Material Circularity across the Semiconductor Value Chain: Prioritizing and Mobilizing Action

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1. Executive Summary

A new generation of business strategies for the semiconductor value chain has expanded the industry's focus on the circular economy, a system that eliminates waste and keeps materials in circulation through processes like recycling and remanufacturing. Early initiatives were anchored primarily to waste management, waste-to-energy, diversion from landfill, and recycling programs. Newer directions include novel raw materials strategies, waste repurposing methods, and improvement of remanufacturing through resale at "new-product" performance and quality.

Yet most breakthroughs in research and industry adoption of circular practices are happening in relative isolation across the value chain. There is no widely recognized system for identifying and ranking materials used in manufacturing to prioritize where conversion from linear to circular use would provide the most gains.

A framework is needed to prioritize the development and adoption of circular methods for the materials that would generate the most strategic, economic, and environmental gain. These materials should be ranked by and for the semiconductor value chain.

This report – a collaboration between SEMI and imec – presents an inventory of 69 distinct materials prioritized for circularity along with the framework for ranking. Sharing the method supports recalibration to fit specific use cases. The outputs will be immediately useful for decision-makers across functions in the semiconductor value chain – including, but not limited to, procurement, sustainability, EHS (environment, health, and safety), and risk management. These professionals now have a cross-industry reference for driving impactful circular initiatives at their firms.

In a broader context, the outputs of this study are intended to mobilize collective action by the ecosystem of companies and research organizations seeking to improve the sustainability and circularity of the semiconductor industry. In conjunction with this publication, SEMI and imec present an invitation to collaborate on related R&D projects here.

To support this effort, we consulted industry practitioners and researchers with direct expertise from a range of value chain segments. Of the 69 materials, 12 are used in the operations of equipment, subsystems, and components companies; 35 are used in wafer fabrication fabs, foundries, and their facilities and infrastructure; 13 are used in outsourced and other assembly and test manufacturing; and 17 are used by end product and application companies.

The project outputs support the following groups of stakeholders:

Research teams in the private and non-profit sectors advancing technologies that enable purification, re-use, and/or resale of materials that are used or consumed in manufacturing across the semiconductor value chain

EHS (environmental, health, and safety) managers and engineers developing ways to reduce waste and emissions, optimize efficiency, and capitalize on circular opportunities

Procurement professionals seeking to integrate circularity criteria into materials sourcing processes

Corporate sustainability and ESG practitioners building initiatives to improve performance and reporting on circularity

Enterprise risk management professionals assessing supply and regulatory risks related to process materials and manufacturing waste

Consultants and advisors providing services to any of the above.

2. Introduction

The semiconductor industry has already made commendable progress toward embracing circular economy practices, particularly in water circularity, where significant advancements have been achieved in recycling and reuse. However, substantial untapped potential remains in addressing material circularity practices, especially for critical materials and materials consumed in large volumes. This opportunity is gaining increasing attention from business leaders and policy-makers as they face challenges such as price volatility, regulation pressures, manufacturing growth, supply chain disruptions, geopolitical uncertainty, environmental concerns, and evolving standards in corporate responsibility.

Anticipating this shift, the SEMI Circularity Working Group was established in 2023 to convene experts from industry and research institutions toward developing new pathways for strengthening the circular economy across the semiconductor value chain. Through approximately 49 participating member organizations, the working group is an industry-leading network with global reach and expertise. It supports best-in-class awareness, research, and validation for novel deployments of circular strategies by semiconductor manufacturing companies and their business partners. The group continues to expand in size and gain traction in the value chain from its hub at SEMI, the world's leading microelectronics industry association.

In 2024, the SEMI Circularity Working Group began collaborating with the Sustainable Semiconductor Technologies and Systems (SSTS) program at imec, the world's largest independent innovation center for nanoelectronics and digital technology. This collaboration established a focused project called "Material Circularity across the Semiconductor Value Chain."

This SEMI-imec project has taken significant strides toward defining priority materials for circularity activities across four semiconductor value chain segments (see Figure 1):

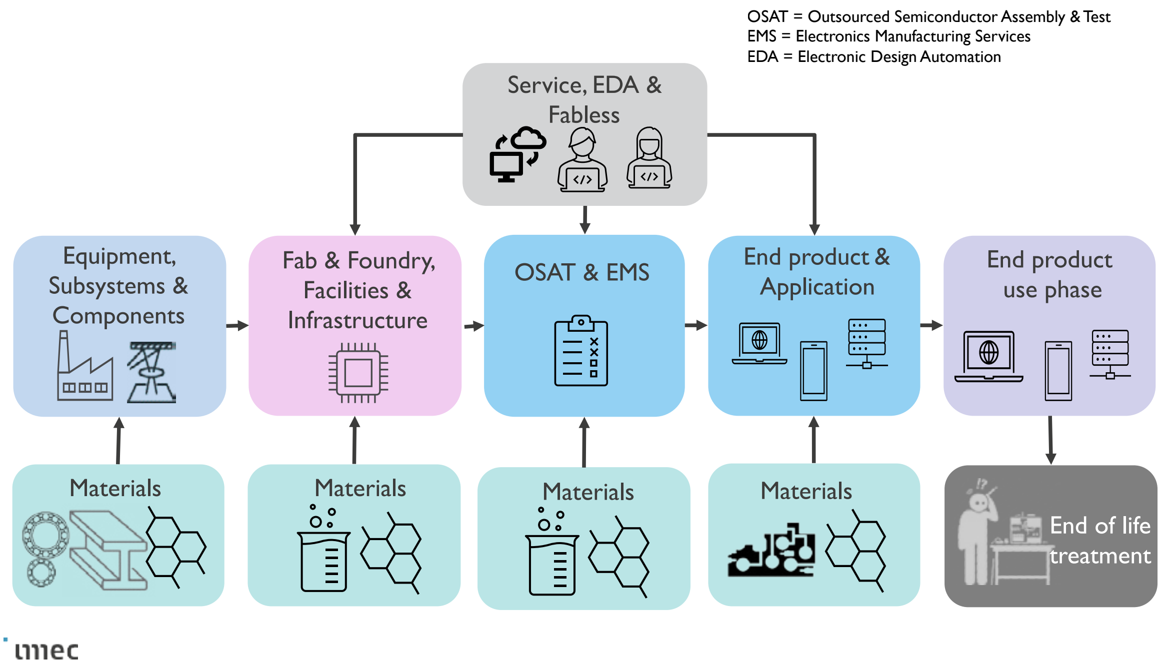

Figure 1: Semiconductor Value Chain Segments

(1) Equipment, Subsystem and Components, (2) Fab and Foundry, Facilities and Infrastructure, (3) Outsourced Semiconductor Assembly and Test (OSAT), Electronics Manufacturing Services (EMS), (4) End Product and Application manufacturers. In Q4 2024, the SEMI-imec collaboration produced a list of 69 distinct materials prioritized for circularity by and for the semiconductor value chain. By value chain segment, 12 of these materials are used in the operation of equipment, subsystems, and components companies; 35 are used in wafer fabrication plants, foundries, and their facilities and infrastructure; 13 are used in outsourced and other assembly and test manufacturing; 17 are used by end product and application companies. (Some materials are consumed in multiple value chain segments, so the sum of materials identified for value chain segments is greater than 69.) This inventory is a novel contribution to industry and a means for mobilizing research and development (R&D) and can be found in Annex 1. In parallel, the prioritization framework that underlies the inventory's structure is anticipated to be made open-source, with publication in progress.

This report presents an inventory of priority materials that can serve as a strategic reference for decision-makers across the semiconductor value chain to drive impactful circularity initiatives. By identifying materials with high circularity potential, this project supports industry efforts to enhance sustainability, reduce supply chain risk, and align with environmental objectives. The value chain perspective employed here emphasizes which spent materials companies should reintegrate back into the value chain as resources. It also provides insight regarding why the materials are prioritized for circularity (e.g., supply chain risk), which equips decision-makers with a substantive basis for taking action.

This report outlines a weighted prioritization framework that enables users to generate a material priority list for circularity. The flexible framework offers two approaches: a **generalized approach** based on high-level, qualitative, and non-region-specific data, and a **case-specific approach** based on detailed, facility-specific process data when available. Users can apply the generalized approach or adapt it into a more granular, case-specific evaluation to compare an innovative recovery process with an established reference process.

The report is structured as follows:

1. **Problem Statement** – Context and motivation for prioritizing circularity in the semiconductor industry.
2. **Prioritization Framework Overview** – Key methodology and scoring criteria.
3. **Framework Development Phases** – Five-step process for building the prioritization model.
4. **Limitations & Assumptions** – Considerations and constraints of the framework.
5. **Results & Analysis** – Key findings from applying the framework.
6. **Summary & Looking Ahead** – Next steps for enabling industry collaboration and research to integrate circular solutions into supply chains.

The prioritization framework and resulting inventory serve as a foundation for future action. The semiconductor value chain must collaborate on research and development to demonstrate how circular solutions for these prioritized materials can be integrated into supply chains to create value. Supporting and enabling this industrywide collaboration will be the next phase of this project.

3. Problem Statement

Semiconductor companies and their business partners have seen periods of rapid growth.[1] As part of this growth, increased consumption of materials and chemicals has enlarged the value chain's adverse environmental impacts, along with driving a rise in liability and disposal costs.[2] Contrary to many other sectors, in the semiconductor industry larger company size, higher value-added per unit of production, and higher technological capacity are not always related to lower quantities of waste per unit of production.[3] To date, most of the industry has been part of the linear economy of take, make, and waste. Optimizing within the linear economy will only delay the inevitable issues of business resilience and license to operate that underpin this system.

Recognizing these challenges, leading semiconductor companies are actively pursuing circular economy initiatives to enhance resource efficiency and minimize waste. For instance, TSMC has invested in in-house recycling facilities to transform waste into reusable resources.[4] Samsung Electronics has committed to sustainable resource management in a collaboration with customers and partners to improve resource circularity.[5] These proactive measures -- and others by industry leaders such as Intel,[6] STMicroelectronics,[7] and GlobalFoundries[8] -- underscore a significant shift towards sustainable practices, aiming to transform waste management and resource utilization in semiconductor manufacturing.

The circular economy is not just an alternative business framework but a critical element of a sustainable value chain. Across industries, early circularity strategies are anchored primarily to waste management, waste-to-energy, waste diversion, and recycling programs. However, circular approaches have expanded to include raw materials strategy, material flows, waste repurposing, and improvement of remanufacturing through resale at "new product" performance and quality. This project seeks to mobilize a new generation of circular strategies for the semiconductor value chain.

There are two interrelated, politico-economic drivers that make this project

[1] Inna Skvortsova and Boris Metodiev, "Semiconductor Manufacturing Monitor," (October 2024), https://www.semi.org/en/products-services/market-data/manufacturing-monitor.

[2] Marcello Ruberti, "The Chip Manufacturing Industry: Environmental Impacts and Eco-Efficiency Analysis," *Science of The Total Environment* 858, no. 2 (2023): 159873, https://doi.org/10.1016/j.scitotenv.2022.159873.

[3] Marcello Ruberti, "The Chip Manufacturing Industry: Environmental Impacts and Eco-Efficiency Analysis," *Science of The Total Environment* 858, no. 2 (2023): 159873, https://doi.org/10.1016/j.scitotenv.2022.159873.

[4] TSMC, "2023 Sustainability Report," (July 2024), https://esg.tsmc.com/file/public/e-all_2023.pdf, 117.

[5] Samsung Electronics, "Circular Economy," n.d., https://www.samsung.com/global/sustainability/planet/circular-economy/, accessed March 3, 2024.

[6] Kathleen Fiehrer, Angie Esparza, Taimur Burki, and Linda Qian, "Circularity in Intel's Semiconductor Manufacturing: Recovery and Reuse," Intel White Paper (2019), https://community.intel.com/legacyfs/online/files/Circularity-at-Intel-Waste-Recovery-and-Reuse-November-2019.pdf.

[7] STMicroelectronics, "2024 Sustainability Report: 2023 Performance," (2024), https://sustainabilityreports.st.com/sr24/, 119-29.

[8] GlobalFoundries, "Resource Conservation is Key to GF's Sustainability Efforts," (April 26, 2024), https://gf.com/blog/resource-conservation-is-key-to-gfs-sustainability-efforts/.

fundamental for industry. First, many critical raw materials (CRM) utilized by the semiconductor value chain are also critical for the transition to low-carbon energy and climate-impact reduction technologies.[9] For example, gallium and Germanium are essential for manufacturing RF (radio frequency) semiconductor technology and solar-photovoltaic cells. Second, low-carbon energy technology components rely to different degrees on certain minerals, which in turn have different criticality profiles dependent on factors such as price volatility and stability of the producer country.[10] Some suppliers and refineries for these minerals are highly concentrated in a few countries.[11] Therefore, supply chain security for critical raw materials used in semiconductor manufacturing has become a strategic issue for governments and the private sector, not only because it could affect the pace of the energy transition but also because materials sourcing has become contested among geopolitical rivalries and alliances.[12] Demand for semiconductors is projected to grow in the next decade, leading to increased demand for critical raw materials.[13,14] As a means for business resilience, circular strategies in the semiconductor value chain must account for the criticality of materials in geopolitical, macroeconomic context.

Definition of Circularity Potential

We define circularity potential as the feasibility and impact of recovering, reusing, or recycling a material to minimize waste, reduce environmental footprint, and enhance supply chain resilience. It is a measure of how effectively a material can be reintegrated into the production cycle based on economic, regulatory, and technical factors.

Another key driver of material circularity in the semiconductor industry is the need to adopt sustainable material sourcing practices to mitigate the upstream environmental and climate impacts of material production. As semiconductor companies increasingly transition to renewable, non-fossil-based electricity for their operations, the relative contribution of upstream embodied emissions—those associated with the extraction, processing, and transportation of raw materials—becomes a more significant portion of their overall carbon footprint. This shift underscores the importance of addressing the environmental impact embedded within the supply chain, as operational decarbonization alone will be insufficient to meet long-term climate targets.

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[9] Joris Teer and Mattia Bertolini, "Reaching Breaking Point: The Semiconductor and Critical Raw Material Ecosystem at a Time of Great Power Rivalry," The Hague Centre for Strategic Studies (October 2022), https://hcss.nl/report/reaching-breaking-point-semiconductors-critical-raw-materials-great-power-rivalry/

[10] See, e.g., Jane Nakano, "The Geopolitics of Critical Minerals Supply Chains," Center for Strategic and International Studies (CSIS) (March 1, 2021), https://www.jstor.org/stable/resrep30033; Baker Institute 2022

[11] International Energy Agency, "Global Critical Minerals Outlook 2024," (2024), https://www.iea.org/reports/global-critical-minerals-outlook-2024.

[12] See SEMI Supply Chain Management Initiative, https://www.semi.org/en/industry-groups/supply-chain-management; Kimberley Botwright and Guillaume Dabré, "Translating Critical Raw Material Trade into Development Benefits," World Economic Forum (May 2024), https://www.weforum.org/publications/translating-critical-raw-material-trade-into-development-benefits/.

[13] Linda R. Rowan, "Critical Mineral Resources: National Policy and Critical Minerals List," U.S. Congressional Research Service R47982 (April 8, 2024), https://crsreports.congress.gov.

[14] O. Goswami, "Chipping In: Critical Minerals for Semiconductor Manufacturing in the U.S.," *MIT Science Policy Review* 4 (2023), 118–126, https://doi.org/10.38105/spr.tnepby7ntp

4. Prioritization Framework Overview

A prioritization framework was established to identify and rank materials utilized and consumed by semiconductor value chain segments in order of circularity potential. The prioritization framework is highly flexible, allowing users to tailor their approach based on the data available to them. Users can start with the generalized approach, which uses high-level, qualitative, and non-region-specific data, and refine it into a more granular, case-specific evaluation as more data becomes available.

To demonstrate the material prioritization framework, four value chain segments (including their upstream material providers) were selected based on current gaps in research and collective action. The value chain segments in scope are (1) equipment, subsystems, and components; (2) wafer fabrication plants, foundries, and their facilities and infrastructure; (3) outsourced and other assembly and test manufacturing; (4) end product and application. Figure 1 illustrates the semiconductor value chain segments.

5. Framework Development Phases

The material prioritization framework was developed in five phases. It started with scoping and proceeded through several rounds of refinement and validation. The five phases are as follows and will be described in detail in the following sections: (1) inventory development, (2) preliminary prioritization criteria and scoring development, (3) administration of expert panel, (4) establishment of weights and normalization for generalized approach, and (5) differentiation of case-specific approach.

Phase 1: Inventory development

The investigators leveraged the SEMI Circularity Working Group to create an initial inventory of materials to consider for circularity potential. Members received a spreadsheet organized around the four value chain segments in scope. Volunteer contributors were asked to propose solids, liquids, and gases used in each value chain segment. The spreadsheet guided them to assess existing ideas of materials and generate new ideas by considering sources such as corporate sustainability and annual reports, the imec.netzero virtual fab webapp,[15] industry presentations previously given in working group meetings, and publicly available information found on corporate and nonprofit websites. Contributors indicated reasons why specific materials might deserve to be high-priority for circularity, e.g., high utilization and consumption volume, high embodied emissions (Global Warming Potential [GWP] as measured by Green House Gas (GHG) emissions associated with material sourcing and manufacturing), supply risk, critical designation by regulation or policy, cost of the material, and recycle rates. The contributors provided an overview of how specific materials are already being reused, upcycled, recycled, and resold with examples of companies in the semiconductor value chain that engage in these practices.

Phase 2: Preliminary prioritization criteria and scoring development

To organize the initial inventory into a resource suitable for further analysis, the investigators created a preliminary set of prioritization criteria and scoring. Six criteria and associated scoring were chosen (see Table 1).

[15] https://netzero.imec-int.com/

Table 1: Criteria Explanation

Criteria	Explanation
M	Mass of the material consumed/spent material generated per year from a large factory in metric tons
V	Value of spent material on the market
RR	Spent Materials Regulatory Risk
R	Ease of Recycling
CRM	Critical or Conflict material by regulation/policy in the EU, Japan, or the United States* (includes derivatives and feedstocks.)
GWP	Embodied Global Warming Potential as measured by greenhouse gas emissions potential of replaced virgin material**

* See Annex II, a select combination of critical or conflict materials drawn from EU, Japan, and US policies and/or trade agreements.

** The embodied global warming potential (GWP) emission factor is rounded either to protect the intellectual property of licensed commercial data used by the investigators, to produce an estimate for mixtures, or both. For example, the wafer fabrication bulk solvent waste is a mixture, not a pure chemical; therefore, a ratio had to be utilized to estimate the embodied GWP of the replaced virgin material.

Phase 3: Administration of expert panel

To validate and improve the preliminary prioritization criteria and scoring, the investigators convened an international panel of industry experts. Recruitment occurred in October-November 2024. To capture a range of perspectives, the recruitment targeted companies in the four selected value chain segments based in North America, Asia Pacific, and Europe. It sought panelists from a range of professional disciplines, such as process engineering, commodity management, operations, and environmental engineering. The investigators identified potential subjects using purposive sampling, a non-probability selection based on judgment of their role in an organization and their capacity to assess waste management and circularity practices and markets. Peer recruitment was conducted among the SEMI membership.

The panel was composed of professionals from 5 countries and 5 organizations:

- Lars-Ake Ragnarsson (imec), Belgium
- Dave Medeiros (Entegris), United States
- Nils Ross (ASM), Ireland
- Mart Beune (ASML), Netherlands
- Dragan Veljanovski (Apple), Germany

Each panelist's participation was for empirical purposes only and does not imply endorsement of this report or the methodology. Observations, conclusions, and recommendations are made solely by the authors.

Several design decisions were intended to mitigate bias and reduce respondent fatigue. The interviewer provided panelists with the inventory developed in a rubric containing prioritization criteria and scoring (see Tables 2 and 3 below). To enable panelists to put market and regulatory conditions into proper context, the interview proceeded by region (North America, Asia Pacific, Europe).

Interviews took place in November 2024. They were semi-structured, carried out by Taimur Burki using a spreadsheet as a visual guide. Neither audio nor video was recorded. Burki recorded notes, which were discussed with Lizzie Boakes as basis for interpretation.

Phase 4: Establishment of framework, weights, and normalization for generalized approach

Based on feedback collected from the panel, the investigators adjusted the prioritization criteria and scoring by establishing weights and normalization. They developed a generalized approach which allowed them to showcase the material prioritization framework and provide firsthand insights into which materials have high circularity potential.

The prioritization framework consists of four steps as follows:

Step A: Criteria definition
Step B: Criteria score allocation
Step C: Normalization
Step D: Weighting

Generalized Approach:

Step A: Criteria definition

The six criteria defined in Table 1 are applied in the generalized approach.

Step B: Criteria score allocation

For every material in the inventory, a score is allocated for each criterion. In the generalized approach, a criteria score out of 3 is determined by:

- High-level generalized values from above
- Qualitative description
- Non-region-specific regulation or industrial network

Table 2 outlines how a score out of 3 was allocated to each criterion defined in Table 1. The higher the allocated score, the higher the circularity potential and thus the higher priority for circularity.

Table 2: Prioritization Scoring for the Generalized Approach

High Priority

Criteria	Score			
	1	2		3
M	<100 tons	100-1000 tons		>1000 tons
V	Low (paying for disposal)	Due to the cost of transport this is still a cost		Pays for the cost of transport and credit/ money is returned to producer
RR	Heavily regulated and will require exemptions	Regulated material but well established regulations to allow for beneficial re-use		Non regulated
R	No current methods	Offsite recycling and refinement		Onsite recycling/reuse or resale off site (exempted)
	0			3
CRM	Not on CRM or conflict list (see Annex II), and not a feedstock to or derivative of materials on the list			On CRM or conflict list (see Annex II). Includes feedstocks to and derivatives from materials on the list
	1	1.5	2.5	3
GWP	<1 kg CO_2/kg	1-10 kg CO_2 /kg	10-100 kg CO_2/kg	>100 kg CO_2 /kg

Step C: Normalization

This step is especially important if the criteria have variation in the maximum possible score (see phase 5: Differentiation of case-specific approach). The Normalized Criteria Score is calculated using the equation below. The allocated score for each criterion is divided by the maximum possible score for that criterion. This is then summed over the total number of criteria (n). The range of the Normalized Criteria Score using the generalized approach is 1.66 to 6.

$$Normalized\ Criteria\ Score = \sum_{1}^{n} \frac{Criterion\ score_n}{Max\ possible\ criterion\ score_n}$$

Step D: Weighting

The weighting step introduces a value chain perspective by allowing the user to apply company- or value chain segment-specific weighting factors which reflect their motivation for circularity innovation, e.g., the desire to minimize GWP emissions during operation would lead to a larger weighting factor for the criterion GWP.

In Table 3, the investigators propose a set of weighting factors which provide an example of the degree of importance a specific criterion bears on the circularity potential and thus the prioritization of materials for circularity innovation. They assigned a weighting factor of 5 to the criterion GWP, as GHG emission reduction is considered a significant driver for sustainability innovation in the industry. For instance, members of the Semiconductor Climate Consortium at SEMI are tracking the value chain's progress in this area and have increased their efforts to report GHG emissions with higher transparency.[16] A weighting factor of 5 was also assigned to the criterion CRM, as supply chain security within the current geopolitical climate is considered a significant driver for circularity innovation. A weighting factor of 10 was assigned to criterion M because the mass of spent material produced heavily determines the benefit of circularity innovation by linearly scaling all other criteria. The remaining criteria were assigned a weighting factor equal to 1.

[16] SEMI, Semiconductor Climate Consortium, and BCG, "Transparency, Ambition, and Collaboration: Advancing the Climate Agenda of the Semiconductor Value Chain," (September 2023), https://discover.semi.org/transparency-ambition-and-collaboration-white-paper-download-registration.html.

Table 3: Weighting Factors for each Criterion for Value Chain Perspective Equation

Criteria	Weighting Factor
R	1
RR	1
V	1
CRM	5
GWP	5
M	10

Value chain perspective relative weighted prioritization score equation:

$$Weighted\ Prioritization\ Score = \sum_{1}^{n}\left(\frac{Criterion\ score_n}{Max\ possible\ criterion\ score_n} * \frac{Criterion\ Weighting\ Factor_n}{Sum\ of\ Weighting\ Factors}\right)$$

Once the weighted prioritization score has been calculated for all considered materials, ranking the materials from the largest weighted score to smallest will provide the final prioritized ranking of materials with highest circularity potential to lowest, respectively.

The generalized approach provides a generic priority ranking of materials. The normalization and weighting steps introduce a value chain perspective which considers that not all criteria are equally significant to motivate circularity innovation.

Phase 5: Differentiation of case-specific approach

The generalized approach outlined in phase 4 showcases the material prioritization framework. This framework can be tailored for a case-specific analysis when granular data is available to the user.

In step A of the framework, the generalized approach proposed six criteria, however, more criteria can be added to the analysis depending on the specific interests of the user, e.g., cost of recovery system, or purity and contamination risk.

In step B of the framework, the criteria score can be made more granular, for example having a maximum possible score of 10, which will allow the user to have a more refined prioritization. This will require that the user has access to more granular data to allocate a score. The data quality can be improved by replacing high-level, qualitative, and non-region-specific data used in the generalized approach, with primary, and supplier/region-specific data in a case-specific approach (as outlined in Figure 2).

Steps C and D can be conducted using company-specific factors. For example, applying weighting factors based on specific company sustainability objectives.

The Weighted Prioritization Score using the case-specific approach could be used as a circularity score to compare an innovative recovery process with a process of reference.

Figure 2: Differences in Generalized and Case-specific Approach

High-level strategic inventory of prioritized materials

Methodology for prioritization of materials for circularity - work in progress

Generalized

- **Six criteria**
- Criterion Score out of 3 determined by:
  - **High-level** generalized values
  - **Qualitative** description
  - **Non-region-specific** regulation or industrial network
- **Output:** a generic priority ranking of all materials used by the focus semiconductor value chain segment

Case-specific

- **More criteria**
- Granular Criterion Score (e.g., out of 10) determined by:
  - **Primary data from operations**
  - **Product carbon footprint data from material supplier**
  - **Region-specific regulation and industrial networks**
- **Output:** a circularity score to compare an innovative recovery process with a process-of-reference

6. Limitations and Assumptions

Although this work is a major step toward defining a methodology to identify and rank materials that are utilized and consumed by semiconductor value chain segments in order of circularity potential and thus offers a framework for shaping circular industry practices, the approach has some limitations.

With its targeted samples of contributors to the initial inventory and panel, this study makes no claim to be representative of all companies in the four semiconductor value chain segments selected for analysis. Selection effects may be at play; in other words, this project may have attracted participants with strong views about practices relevant to the study topic and furthermore is limited by its use of purposive sampling, a non-probability technique. Furthermore, although we invited professionals from companies headquartered in the Asia Pacific region to participate in the panel, none accepted, and thus to address the gap we had to rely on professionals with global knowledge who are based in other regions. Collaborators who accepted our invitation to participate do not directly represent the Outsourced Assembly and Test (OSAT) manufacturing segment of the value chain. Although we invited representatives from this segment to take part in phases 1 and 3 of this study, we were unsuccessful. Therefore, these results reflect industry knowledge from adjacent segments and should be interpreted with caution.

The basis of judgments regarding ease of recycling is a combination of publicly available corporate responsibility, sustainability, and other reports and the investigators' own industry knowledge of state-of-the-shelf technology (Table 4). Thus, scores determined in the analysis are based on assumptions that may not fully reflect emerging practices or technologies over time.

Table 4: Current Technologies

Spent Materials	State of the Shelf Technology
Acids containing copper or cobalt	Electrowinning or precipitation
Solvents	Direct re-sale, distillation and then sold onto the merchant market, or waste to energy
Spent acids	Direct re-sale
Wood pallets	Re-used on site or sold
Ammonia	Treated onsite to make ammonium sulfate and sold as fertilizer
Developer (TMAH)	Shipped offsite and fuel blended and sent for waste to energy
Mixed solvents	Blended with other waste and used as a fuel for cement kilns or distilled then sold onto the merchant market
Empty plastic drums/totes	Triple rinsed and then sent for grinding and made into new plastics

Global Warming Potential (GWP) in this analysis is rounded and constructed from imec life cycle analysis databases and commercial life cycle analysis databases. Spent materials have impurities and are often mixtures, so an exact GWP is not possible. Mixed solvent waste is a ratio of the GWP of the solvents that are normally present.

The results of this study should be treated as a living document. Feedback and updates from the industry, research, and policy communities are welcome.

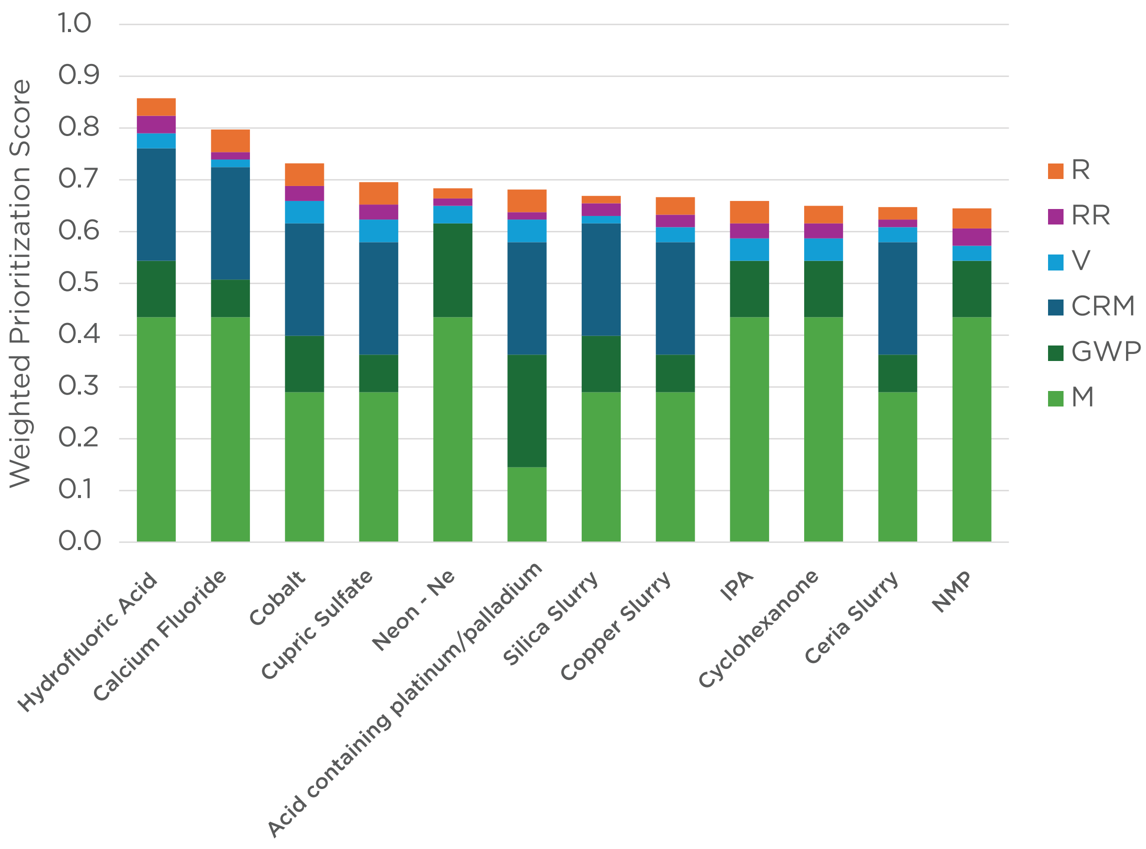
7. Results and Analysis

The results in this report provide a ranking of materials prioritized for circularity potential across the semiconductor value chain. The generalized approach with the scope defined in the previous sections of this report was applied to this analysis. Therefore, the limitations of the generalized approach should be considered when interpreting the following results.

The results of the top 12 materials ranked by their Weighted Prioritization Score for each value chain segment will be discussed.

Fab, Foundry, Facilities and Infrastructure

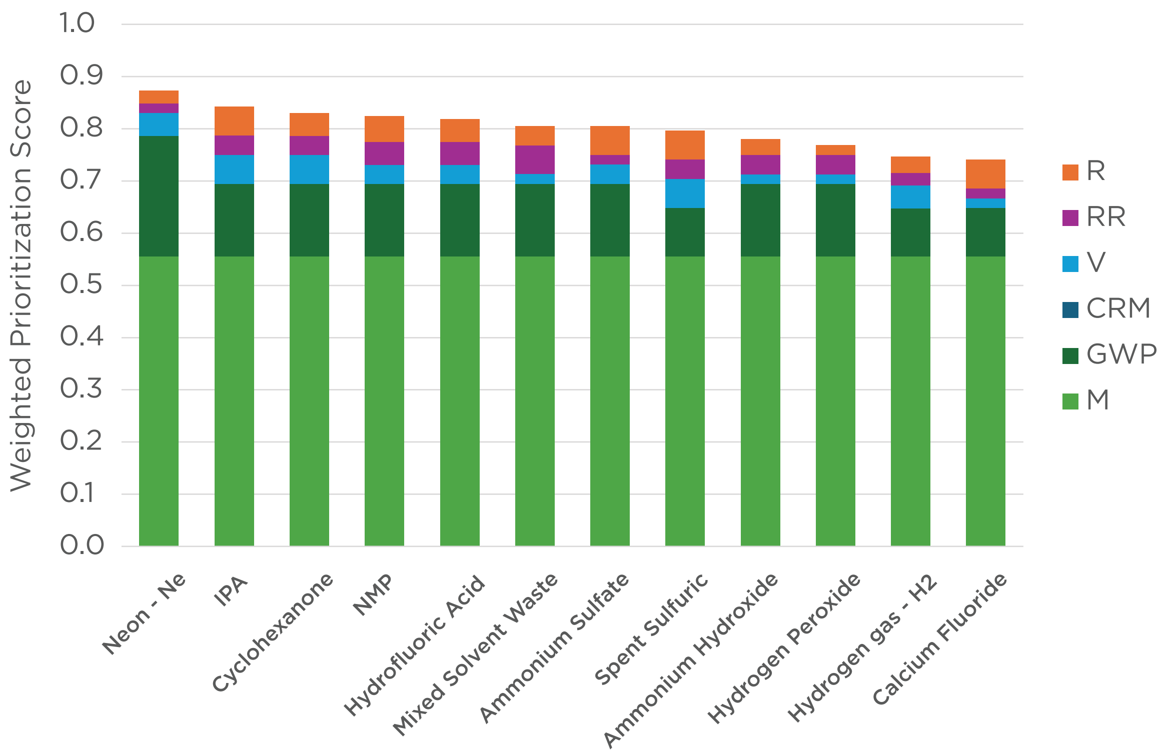
Graph 1: Prioritized Materials for Fab, Foundry, Facilities and Infrastructure



The results for wafer fabrication plants, foundries, and their facilities and infrastructure show that fluoride-bearing compounds like hydrofluoric acid and calcium fluoride are priorities due to criticality and very high volumes. The same rationale applies to cobalt, ceria slurry, and cupric sulfate. Liquids such as hydrofluoric acid (HF), isopropyl alcohol (IPA), cyclohexanone, and N-Methyl-2-pyrrolidone (NMP) show up in the ranking due to their large consumption volumes.

To illustrate the effect of changing the weighting factor values, Graph 2 displays the same analysis under the same generalized model assumption except that the weighting factor for CRM was changed from 5 to 0.

Graph 2: Prioritized Materials for Fab, Foundry, Facilities and Infrastructure. CRM weighting factor equal to zero.



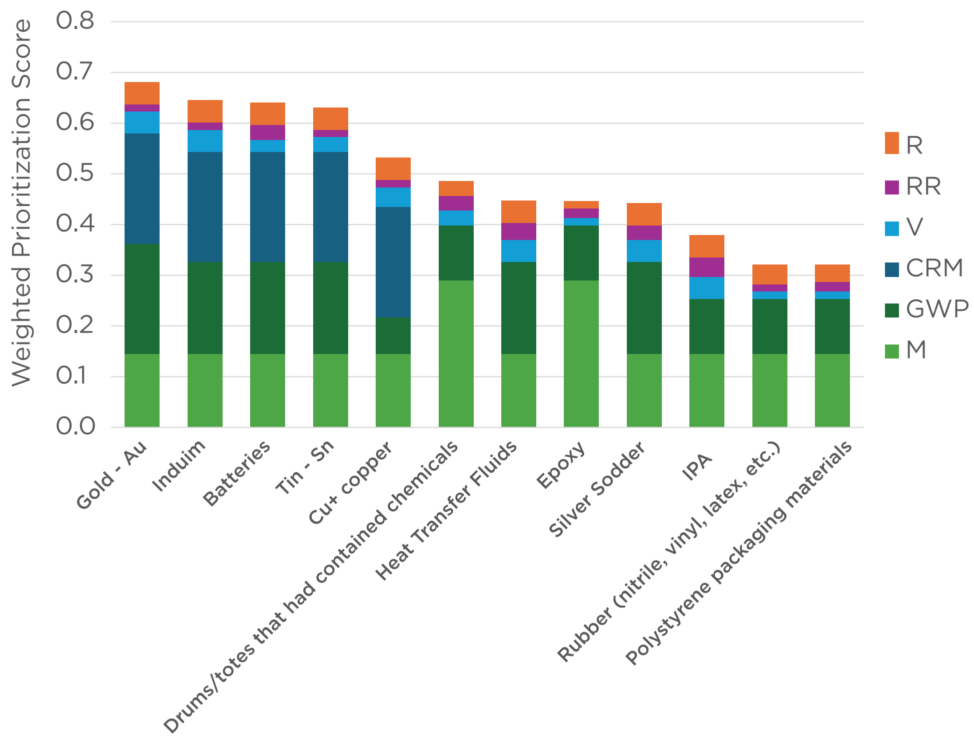
Graph 2 shows that when the weighting factor of CRM is set to 0, then neon, the solvents, and major waste streams from the fabs become priorities versus the metals or rare earths. Due to the spent materials' global warming potential as measured by CO2e and the sheer amount of the waste, fab wastes have significant environmental benefits if converted from linear to circular uses. For example, by enabling the re-use of solvents, the environmental impacts of drilling and refining are avoided.

The weight given to CRM significantly affected the results. Comparison of Graphs 1 and 2 shows that the criticality criterion had the largest impact on rank of materials. This was the case even when considering the solvents, which constitute the largest waste stream with some of the larger GHG emissions. Although solvent usage in the fabs is very high, metals' and rare earth minerals' GHG emissions are higher than those of solvents while the status of some minerals as critical materials tipped their priority even higher. Hydrofluoric acid has a high usage and is made from a critical material.[17] Cobalt has high usage, high GHG emissions, and is a critical material.

OSAT: Outsourced Assembly and Test Manufacturing

The results for the OSAT value chain segment show that gold, indium, tin, and copper are the highest priority for circularity (Graph 3). Notably, containers for chemicals such as drums and totes are used at such high volume that they earn a relatively high priority rank. By contrast, epoxy is used at high volume but presents a practical problem. Epoxy is very difficult to upcycle because as a spent material it exists as residue in cartridges, is not easily segregated, and has very little value.

Graph 3: Prioritized Materials for Outsourced Assembly and Test Manufacturing

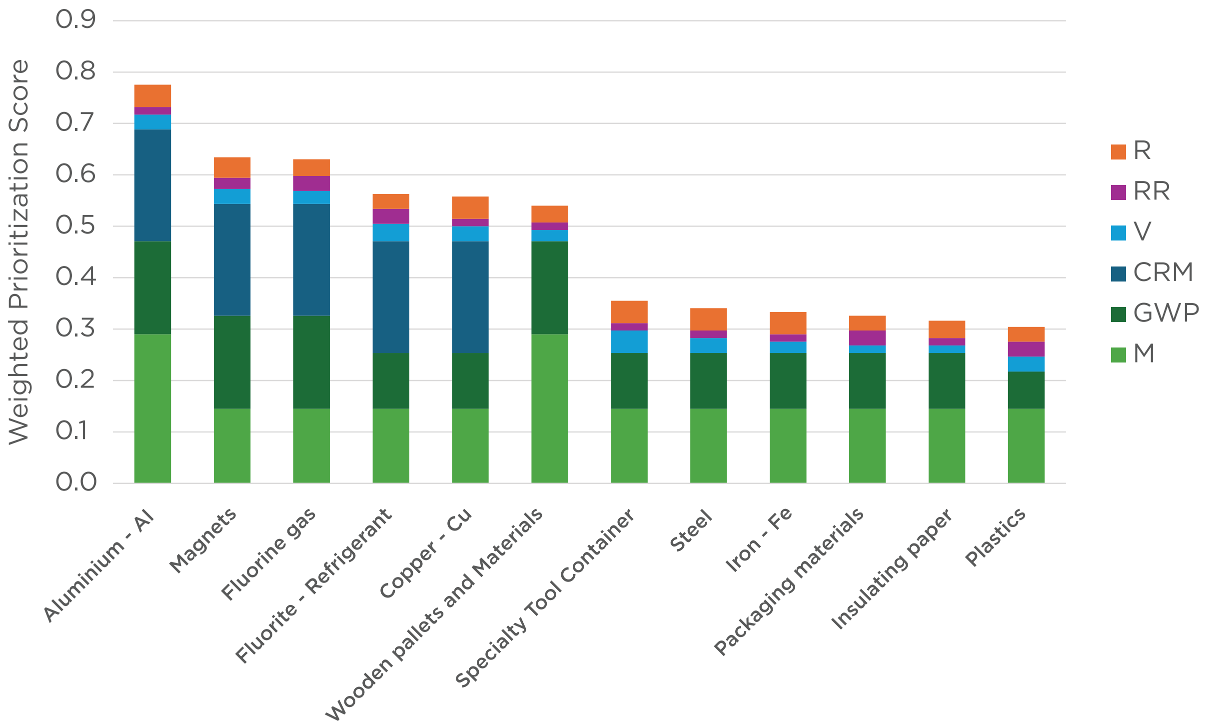


[17] Hydrofluoric acid (HF) is produced by the reaction of concentrated sulfuric acid with fluorspar (also called fluorite).

Equipment, subsystems, and components

The results for the equipment, subsystems, and components value chain segment show that aluminum, magnets, and fluorine gas are highest priority for circularity (Graph 4).

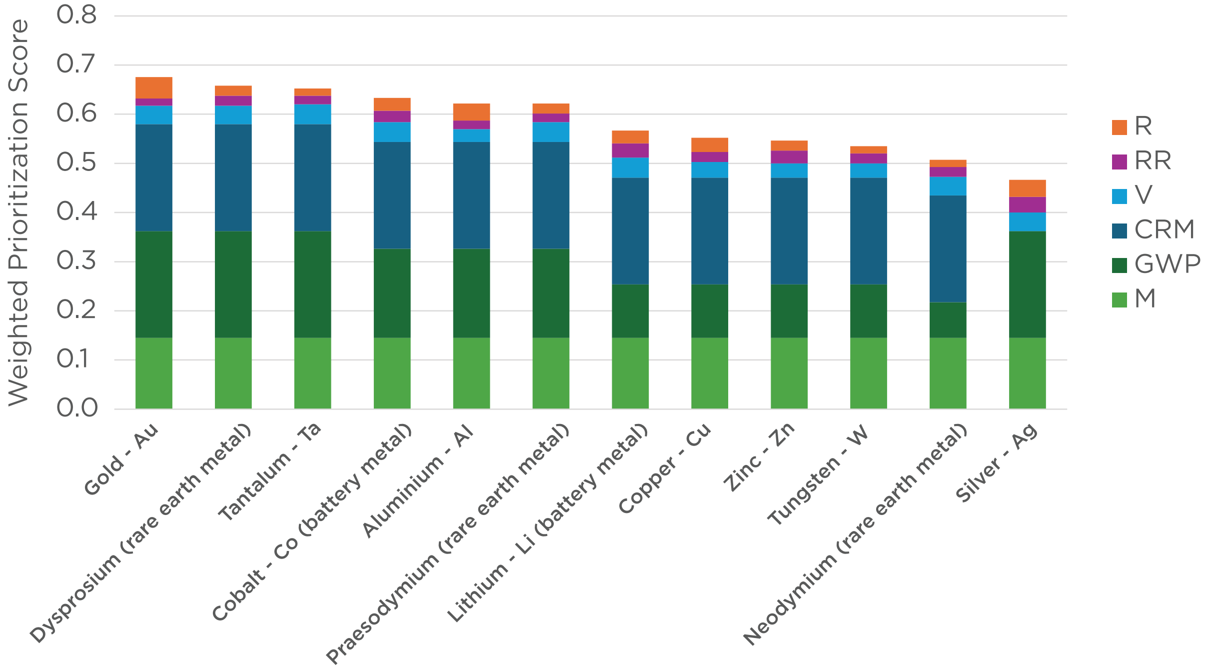
Graph 4: Prioritized Materials for Equipment, Subsystems, and Component Suppliers



End product and application

For end product and application companies, gold, dysprosium (a rare earth), tantalum, and cobalt are highest priority for circularity using our generalized model assumptions (Graph 5).

Graph 5: Prioritized End Product and Application Spent Materials



The results showcase how the prioritization framework can be used to rank materials based on their circularity potential. Under the assumptions defined in this report for the generalized approach, the results show that materials from our selection of CRM or materials with relatively high embodied GHG emissions are ranked as high priority. The results can be justified by comparing the prioritization list with start-of-the-art recycling and recovery systems that are implemented in industry. For example, state-of-the-shelf recovery systems for HF, IPA, and cyclohexanone have successfully been implemented at offsite chemical recycling or hazardous waste facilities.

When the weighting factor for CRM was reduced to 0 from 5 (Graph 2 and Graph 1 respectively), the prioritization ranking then shifted the focus areas dramatically to materials that have relatively high embodied emissions and consumption volume, such as neon gas and IPA. This emphasizes the benefit of implementing a case-specific analysis which relies on higher quality input data and case-specific weighting factors.

8. Summary

This project launched in 2024 to define a focus list of priority materials for circularity in the semiconductor value chain (Annex I) with the goal of providing a foundation that can mobilize R&D action. As part of this foundation, a flexible framework was developed to rank materials used or consumed in manufacturing based on their circularity potential and thus provide decision-making support to users.

We anticipate that the project outputs will be helpful to the following stakeholders:

- **Research teams in the private and non-profit sectors** advancing technologies that enable purification, re-use, and/or resale of materials that are used or consumed in manufacturing across the semiconductor value chain;
- **EHS (environmental, health, and safety) managers and engineers** developing ways to reduce waste and emissions, optimize efficiency, and capitalize on circular opportunities;
- **Procurement professionals** seeking to integrate circularity criteria into materials sourcing processes;
- **Corporate sustainability and ESG practitioners** building initiatives to improve performance and reporting on circularity;
- **Enterprise risk management** professionals assessing supply and regulatory risks related to process materials and manufacturing waste;
- **Consultants and advisors** providing services to any of the above.

This report showcases how users can apply the framework by conducting a generalized approach analysis for four segments of the semiconductor value chain. The generalized approach assumptions are based on high-level, qualitative, and non-region-specific data. Under these assumptions, we found that our critical raw materials criterion significantly impacts the prioritization. Across all four value chain segments, the top five spent materials are hydrofluoric acid, aluminum, gold, acids containing platinum/palladium, and cobalt as analyzed through the framework. This finding aligns with state-of-the-art material recovery systems in industry such as making calcium fluoride or fluorspar from hydrofluoric acid; recovery of precious metals via precipitation; and electrowinning and precipitation for acids containing valuable minerals or metals.

We presented a ranking of materials for each of the four value chain segments and encourage readers to consult the full rankings published in the Results and Analysis section. The top three materials for each value chain segment, based on our generalized model assumptions, are:

Fab, Foundry, Facilities and Infrastructure
Hydrofluoric acid, calcium fluoride, cobalt

OSAT: Outsourced Assembly and Test Manufacturing
Gold, indium, batteries

Equipment, subsystems, and components
Aluminum, magnets, fluorine gas

End Product and Application
Gold, dysprosium, tantalum

This framework can be used to identify and justify areas for circularity investment and innovation.

To improve the usability of the prioritization framework, we offer an approach that users can adapt to their specific needs. We refer to this offering as the “case-specific approach,” and it is described above in Phase 5: Differentiation of case-specific approach.

9. Looking Ahead

With a list of priority materials for circularity now defined, semiconductor companies and their business partners need to enable processes that allow for capture of spent materials and upcycling. However, technology and local infrastructures are highly underdeveloped. In some cases, technology may be available, but the localized hub and spoke models to allow a feedstock of critical materials to centralized processing centers or onsite recovery processes have not been established. In other cases, innovation is needed to insert new technology into existing business-to-business networks.

To address these gaps, SEMI and imec are forming a network of research affiliates called the Circular Semiconductors Research Network. SEMI and imec invite collaboration from teams that develop technology for business-to-business mobilization of circular economies for semiconductor manufacturing. We seek research affiliates who align with our objective to build a circular, localized supply chain through considerations of sustainable semiconductor manufacturing.

An invitation to collaborate, gives a full description of application requirements and evaluation criteria for prospective parties interested in joining the affiliation.

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Each individual's participation was for empirical purposes only and does not imply endorsement of this report. Analysis and conclusions are made solely by the authors.

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Annex 1: Inventory of Priority Materials for Circularity in the Semiconductor Value Chain

Value Chain Segment	Material Name
Fab Foundry and Facilities	Acid containing Platinum/Palladium
Equip Subcomponents and Components	Aluminium - Al
End Product	Aluminium - Al
Fab Foundry and Facilities	Ammonium Hydroxide
Fab Foundry and Facilities	Ammonium Sulfate
OSAT	Batteries
Fab Foundry and Facilities	Calcium Fluoride
Fab Foundry and Facilities	Ceria Slurry
End Product	Cobalt - Co (battery metal)
Fab Foundry and Facilities	Cobalt sulfate
Equip Subcomponents and Components	Copper - Cu
End Product	Copper - Cu
Fab Foundry and Facilities	Copper Slurry
OSAT	Copper - Cu
Fab Foundry and Facilities	CuMn alloy targets
Fab Foundry and Facilities	Cupric Sulfate
Fab Foundry and Facilities	Cyclohexanone/Cyclopentanone
OSAT	Drums/Totes that had contained chemicals
Fab & Foundry / IC chip manufacturers / Facilities & Infrastructure	Drums/Totes that had contained chemicals
End Product	Dysprosium (rare earth metal)
OSAT	Epoxy
Fab Foundry and Facilities	Ethyl Lactate
Equip Subcomponents and Components	Fluorine gas
Equip Subcomponents and Components	Fluorite - Refrigerant
End Product	Glass
End Product	Gold - Au
OSAT	Gold - Au
OSAT	Heat Transfer Fluids

Fab & Foundry / IC chip manufacturers / Facilities & Infrastructure	Helium
Fab & Foundry / IC chip manufacturers / Facilities & Infrastructure	HFCs (e.g. Process Gases such as CHF3, Refrigerants)
Fab Foundry and Facilities	Hydrofluoric Acid
Fab & Foundry / IC chip manufacturers / Facilities & Infrastructure	Hydrogen gas - H2
Fab Foundry and Facilities	Hydrogen Peroxide
OSAT	Indium
Equip Subcomponents and Components	Insulating paper
Fab Foundry and Facilities	Ion Exchange Beds
Fab Foundry and Facilities	IPA
OSAT	IPA
Equip Subcomponents and Components	Iron - Fe
End Product	Iron - Fe
End Product	Lithium - Li (battery metal)
Equip Subcomponents and Components	Magnets
Fab Foundry and Facilities	Mixed Solvent Waste
Fab Foundry and Facilities	Nbutyl Acetate
End Product	Neodymium (rare earth metal)
Fab & Foundry / IC chip manufacturers / Facilities & Infrastructure	Neon - Ne
Fab Foundry and Facilities	Nitric Acid
Fab Foundry and Facilities	NMP
Equip Subcomponents and Components	Packaging materials
End Product	Packaging materials
End Product	Paper
Fab Foundry and Facilities	PGME
Fab Foundry and Facilities	PGMEA
Fab Foundry and Facilities	Phosphoric Acid
Fab Foundry and Facilities	Photomasks
Equip Subcomponents and Components	Plastics
Fab Foundry and Facilities	Polyimide
OSAT	Polystyrene packaging materials

End Product	Praesodymium (rare earth metal)
OSAT	Rubber (nitrile, vinyl, latex, etc..)
Fab Foundry and Facilities	Ruthenium - Ru
Fab Foundry and Facilities	Silica Slurry
Fab Foundry and Facilities	Silicon wafer
End Product	Silver - Ag
OSAT	Silver Sodder
Equip Subcomponents and Components	Specialty tool container
OSAT	Specialized plastics for packaging
Fab Foundry and Facilities	Spent Sulfuric
Equip Subcomponents and Components	Steel
End Product	Steel
End Product	Tantalum - Ta
OSAT	Tin - Sn
Fab Foundry and Facilities	TMAH at 2-10%
End Product	Tungsten - W
Fab Foundry and Facilities	Wastewater treatment sludges
Equip Subcomponents and Components	Wooden pallets and materials
End Product	Zinc - Zn

Annex II: Critical Raw Materials in Scope

The prioritization framework offered in this paper includes a score denoted CRM for selected critical and conflict materials drawn from E.U., Japan, and U.S. policies. Materials in the list below, as well as derivatives from or feedstocks to these materials, were considered in scope.

Notes:

1. The list below contains some duplicates, since there is some overlap in policies among the jurisdictions. For example, arsenic is listed twice because it is identified in the U.S. and E.U. policy documents consulted.
2. The list should not be considered universal. It excludes policies and trade agreements that are either in place or being considered by jurisdictions as of the time of publication.

Sources:

USA

U.S. Department of Energy, Notice of Final Determination on 2023 DOE Critical Materials List, Federal Register vol. 88, no. 149 (August 4, 2023), https://www.govinfo.gov/content/pkg/FR-2023-08-04/pdf/2023-16611.pdf [includes critical minerals on the 2022 final list published by the Secretary of the Interior]

Japan

Enforcement Order of the Act on Promotion of Ensuring Security by Implementing Economic Measures in an Integrated Manner, Article 1, Part 10 (2024), https://laws.e-gov.go.jp/law/504CO0000000394

EU

European Critical Raw Materials Act, Regulation (EU) 2024/1252 of the European Parliament and of the Council of 11 April 2024 establishing a framework for ensuring a secure and sustainable supply of critical raw materials and amending Regulations (EU) No 168/2013, (EU) 2018/858, (EU) 2018/1724 and (EU) 2019/1020 (rev. March 5, 2024), https://eur-lex.europa.eu/eli/reg/2024/1252/oj/eng

USA	EU	Japan
aluminum	antimony	antimony
antimony	arsenic	barium
arsenic	baryte	beryllium
barite	bauxite/alumina/aluminum	bismuth
beryllium	beryllium	boron
bismuth	bismuth	cesium
cerium	boron	chromium
cesium	boron — metallurgy grade	cobalt
chromium	cobalt	fluorine
cobalt	coking coal	gallium
copper	copper	germanium
dysprosium	feldspar	graphite
electrical steel	fluorspar	hafnium
erbium	gallium	indium
europium	germanium	lithium
fluorine	graphite	magnesium
fluorspar	graphite — battery grade	manganese
gadolinium	hafnium	molybdenum
gallium	heavy rare earth elements	nickel

germanium	helium	niobium
graphite	light rare earth elements	phosphorus
hafnium	lithium	platinum group
holmium	lithium — battery grade	rare earth metals
indium	magnesium	rhenium
iridium	magnesium metal	rubidium
lanthanum	manganese	selenium
lithium	manganese — battery grade	silicon
lutetium	nickel — battery grade	strontium
magnesium	niobium	tantalum
manganese	phosphate rock	tellurium
natural graphite	phosphorus	thallium
neodymium	platinum group metals	titanium
nickel	rare earth elements for permanent magnets (Nd, Pr, Tb, Dy, Gd, Sm, and Ce)	tungsten
niobium	scandium	uranium
palladium	silicon metal	vanadium
platinum	strontium	zirconium
praseodymium	tantalum	
rhodium	titanium metal	
rubidium	tungsten	
ruthenium	vanadium	
samarium		
scandium		
silicon		
silicon carbide		
tantalum		
tellurium		
terbium		
thulium		
tin		
titanium		
tungsten		
vanadium		
ytterbium		
yttrium		
zinc		
zirconium		