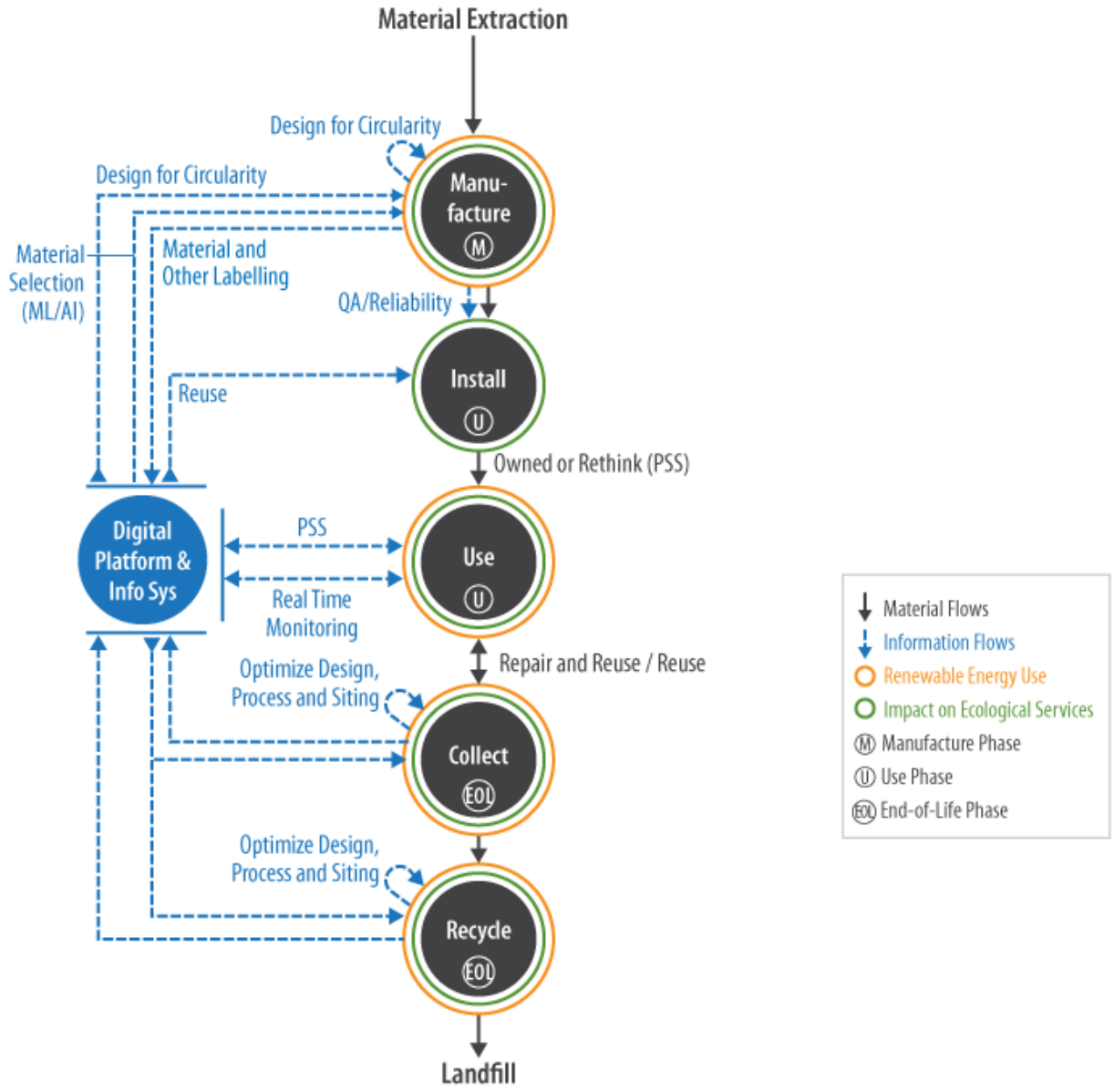
Conclusion #2: Support Technology Deployment with Economic, Environmental and Policy Analysis



- 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.

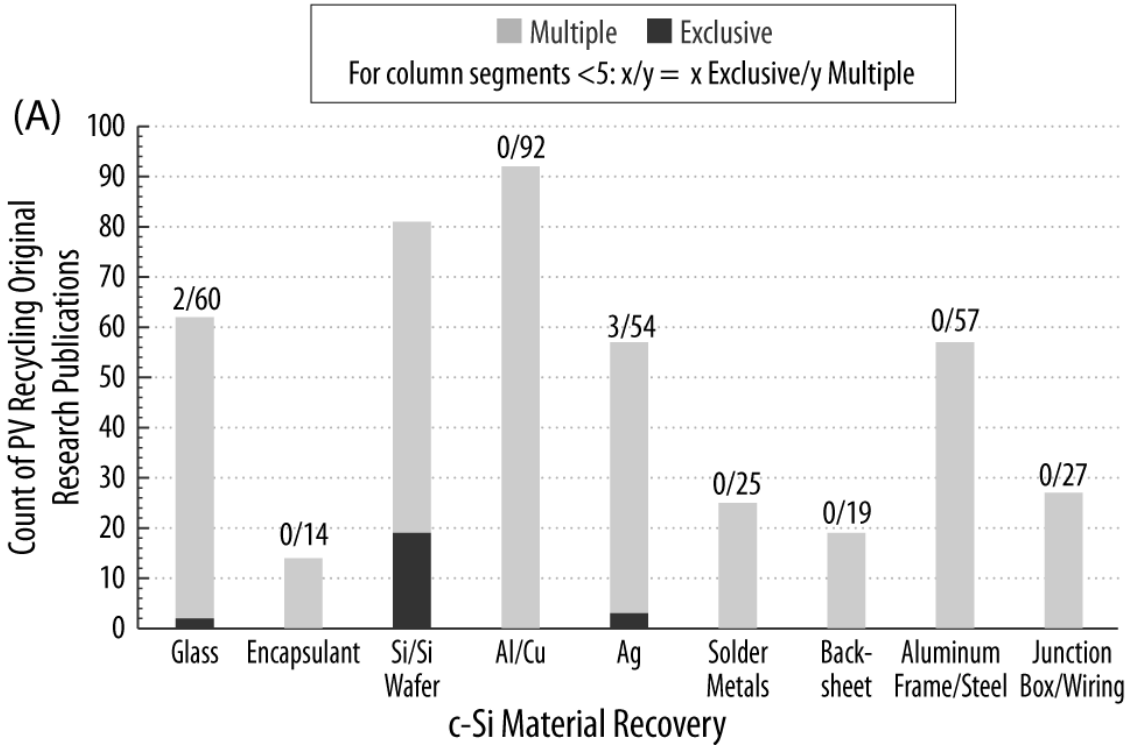
Conclusion #3: Leverage Digital Information Systems

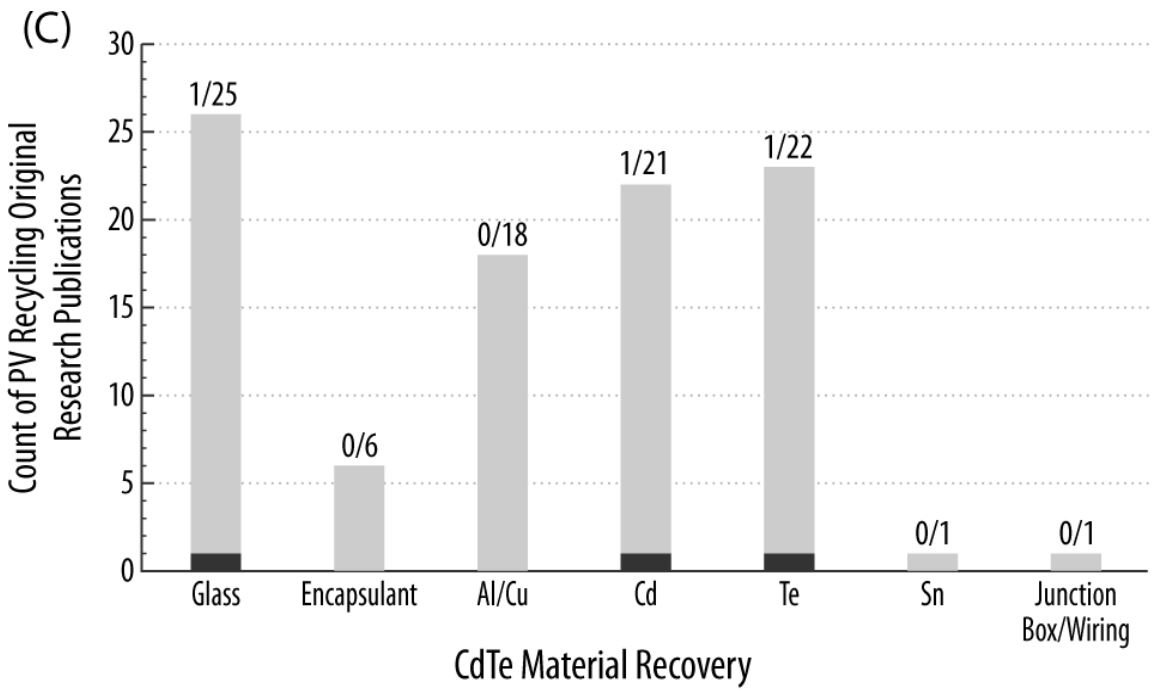
- Digital platforms and information systems can be leveraged to implement and improve CE strategies across all three life cycle stages.
- We find that digital pathways deserve more attention to explore their technical potential, benefits and trade-offs.



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 PV Markets

- Data will need to be collected at regular intervals on the PV market, and its 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 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.

Discussion

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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.

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.

Source: Ellen MacArthur Foundation, 2022 https://ellenmacarthurfoundation.org/press-release-universal-policy-goals

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