Towards Circular and Sustainable Semiconductor Manufacturing

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Sensors Related to Human Cognition and Sustainability in Semiconductor Manufacturing
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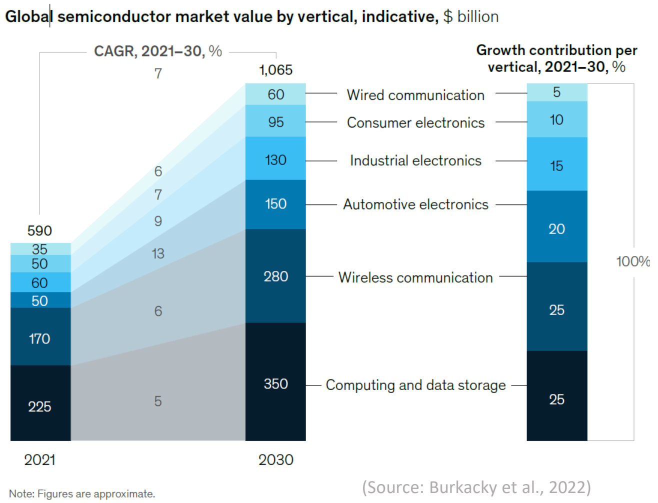
Semiconductor Manufacturing: A Reflection

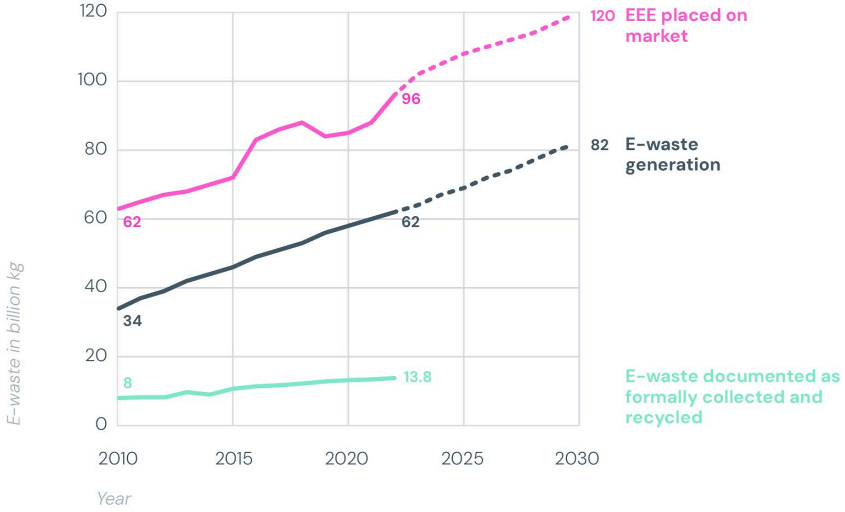
- High energy consumption, water use and rare/critical materials
  (Hsieh et al., 2023, Harrington et al., 2022, Gatto and Nuta, 2024)
- GHG emissions, pollution and health hazards
  (Harrington et al., 2022; Ruberti, 2023, Nagapurkar et al., 2024)
- And (!), Semiconductor chip use is ubiquitous and proliferating

Global Semiconductor Market



(Source: Burkacky et al., 2022)

E-waste Generation



(Source: https://unitar.org/about/news-stories/press/global-e-waste-monitor-2024-electronic-waste-rising-five-times-faster-documented-e-waste-recycling)

E- waste rising 5 times faster than documented E-waste recycling

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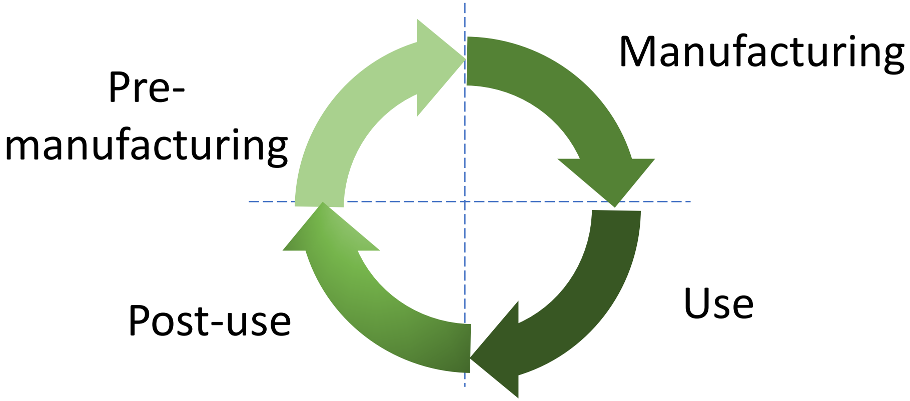
Introduction: 6R-based Approach for Sustainable Manufacturing

Sustainable manufacturing at ***product, process and systems*** levels must:

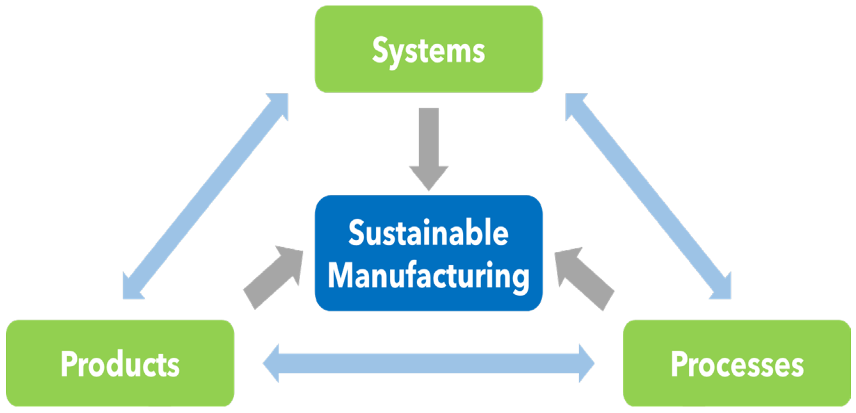
- demonstrate reduced ***negative environmental impact,***
- offer improved ***energy and resource efficiency,***
- generate ***minimum quantity of wastes***,
- provide ***operational safety,*** and
- offer improved ***personnel health***

while maintaining and/or improving the product and process quality with the overall life-cycle cost benefits.

(**Source:** NIST Sustainable Manufacturing Roadmapping Workshop, (2014) – Adapted from US Department of Commerce (2009) and EPA (2011)



Emphasis on the 'Total' Life Cycle



Emphasis on Products, Processes and Systems

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Introduction: 6R-based Approach for Sustainable Manufacturing

Reduce
resources, waste/emissions, impacts over the total lifecycle

Hierarchy for value recovery from end-of-life products: Reuse > Remanufacture > Recycle

(Source: Jawahir and Bradley, 2015)

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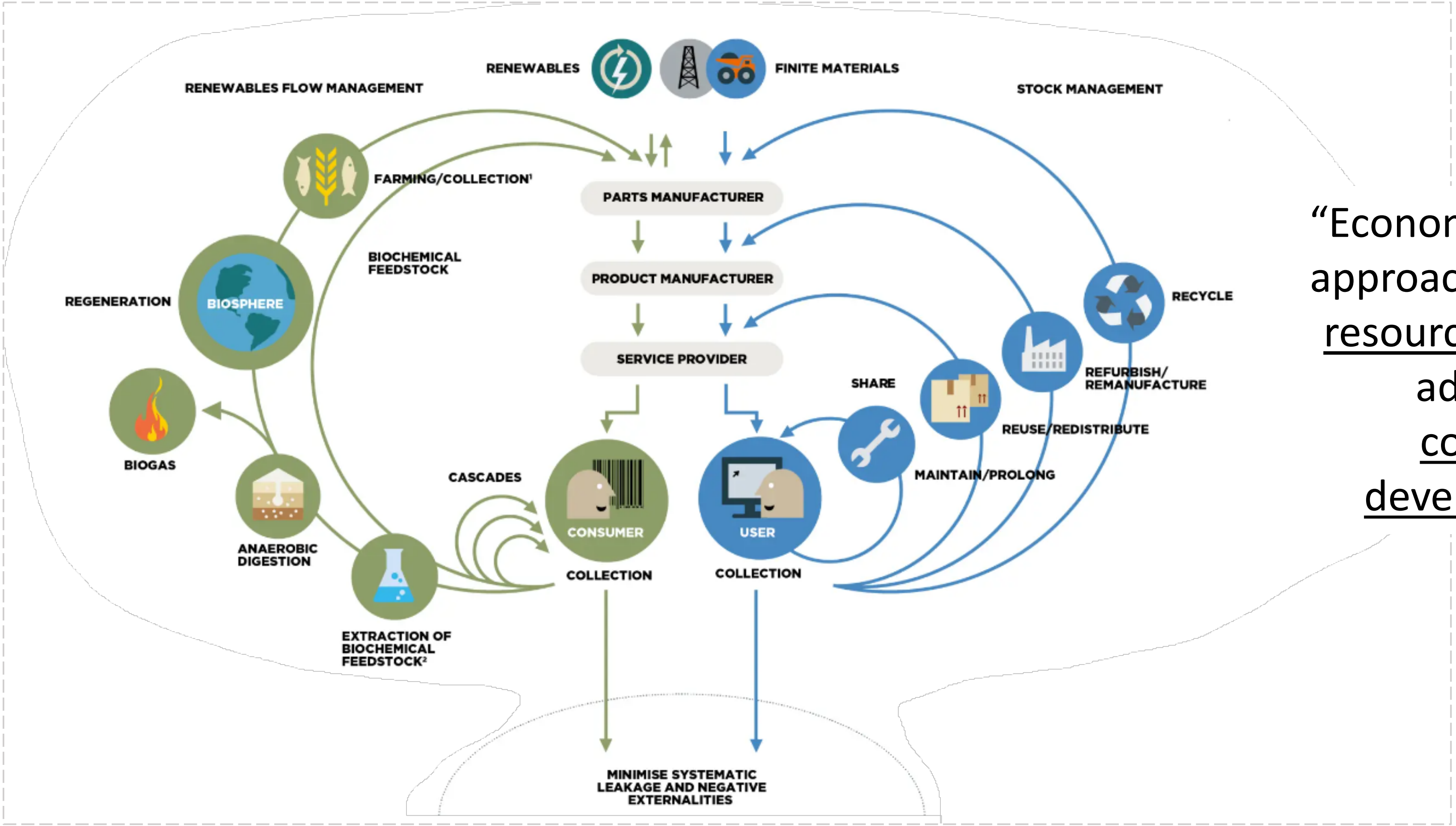
Operationalizing Circular Economy



"Economic system that uses a systemic approach to maintain a circular flow of resources, by recovering, retaining or adding to their value, while contributing to sustainable development" (ISO 59004, 2024)

(Source: https://www.ellenmacarthurfoundation.org/articles/the-technical-cycle-of-the-butterfly-diagram)

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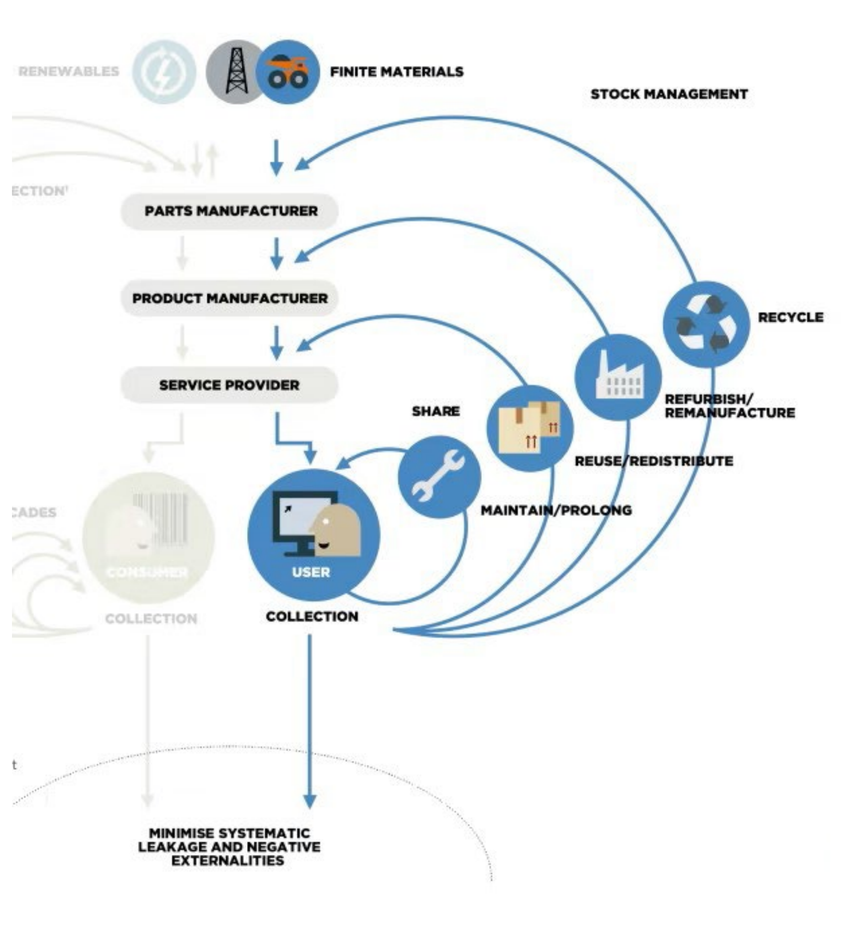
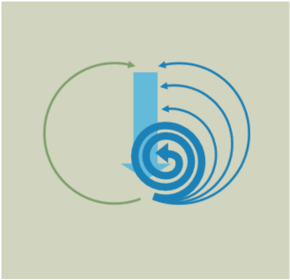
Operationalizing Circular Economy (Contd.),



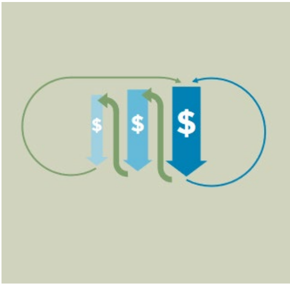
(Source: https://www.ellenmacarthurfoundation.org/articles/the-technical-cycle-of-the-butterfly-diagram)

Power of inner circles

Power of circling longer



Power of cascaded use



(Images from Towards the Circular Economy by EMF, 2013)

Operationalizing/implementing Circular Economy practices at the product level?

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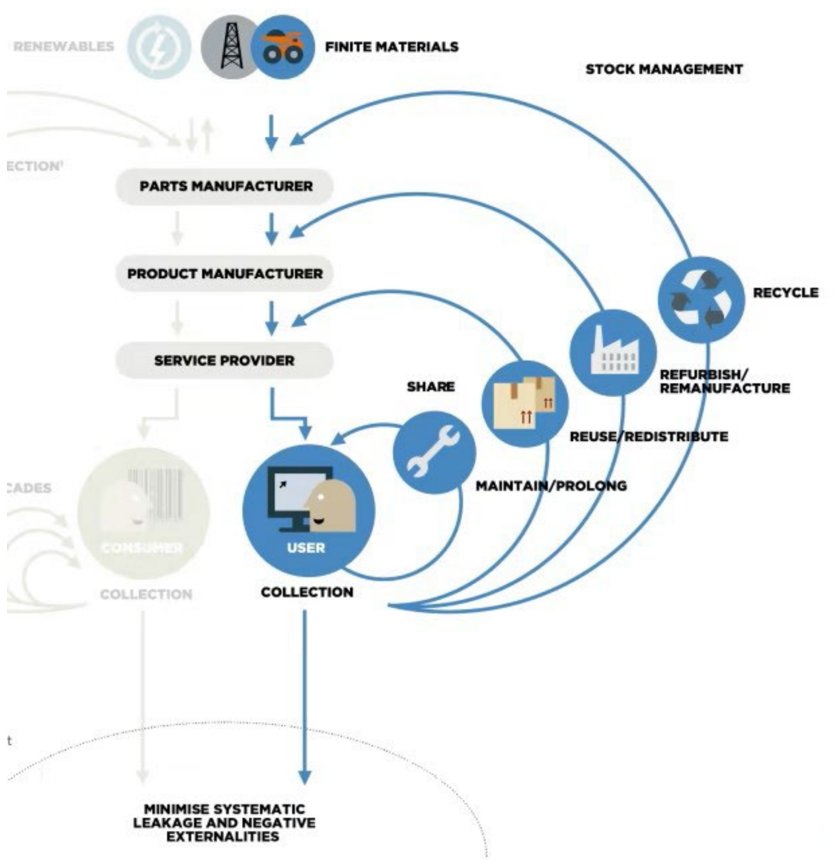
Operationalizing Circular Economy (Contd.),



(Source: https://www.ellenmacarthurfoundation.org/articles/the-technical-cycle-of-the-butterfly-diagram)

Power of inner circles

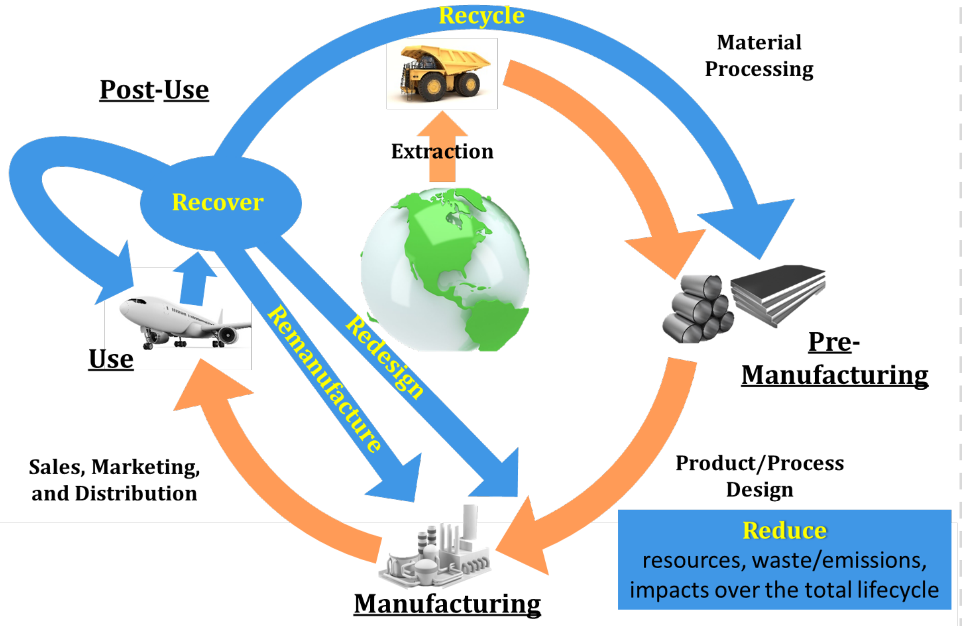
Power of circling longer

Power of cascaded use

(Images from Towards the Circular Economy by The Ellen MacArthur Foundation, 2013)

6R Methodology

(Reduce, Reuse, Recycle, Recover, Redesign, Remanufacture)



(Based on: Jawahir et al., 2006, Jawahir and Bradley, 2015)

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Product Circularity?

- No clear consensus on what characterizes Circular Products (CPs)
  - Varied CE definitions [Kirchherr et al. (2017; 2023); Ellen MacArthur Foundation (EMF, 2015), US EPA, 2022); newly introduced ISO 59004, 2024)]
  - Many CP descriptions [Romero et al. (2017), EMF (2020), Gossen et al. (2022)]

- Numerous limitations in existing methods for CP evaluation
  - Considerable research related to requirements for CPs [Meloni (2019), Boyer et al. (2021), Suppipat & Hu (2022), and others]
  - Criteria and attributes considered are highly varied
  - Most focus on limited aspects such as resource efficiency (Ko et al., 2024)
  - Developed without focus on a target end user/product
  - No stakeholder engagement
  - Low industry adoption

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Circular Design and Product Circularity Assessment

- Multiple projects funded by the **National Institute of Standards and Technology (NIST)**, in collaboration with industry partners for:
  - Project 1: Metrics-based System for Evaluating Product Circularity and Enhancing the Circular Design of *Consumer Electronics Products* (2022-23)
  - Project 2: A Comprehensive Approach for Product Circularity Assessment Towards Sustainable Value Creation (2023-24)
  - Project 3: Developing Methods for Assessing and Improving Circularity of *Consumer Electronics Products and Semiconductor Chips* (2024-25)

amazon

hp

Panasonic

NIST NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
U.S. DEPARTMENT OF COMMERCE

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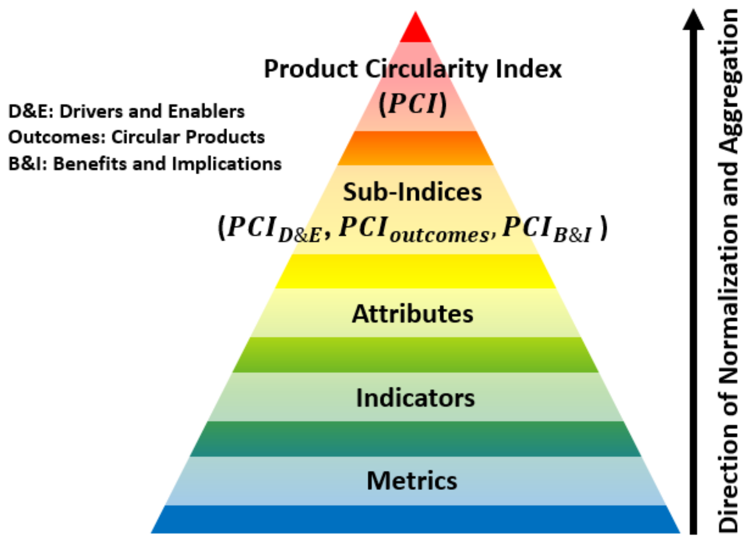
Product Circularity Assessment (PCA) Method

- Thorough review of existing methods
- Extensive industry engagement
  - Initial workshop
  - One-on-one meeting with major consumer electronics OEMs
  - Regular meetings with industry partners and NIST experts

- Criteria (**A**ttributes, **I**ndicators, and **M**etrics – AIM) to assess consumer electronics product circularity
- Suitability of AIM, data sources, measurement feasibility, etc.

- Hierarchical approach for PCA
- Leveraging approach from other methods



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ASTM "New Guide for Principles for Circular Product Design" (ASTM WK 83603)

NWI – Principles for Circular Product Design

Scope:

"These principles provide guidelines and supplementary context for product designers to better understand, apply, and qualify design decisions advantageous for the introduction of products to the Circular Economy. A Circular Economy is a holistic approach to an interconnected closed-loop systems of goods and material flows that eliminates waste and retains resource value for as long as possible. These principles standardize sustainable design guidelines factoring in systems thinking to expand design practices from cradle-to-grave to cradle-to-cradle."

Approach:

- Principles – General considerations and rules that are applicable to a wide set of design problems
- Guidelines – Sector-specific suggestions to operationalize related Circular Design principles

Explicit Considerations:

- Principles and subsequent guidelines should be applicable over wide variety of enterprise capability and inclusive to limited resource SMEs.
- Principles and Guidelines should foster business transition to circular economy systems. As in the principles may be applied before full CE systems are in place to fully operationalized the guideline.

Year 1 Plan:

- A standard Circular Product Design definition (CPD) based on (ISO + Literature).
- Defining differences and similarities of Sustainable design and Circular Design. Defining Standard Scope in this context.
- <20 Principles for approachable CPD.
- Contextualizing Principle relationships
- Appendix:
  - Principles and Guidelines for consumer product design, electronics, and more
    - Application checklist
    - Example

Membership:

- **~170 interested participants**
- **~70 active members in the collaboration space**
- **Still GROWING!!!**

NIST

- Variety of stakeholders in drafting team
- University of Kentucky engaged as the only US academic partner

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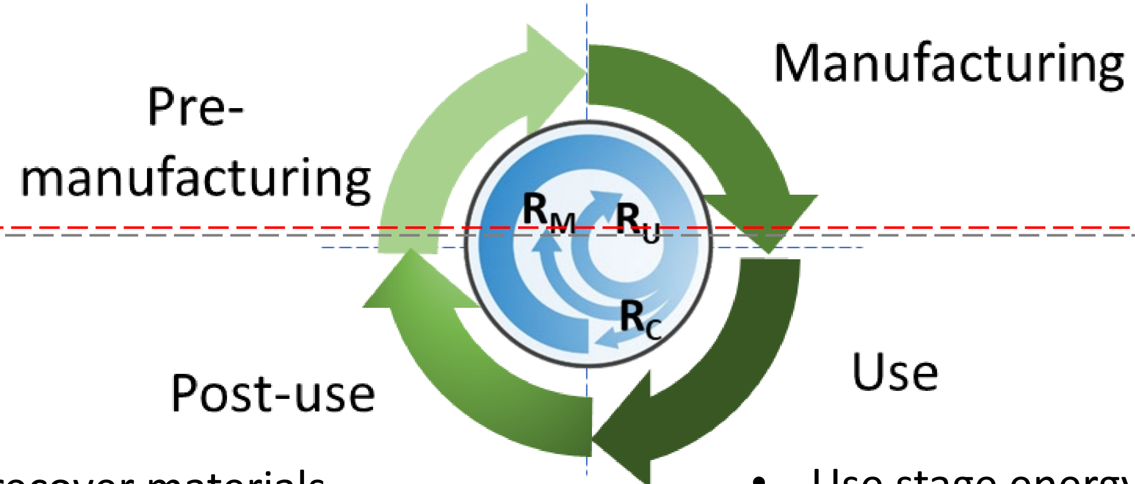
(Slide courtesy of Dr. Hapuwatte, NIST)

Improving and Assessing Circularity of Semiconductor Chips

Current primary emphasis (industry and academia):

- Alternate materials
- New/better manufacturing technologies
- Reducing toxicity and hazardous substances
- Zero-waste practices

- Improving energy efficiency
- Reducing GHG emissions
- Improving water efficiency
- Use of renewable resources



- Recycling to recover materials

- Use stage energy reduction with technology advances

What constitutes success in terms of circularity (closing the loop) for sustainability?

Legend: R_U: Reuse; R_M: Remanufacture; R_C: Recycle

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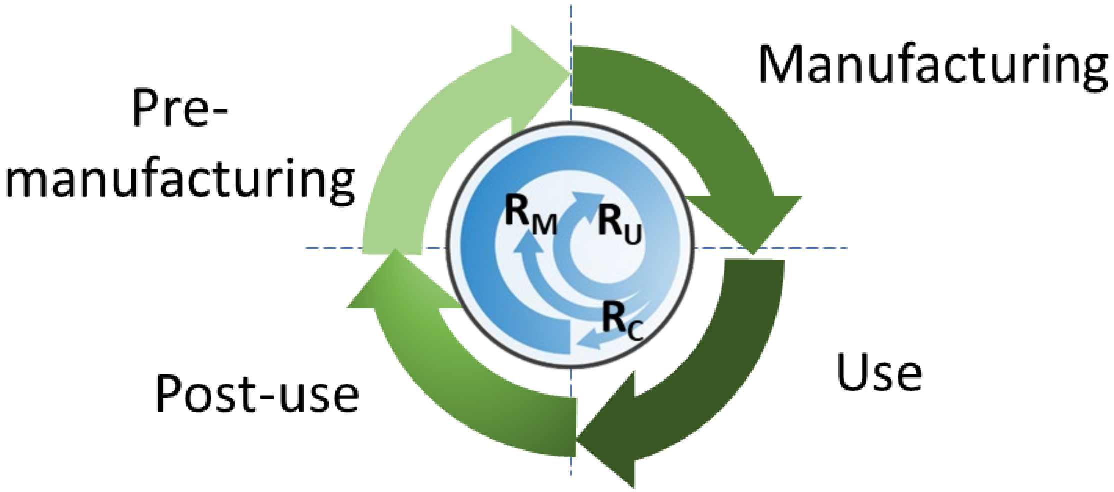
Improving and Assessing Circularity of <u>Semiconductor Chips</u>

Other potential considerations:

- Chip 'Reuse' an option?
  - Improvements with each new generation of chips (die size, use phase energy)?
  - EarthShift Global (2023) (NIST-funded): manufacturing & life cycle GHG impact of reused chips
  - 'Redesign' to facilitate 'Reuse'?
- Emerging regulations
  - E.g.: European Union Right to Repair Directive (R2RD) → changes to product design?
  - Impact on OEMs → semiconductor industry?
  - Repairability vs. Profitability?
  - Different/new business models
- Stakeholder engagement & collaboration



Project (3) Scope
- Critical assessment of circularity needs
- Define and develop methods for PCA of semiconductor chips

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Legend: R_U: Reuse; R_M: Remanufacture; R_C: Recycle

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Concluding Remarks

- Considerable efforts underway to address semiconductor manufacturing sustainability concerns
    - Primarily in pre-manufacturing and manufacturing, with latter stage consideration often deferred to OEMs
- Circular Economy is an enabler to advance towards sustainable value creation
    - Enhancing capabilities for higher end-of-life value recovery, though challenging, is imperative
    - Emerging regulations, geopolitical concerns, etc., can drive need for circularity
- However, circularity must not be pursued simply for the sake of circularity → sustainability benefits?
    - Numerous challenges to implementing Circular Economy at the micro (product) level
    - Imperative to consider trade-offs and real benefits across total life cycle
    - Tools and technologies can facilitate better assessing circularity and sustainability

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Thank You!
Any Questions?

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