Closing the Loop: Advancing Circularity in Semiconductor Chips and Chip-integrated Components

Fazleena Badurdeen, Ph.D.
Earl Parker Robinson Chair Professor in Mechanical Engineering
Institute for Sustainable Manufacturing,
Department of Mechanical & Aerospace Engineering,
University of Kentucky,
Lexington, KY, USA

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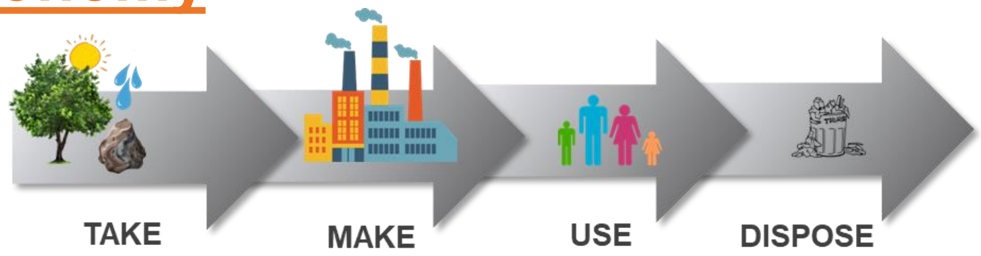
Introduction: Circular Economy

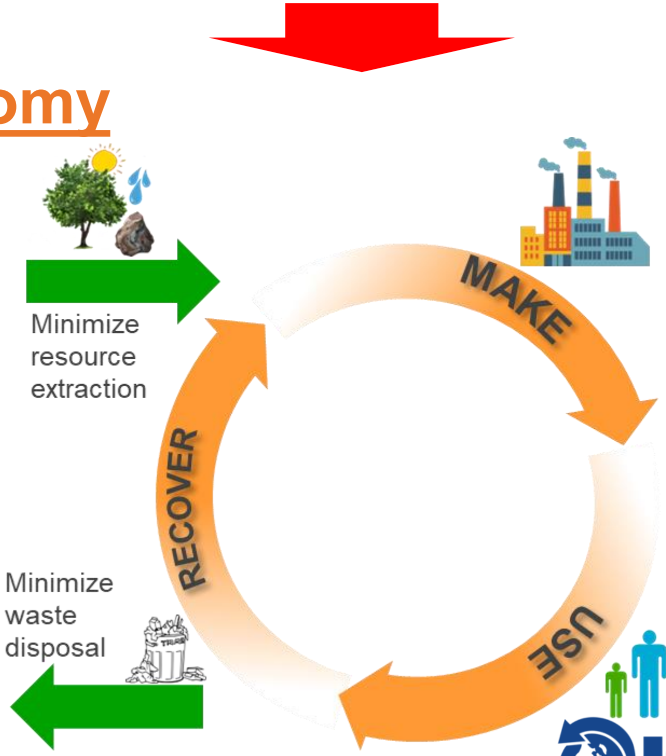
- Transition from the linear take-make-use-dispose approach to an economy with restorative and regenerative flows

- Circular Economy (CE) Principles[1]:
  - Eliminate waste and pollution
  - Circulate materials and products at the highest value
  - Regenerate nature and preserve natural capital

Linear Economy



Circular Economy

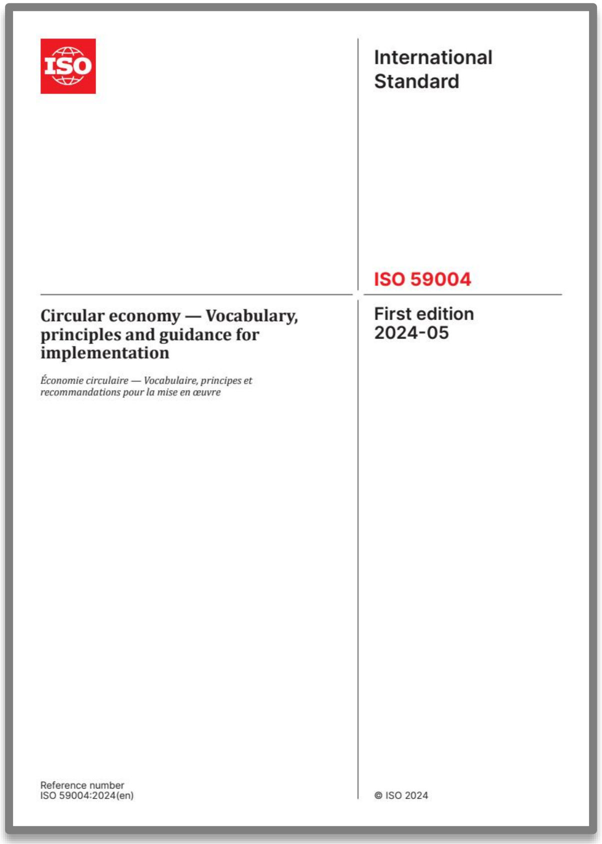


1) Ellen MacArthur Foundation. Towards the Circular Economy Vol. 1: an economic and business rationale for an accelerated transition. Ellen McArthur. 2013.

Defining Circular Economy (CE)

Circular Economy is an

- *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

International Standard

ISO 59004

Circular economy — Vocabulary, principles and guidance for implementation

Économie circulaire — Vocabulaire, principes et recommandations pour la mise en œuvre

First edition
2024-05

Reference number
ISO 59004:2024(en)

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Based on ISO 59004

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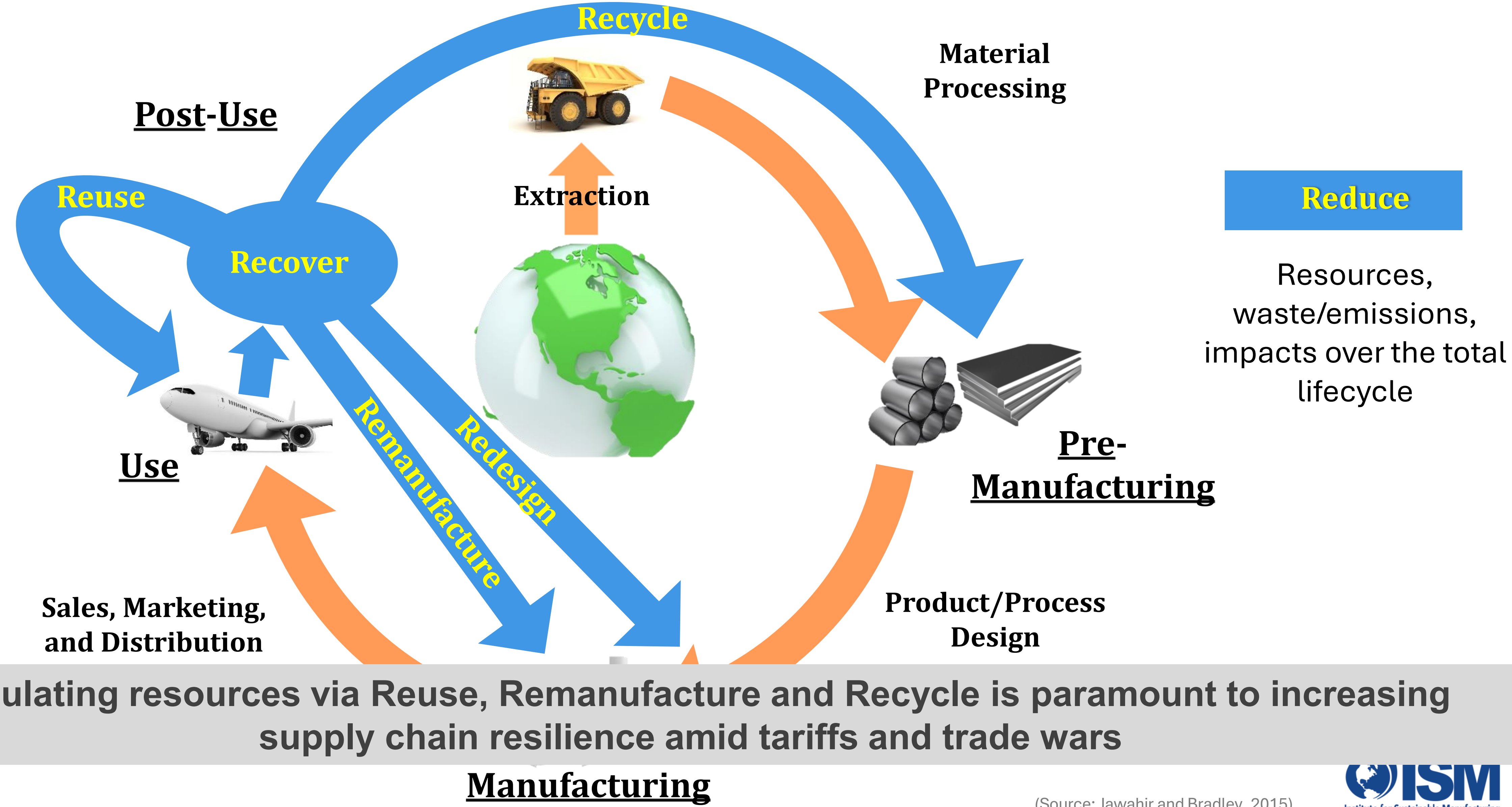
Closing the Loop: Value Recovery at End-of-Life (EoL)

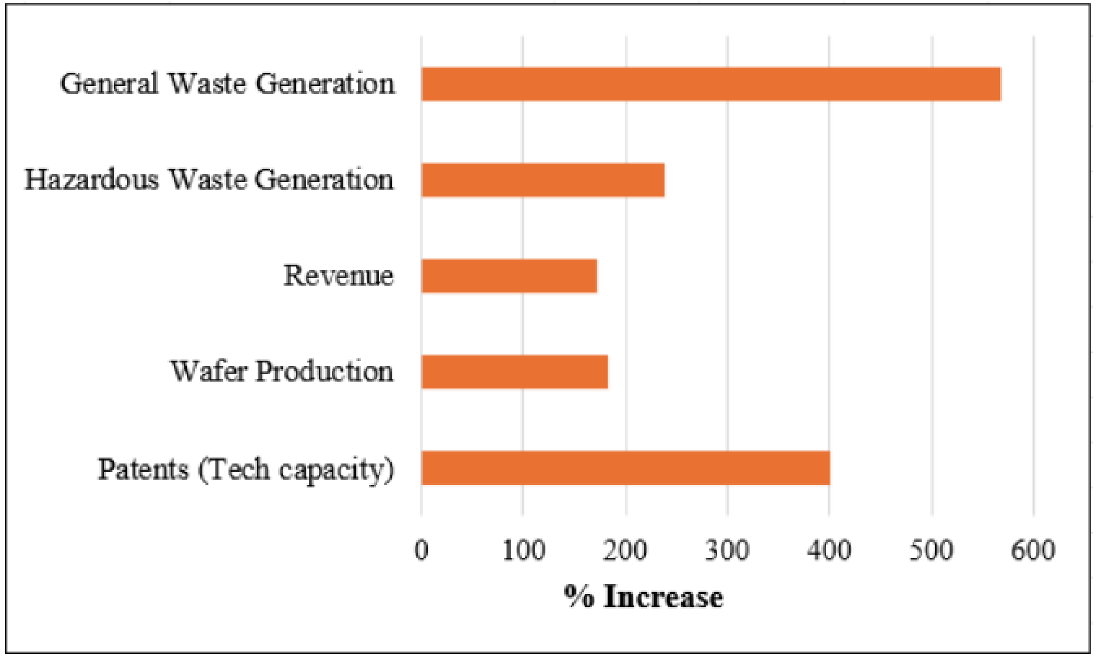


Circulating resources via Reuse, Remanufacture and Recycle is paramount to increasing supply chain resilience amid tariffs and trade wars

(Source: Jawahir and Bradley, 2015)

Semiconductor Manufacturing Sector Status

- High energy consumption, water use and rare/critical materials[1]
- High GHG emissions, pollution and health hazards[2]
- Significant technological advances in design and manufacturing
- However, improvements in waste generation, resource use and impacts not comparable[3]
- Proliferating semiconductor chip use across all sectors[4]



Semiconductor Foundry Performance[5]: Variation from 2012 - 2021

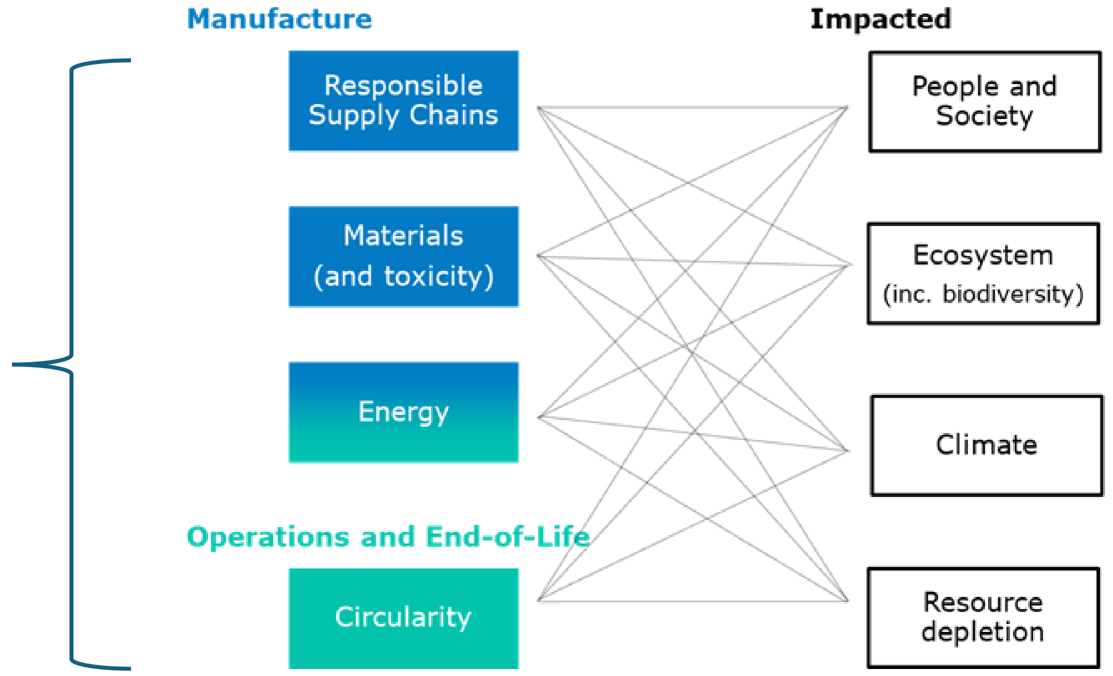
1) Hsieh et al., 2023, Harrington et al., 2022, Gatto and Nuta, 2024;2) Harrington et al., 2022; Ruberti, 2023, Nagapurkar et al., 2024 ; 3) Rubert et al., 2024, Garcia Bardon et al., 2020; 4) Burkacky et al., 2022; 5) Based on Ruberti et al., 2024.

Sustainability in Electronics Sector

- INEMI Sustainable Electronics Roadmap[1]
  - Call for sustainable practices and Circular Economy initiatives in electronics

International Electronics Manufacturing Initiative

Core dimensions for improving sustainability of electronics



Interdependent Impacts of the Electronics Life Cycle[1]

1) Okrasinski, et al. (2023).

INEMI Roadmap: Electronics Industry Issues/Needs

Leadership
- Industry as leading agents
- Environmentally conscious leaders

Design for Circularity
- Proactive design
- Supporting tool capabilities

Education
- Workforce training
- Public outreach

Metrics and Methodology
- Electronics-focused
- Consensus and standardization

Technologies
- Cost-effective recovery
- Digital Product Passport (DPP)

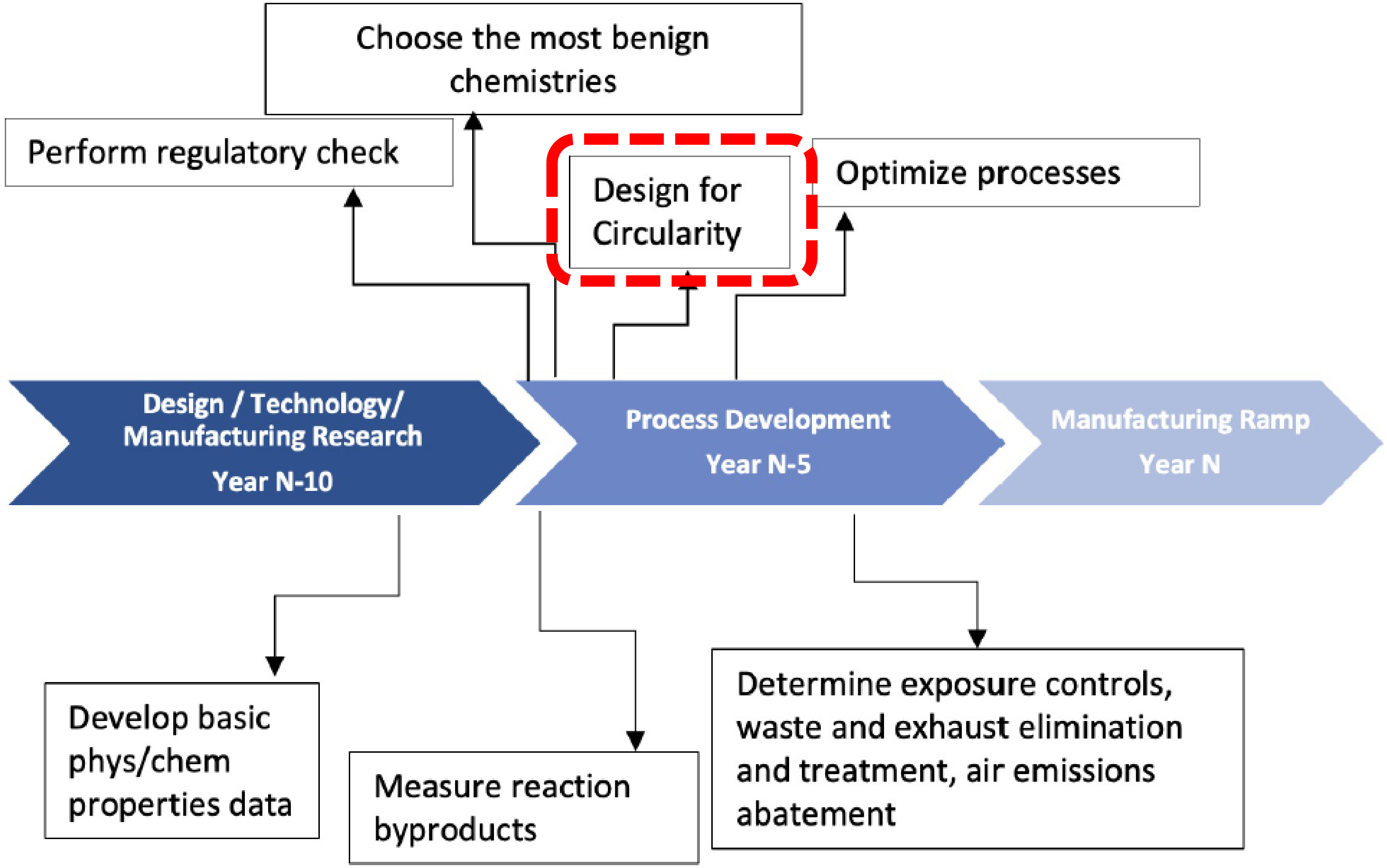
Business Models
- Extended networks
- Service-oriented

Circularity Transition → **Requirements to Promote Circularity in Semiconductor Chips?**

1) Okrasinski, et al. (2023).

Microelectronics & Advanced Packaging Technologies Roadmap (MAPT)

- Semiconductor Research Corporation's (SRC) 2030 Decadal Plan[1]
- Aims to guide semiconductor industry toward sustainable innovation
- Focus on energy, environmental, and workforce sustainability



1) SRC-MAPT. (2023).

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SRC-MAPT Roadmap – Focus Areas

Energy Sustainability

- ❑ Chip Design for Energy Efficiency
- ❑ System in Package (SiPs): Integrating Multiple Chips
- ❑ Transition from 2D to 3D Semiconductor Technologies
- ❑ AI & ML Integration

Environment Sustainability

- ❑ Sustainable Manufacturing
- ❑ Distributed Energy Resources
- ❑ Integrating Environmental Metrics
- ❑ Circular Economy Pathways

Workforce Sustainability

- ❑ Academia, Industry & Government Collaboration
- ❑ Enhance Skills in technological sector
- ❑ Multidisciplinary teams

1) Based on SRC-MAPT. (2023).

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Circular Product Design: Assessment & Improvement

- Industry-engaged efforts for circular product design and assessment
  - Project 1: Metrics-based System for Evaluating Product Circularity and Enhancing the Circular Design of Consumer Electronics Products
  - Project 2: A Comprehensive Approach for Product Circularity Assessment Towards Sustainable Value Creation
  - Project 3: Developing Methods for Assessing and Improving Circularity of Consumer Electronics Products and Semiconductor Chips

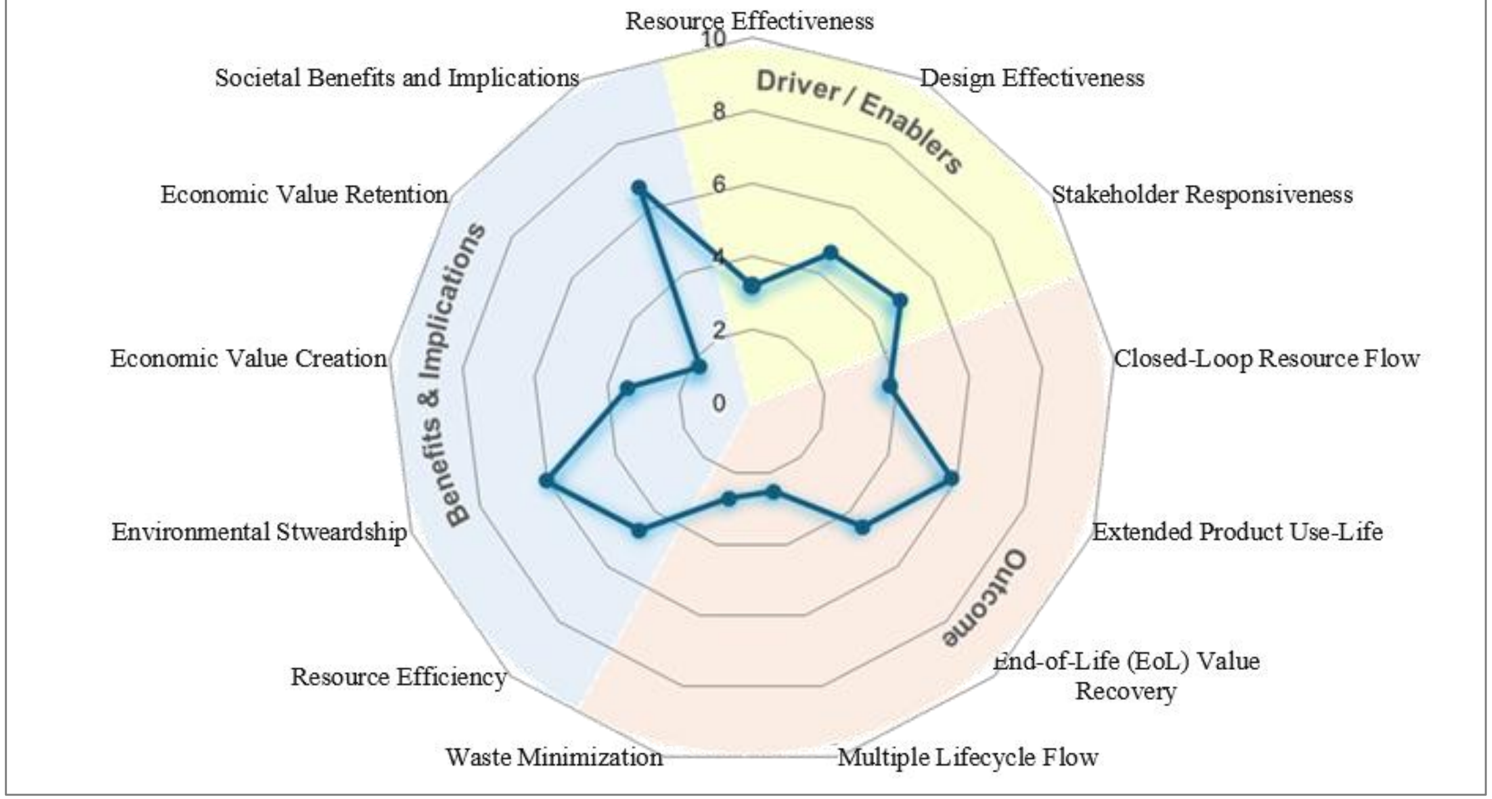
INEMI Roadmap Industry Issues/Needs

MAPT Roadmap Focus Areas

Product Circularity Index (PCI)

- Comprehensive, metrics-based method developed with extensive engagement of industry stakeholders[1]

- Validated through three industry case studies



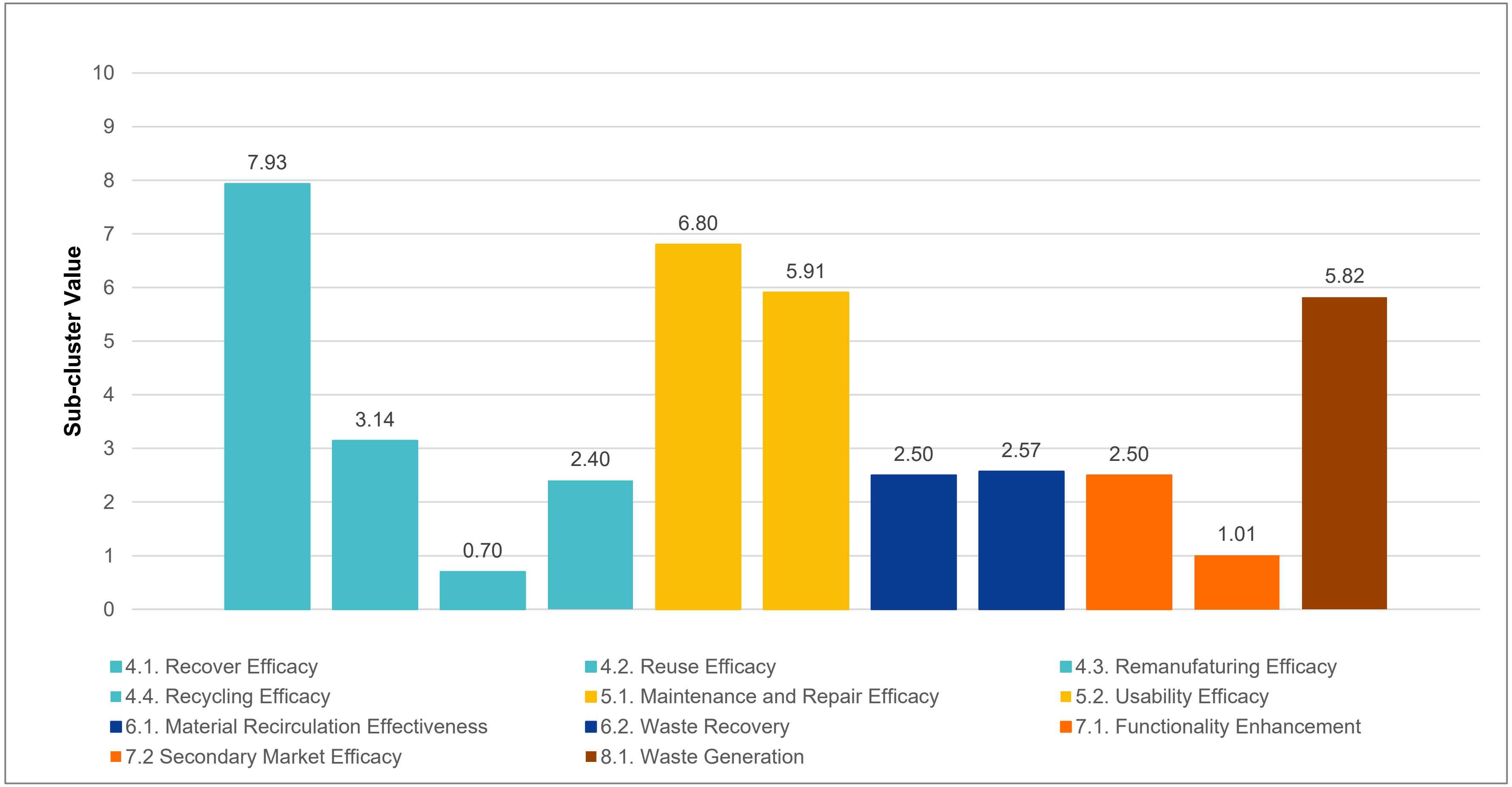
Holistic View of Overall Product Circularity Performance

1) Source: Ko et al, 2025 Forthcoming

PCI Results (Contd.)

- Facilitates assessing key product features and properties to enhance product circularity[1]
- Useful for making design improvement decisions – 'sustainability by design'

1) Source: Ko et al, 2025 Forthcoming



Product Circularity Performance at Sub-cluster Level – An Example

ASTM E3461 – 25: Standard Guide for Principles of Circular Product Design

ASTM E3461-25 aims to…

- Provide guidelines and context for product designers
- Develop based on a comprehensive circular product design literature
- Support better understand, apply, and qualify design decisions

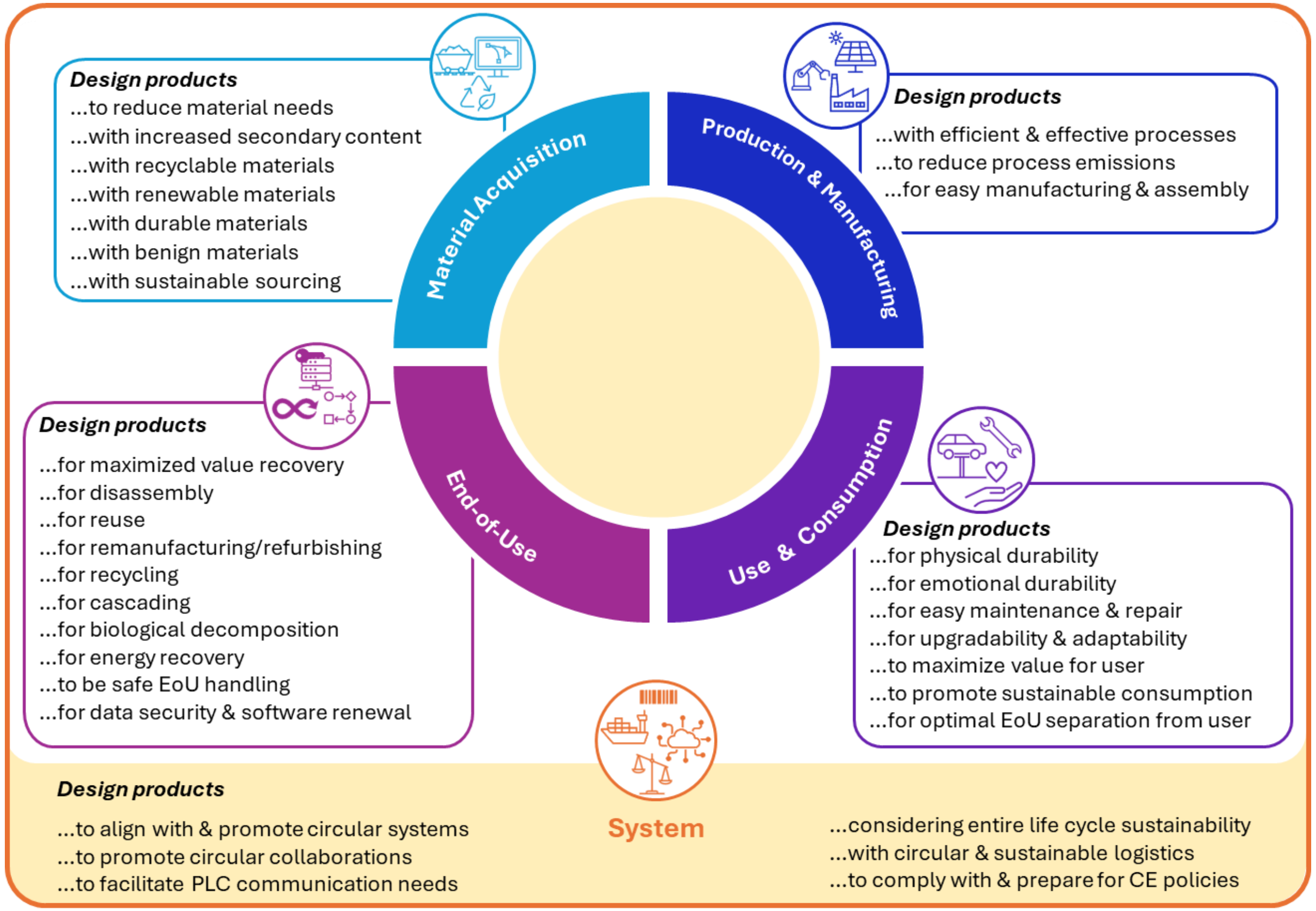
Approach:

- **Main standard** – General considerations and design rules that are applicable to a wide set of design problems
- **Appendices** *(in discussion)* – Sector-specific guidance to operationalize related Circular Design principles

Standard drafting was a multi-stakeholder (industry, academia, government, non-profit, etc.) engaged effort

ASTEM E3461-25: Expansions Under Development

- Specific design guidance for each life cycle stage under development for ASTM balloting process
- Sector specific appendices to adapt general principles into more specific product categories such as:
  - Electronics
  - Healthcare products
  - Textiles, etc.



A draft list of principles based on the literature. The final list is being prepared.

Value Recovery Through Reuse of Chips

- Life cycle climate change impacts of new and reused chips[1]

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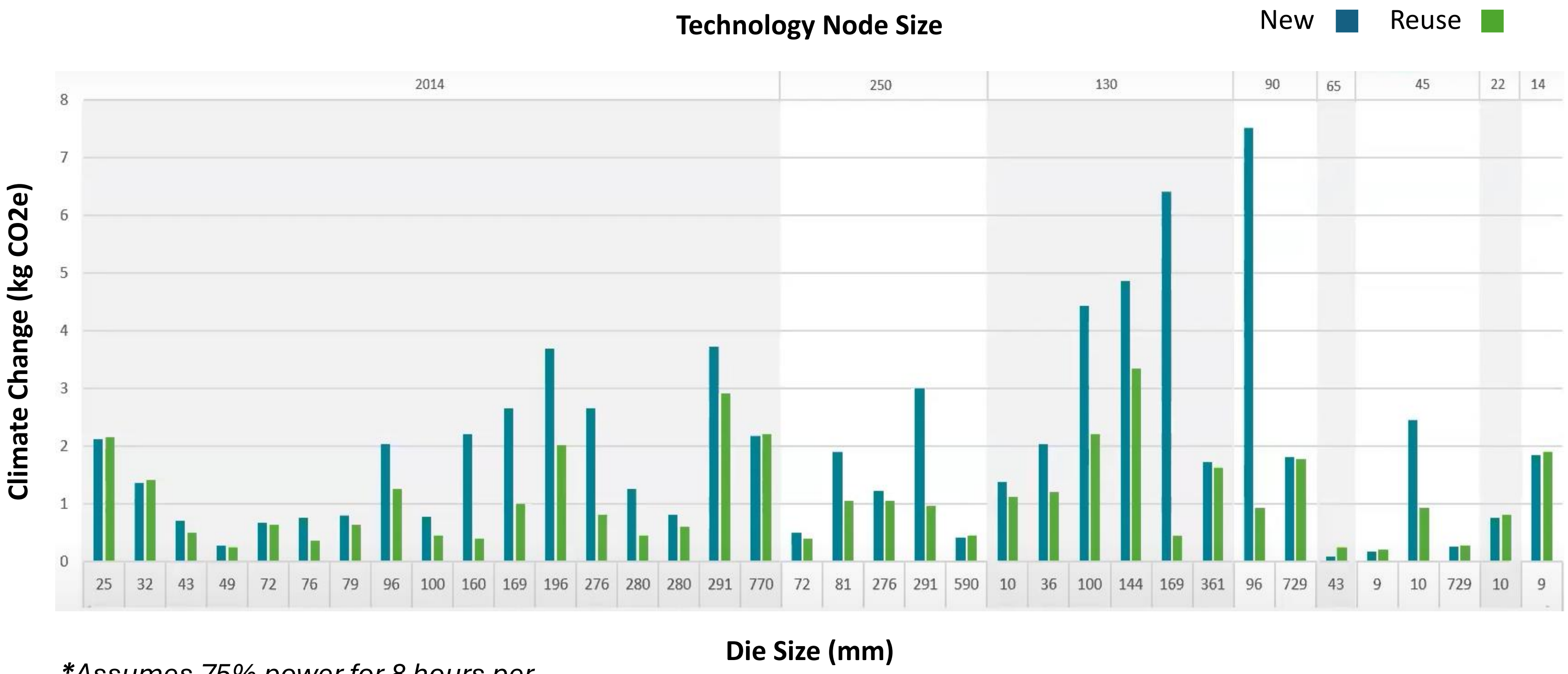

**Assumes 75% power for 8 hours per day, 5 days per week, over 3 years.*

- Based on Life Cycle Assessment
- Generally lower life cycle impacts for reused chips
- New chips may have lower impacts with energy efficiency improvements

1) Ncube, A., & Stoddart, N. (2024)

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Recovering Chips: Potential and Challenges

- 287.5B devices sold annually in the U.S. If 1/1000 chips were reused….

299,130 tons of CO_2e	**14,956,506** trees growing for a year	**66,759** cars off the road	**37,810** homes powered for a year	**83.4** wind turbines running for a year

- Positive outlook on chip reuse from industry stakeholders
- **Challenges identified:**
  - Collaboration necessary for larger scale adoption
  - Limited understanding of the current state of value recovery practices and perceptions
  - Application-specific chip design
  - Complexities in extracting chips without damage

1) Ncube, A., & Stoddart, N. (2024)

Workflows for EoL Value Recovery Strategies

- EoL recovery of chip-integrated components to enhance circularity
  - Focus group meetings with companies (on-going) ➔ Approaches/challenges to EoL value recovery

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- Develop workflows for feasible EoL value recovery strategies
  - Identify potential for reuse or remanufacturing
  - Pilot studies to establish workflows
  - Engage the industrial community for feedback

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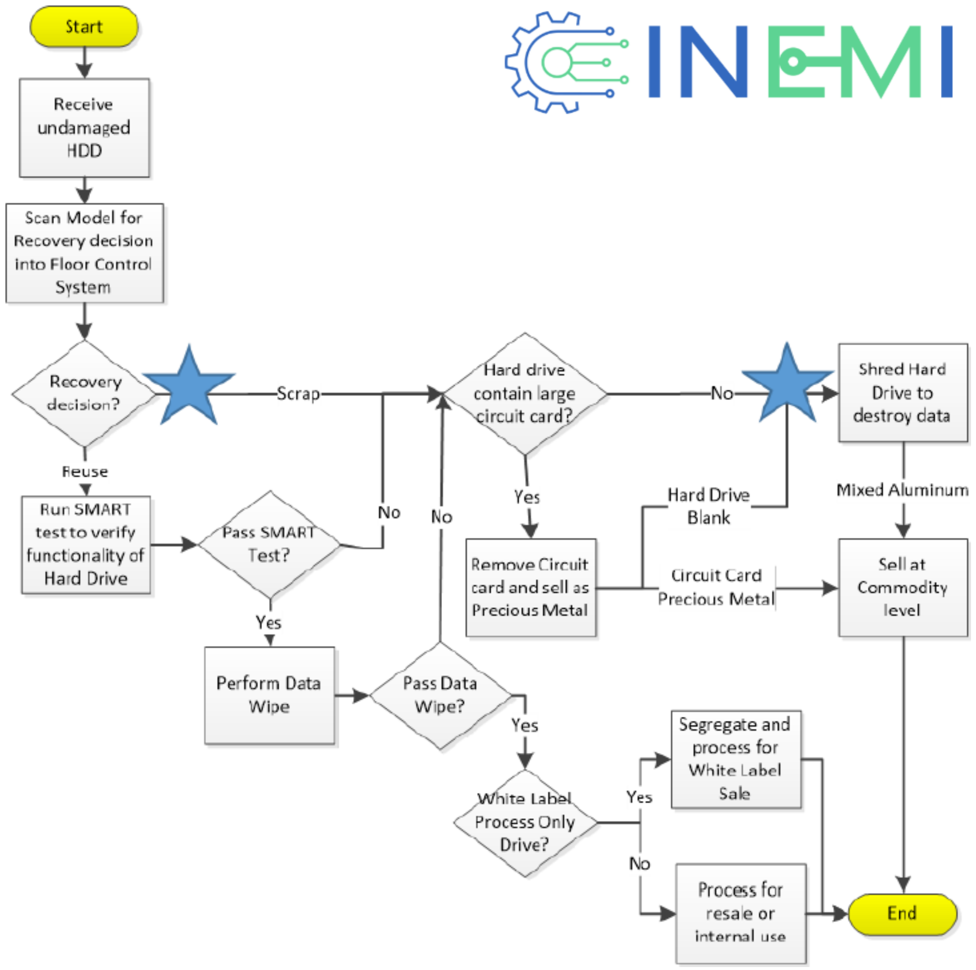

Workflow for Hard Disk Drive Value Recovery[1]

1) Handwereker et al., 2017

Concluding Remarks

- On-going efforts to address semiconductor manufacturing sustainability concerns
- Circular Economy is an enabler to advance towards sustainable value creation
  - Vital for promoting sustainability in 'Semiconductor manufacturing by design'
- Design for circularity key to facilitate higher EoL value recovery
- Imperative to understand challenges to implementing circular strategies
- Tools and technologies can facilitate better assessing circularity, including metrics, must be identified
- Stakeholders to engage and establishing workflows to facilitate chip-integrated component circularity is also vital

Thank you!

Badurdeen@uky.edu