This paper was presented at the XXXVII ISPIM Innovation Conference, held in Granada, Spain on 07 June to 10 June 2026. ISBN 978-952-65771-2-8.

Circular innovation enabling more sustainable semiconductor material use in ecosystems

Katri Valkokari*, Noora Harju

VTT Technical Research Centre of Finland, P.O. Box 1300, FI-33101 Tampere, FINLAND
E-mail: katri.valkokari@vtt.fi

Maija Federley, Henna Sundqvist, Piia Konstari, Mona Arnold, Hanna Pihkola

VTT Technical Research Centre of Finland, P.O. Box 1000, FI-02044 VTT Espoo, FINLAND.
E-mail: maija.federley@vtt.fi; henna.sundqvist@vtt.fi; piia.konstari@vtt.fi; mona.arnold@vtt.fi; hanna.pihkola@vtt.fi

* Corresponding author

Abstract: Semiconductor production is growing rapidly, intensifying environmental pressures and supply risks related to critical raw materials (CRMs). This paper examines how circular innovation can enable more sustainable semiconductor material use by adopting an ecosystem perspective beyond individual firms and linear value chains. As a qualitative case study of Finnish semiconductor actors, we conducted 17 semi-structured interviews across eight value-chain companies and other ecosystem organisations. The analysis applies the R-strategy framework and develops a three-layer view of circular innovation: (i) resource efficiency within the fabrication value chain, (ii) material circularity and substitution solutions networks, and (iii) open cross-industry circular innovation networks. Findings highlight the need of several innovation and business networks with different actors and challenges related to coordination beyond them. We discuss implications for firms and policymakers seeking to strengthen sustainability and supply resilience through collaborative ecosystem design.

Keywords: Circular innovation; innovation ecosystem; semiconductor industry; collaboration; case study

1 Introduction

Circularity of semiconductor materials has become increasingly important as annual device production using semiconductor chips exceeds one trillion, while they are present in nearly every piece of modern technology. The semiconductor industry has already launched several activities to become more environmentally sustainable and enhance circularity of resources. Recent geopolitical shifts have heightened supply security

This paper was presented at the XXXVII ISPIM Innovation Conference, held in Granada, Spain on 07 June to 10 June 2026. ISBN 978-952-65771-2-8.

concerns of the critical raw materials (CRM)[1] needed, increasing interest in circular innovations in the semiconductor industry, particularly in Europe (ECS SRIA 2026). However, semiconductor value chains are highly complex and involve different geographical regions and groups of companies – Japan, Korea and Taiwan typically identified as major players. On the other hand, CRMs are in limited supply and controlled by a small number of actors and suppliers, such as Russia and China. Thereby, supporting further research and development for semiconductor materials and production processes has been emphasized as an option for Europe (Patrahau et al., 2020).

This far, in the context of semiconductor industry, the identified circular economy solutions are water reuse, materials recycling and equipment reuse and remanufacturing, or use of renewable energy (Schröder et al., 2024). From resource management focus, especially, water resources and rare earth minerals use within semiconductor companies, research has examined how effective use of production factors impacts on production efficiency (Cho et al., 2021). The innovation management challenge is related to practices enhancing collaborative innovation processes, from their initiation to implementation and commercialisation. Understanding of such collaborative circular innovation arrangements through which knowledge is shared and integrated within and across organizations and industries is limited. Collaborative innovation in the context of semiconductor industry is an emerging context within innovation management, whereas the previous discussion has mainly focused on formal knowledge protection through patenting. Due to the huge volume of semiconductors in the contemporary economy and the evident material challenges, it is a particularly interesting area for research on circular innovation.

The outlined paper focuses on circular innovation in the context of semiconductor value chains; however, it is built on the assumption that ecosystems- level considerations are needed to enable circularity across the various stages of the value chain or beyond it - as recently highlighted also in academic literature (Brown et al., 2019; Konietzko et al. 2020; Eisenreich et al. 202; Hansen & Schmitt, 2021; Runiewicz-Wardyn, 2023; Dorrego-Viera et al., 2025). Therefore, using an ecosystems perspective, informed by review of academic and grey literature, the paper examines how circular innovation in the context of semiconductor industry can mitigate environmental pressures, reduce dependency on raw materials like silicon and gallium, and enhance resilience against geopolitical disruptions.

2 Theoretical background

Circular economy in the semiconductor industry

Circular Economy advocates reducing consumption and demand of natural resources through the efficient and prolonged use of materials and products. Circular economy innovation emerges from the intersection of circular economy and innovation management research fields, which both are shaped by various philosophical,

---

[1]Already in the early 2000s, supply risks received more attention in the EU, and, consequently, the EU launched the raw material initiative in 2008. These CRMs are resources that have comparatively high economic importance but, at the same time, are associated with remarkably high supply risks, especially because European countries are highly dependent on a limited number of suppliers of CRMs.

commercial, and academic perspectives. This has resulted the conceptual confusion (Pascucci et al., 2023).

However, in the circular economy literature there are several well-established approaches such as three fundamental approaches to the resource use presented by Bocken et al. (2016) or the so-called R strategy framework by Potting et al. (2017). These circularity strategies aim at 1) improving resource efficiency by improved product use and manufacture through refuse (R0), rethink (R1) and reduce (R2), 2) extending the product lifetime through reuse (R3), repair (R4), refurbish (R5), remanufacture (R6), and re-purpose (R7) as well as 3) reducing waste generation and promoting material use through recycling (R8) and recovery (R9) (Potting et al., 2017). These activities are also as often referred in the literature as narrowing, slowing, and closing resource loops (e.g., Triguero et al., 2022).

The academic discussion related to sustainability or circularity in the semiconductor industry is rather fragmented, and there is little discussion about collaborative or ecosystemic innovation models. So far, circular innovations for semiconductors have yet to be explicitly included in foresight studies about circularity and innovation potentials for critical products in strategic technologies (Baldassarre et al., 2023). The prospects of the European semiconductor industry have been studied recently, and the importance of collaborative efforts among various organizations was highlighted as key success factor. Such collaboration is crucial due to the dynamic nature of the industry and the continuous improvement of products (Huggins et al., 2024).

The recent approaches highlight that to enable circularity across the various stages of the semiconductor value chain, circular principles need to be applied during the design stage (Schröder et, 2024). However, opportunities for circular innovation beyond design stage of a certain product, assembly or manufacturing equipment are seldom considered. At the other end of the lifecycle, some companies now offer semiconductor chip recovery and harvesting services, certifying recovered chips for client reuse or resale (Paben, 2023). However, to promote broader acceptance and shape secondary markets for recovered and refurbished semiconductor chips, it is essential to implement standardization and quality assurance programs that guarantee the reliability, compatibility, and performance of these refurbished components (Schröder et, 2024).

This far, in the context of semiconductor industry, the identified circular economy solutions are water reuse, materials recycling and equipment reuse and remanufacturing, or renewable energy. From resource management focus, especially, water resources and rare earth minerals use within semiconductor companies, research has examined how effective use of production factors impacts on production efficiency (Cho et al., 2021). Similarly, from the criticality perspective there are several approaches that can be used from sourcing partnerships and the more effective use of critical materials to research and development of novel technologies for substitution that seeks to replace or reduce the use of the materials (Ku et al. 2018).

Circular innovation within ecosystems

The ecosystem has already become a well-known analogy to explain the interrelated, complex and dynamic relationship among actors. The importance of innovation collaboration within the circular economy has been emphasized by numerous researchers, and there are several conceptualisations highlighting the role of ecosystems. Brown et al. (2019) introduced “collaborative circular oriented innovation,” which integrates circular economy practices into innovation. Konietzko et al. (2020) and Eisenreich et al. (2021) further discuss the concept of "circular innovation ecosystems", emphasising stakeholder engagement as essential for successful circular innovation and even approaching circularity as a property of a system, rather than a single product. Correspondingly, Runiewicz-Wardyn (2023) emphasized that open circular innovation ecosystems rely on resource sharing, knowledge transfer, and collaborative co-creation among actors to develop new technologies and solutions for the circular economy.

These approaches are aligned with need for an industry or system-level change to translate situated innovations into new forms of value creation (Adams, et al., 2016). Likewise, research on innovation ecosystems highlights the importance of (re-) alignment of value creating practices among multiple partners who must interact for a focal value proposition (Adner, 2016). However, there is still limited understanding about how and why ecosystems emerge (Jacobides, et al., 2018) and how they evolve (Paasi et al., 2022).

Framing circular innovation in semiconductor industry ecosystems

The transition to a circular economy in semiconductors requires systemic changes across the value chain and active participation from all stakeholders to address the barriers effectively (Konstari & Valkokari, 2025). Thereby, the conceptualisations of circular innovation ecosystems (Brown et al., 2019; Konietzko et al. 2020; Eisenreich et al. 2021; Runiewicz-Wardyn, 2023) gains practical relevance when positioned within a multi-layered ecosystem beyond semiconductor value chain.

Our preliminary research framework (Figure 1) for circular innovation in semiconductor industry ecosystems distinguishes three layers, i) at the core there is resource efficiency in semiconductor (fabrication) value chain, then ii) material circularity solutions optimizing the use (Cho et al., 2021) or exploring novel solutions for substitution to replace or reduce the use of the materials (Ku et al. 2018) and finally iii) open cross-industry circular innovations (Runiewicz-Wardyn, 2023; Konstari & Valkokari, 2025) that enable circular business over single industrial value chain.

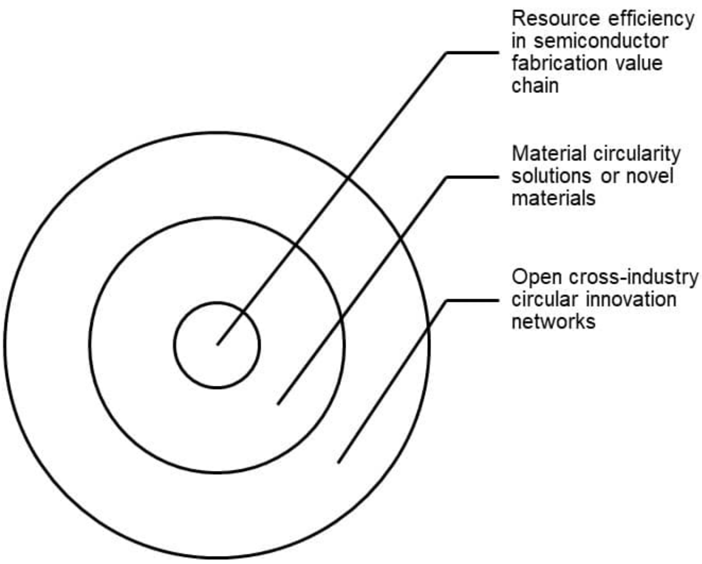

Figure 1 Three layers of circular innovation in semiconductor industry ecosystems.

Subsequently, the layered structure has recently been highlighted also by Thakur and Wilson (2024), who bridged together the two fields of study, i.e. circular economy ecosystem and innovation ecosystem.

3 Methodology

Research design

We focused on the complex and emerging issues of circular innovation and aimed to assess this phenomenon from several perspectives. The study is based on a qualitative research approach. Case study as a research approach focuses on real-life events and takes the context (Yin, 2018), that is, the semiconductor industry into consideration. Moreover, this design responds to the empirical challenge of mapping and analysing diverse stakeholder constellations and insights that shape circular innovation in the context of semiconductor industry.

Finnish actors can provide an interesting area for the study as Finland ranks high on circular economy agendas (Lafortune et al., 2022) and has launched a national agenda several years ago (Ministry of the Environment, 2021). Furthermore, the circularity actions within the semiconductor manufacturing can be identified also as a form of industrial research and development ecosystem[1]. Within this ecosystem boosting circularity is one of the core topics, aiming to make an impact on the consumption of most significant hazardous chemicals, selection of most environmentally friendly chemicals as well as material and energy flows.

The aim of this paper is to advance understanding circular innovation in a multi-actor ecosystem setting and, in particular, the challenges related to involvement of various actors. We focus specifically on circularity of CRMs, and formulate three research questions:

1. What are currently the biggest challenges regarding circular innovation in the context of semiconductor industry?
2. What kind of circular innovation activities are identified as relevant in semiconductor industry?
3. What changes does the circular innovation bring from perspectives of different actors in semiconductor industry value chains and ecosystems?

Data collection and analyses

We conducted semi-structured interviews (n=17) among semiconductor value chain actors, who actively operate or have interest in circularity of CRMs to enhance sustainability, security of supply or resource efficiency (Table 1). We followed purposive sampling (Yin, 2018) and selected the interviewees based on two predetermined criteria.

[1] Chip Zero program aims to create the first semiconductor ecosystem in Finland with a mission to develop chips with zero lifetime emissions. The aim is to lower the deposition emissions of semiconductor manufacturing by 50% and increase the handprint of chips by double digit percentages by 2030, thus leading to an overall zero lifetime emission. https://www.chipzero.tech/

First, the selected actors ought to have been previously identified as having interests or activities for CE in the context of semiconductor industry. Second, the actors were required to be from Finland, i.e. they were operating within the same regulatory environment.

The interviewees were managers and experts in eight semiconductor value chain companies, two research and technology organizations (RTO1 and RTO2), and one public funding agency (O1), one public sector actor (O2), one industry association (O3), and one consulting company (O4). The eight companies had different roles in value chain, i.e. one Design (I1), five Equipment and Material suppliers (I2, I3, I4, I5, I6), and two Integrated Device Manufacturers (I7, I8).

Table 1 Data sources

Organisation	*Number of interviews/actor types*	*Identificators*
Industry	8 company interviews (12 interviewees),	I1, I2, I3, I4, I5, I6, I7, I8
RTOs	2 RTOs, together 5 interviews (5 interviewees)	R1 and R2
Other	1 funding organisation, 1 public sector actor, 1 industry associations, 1 consulting company (together 4 interviewees)	O1, O2, O3, O4

Source: Data sources.

All 17 interviews were recorded, transcribed, thematically coded, and preliminarily analysed to assess data saturation and adjust the interview strategy (Creswell & Poth, 2016). The key topics of thematic coding were following the three research questions, whereas the preliminary research framework was used for analyses. Following the guidelines of Gioia et al. (2013), our data analytics consisted of first- and second-order analyses aiming to aggregated views of circular innovation in the context of semiconductor industry. First, we identified statements related to perception on opportunities and challenges in circular innovation and then grouped these second order themes through identified activities related to R Strategies (Potting et al. 2017) (summarized in Table 2). Finally, we linked the identified collaborative circular innovation opportunities with our preliminary framework (Figure 1). Figure 2 presents these layered opportunities for circular innovation in semiconductor industry ecosystems.

To improve validity, the researchers included expertise in innovation management, sustainability, and semiconductor technology. This kind of investigator triangulation facilitated data analysis and explanation of its different aspects (Archibald, 2016). As the study objective was heavily influenced by the need to shed light on the current state and future potential of circular innovation, we focused not on theory development but on applying theories from the relevant research fields in the context of semiconductor fabrication. Furthermore, the practical validation of interview findings was done in a workshop with six industrial, two stakeholder and seven research participants.

4 Findings

4.1. Challenges related to circular innovations in semiconductor industry

Interviewees identified both industry-specific challenges and shared activities, such as packaging recycling, related to main challenges of circular innovation (RQ1). In this study, we focus on the semiconductor industry specific aspects. Thus, circularity and sustainability were seen in general level as competitive advantage – especially in Europe by some of the interviewees as the below references reveal.

> “European customers have stricter environmental and circular economy requirements.” I5
>
> "Customers aim for closed loop thinking, as mentioned in responsibility reports." I6
>
> "In Europe, the level of knowledge and values regarding environmental issues are high, which leads to greater motivation to implement circular solutions." I7
>
> “Competitive advantage arises from producing sustainably or responsibly... customers may not always pay a premium, but other value is created, such as longer contracts." RTO2

On the other hand, it was stated, that although concerns about environmental impacts are growing, the primary emphasis remains on technological development.

> “Technological development is the main priority; environmental issues are secondary—we are lagging behind.” I6

When considering the global competition between semiconductor industry ecosystems and especially the circularity of CRMs, the interviewees noted that there are conflicting practices and geopolitical tensions. Additionally, it is noted that from a European perspective, there is a lack of competences and/or customers at both ends of the value chain.

> "The Chip Act could bring ICT design back to Europe. There is no longer commercial ICT manufacturing in Finland… it is difficult to influence global suppliers." I8
>
> "The refining of rare earth metals must be moved to China... there is no refining chain here. Mining operations are difficult to carry out, even though there is mineral potential. A strategic step would be to rebuild the refining chain from the ground up. ...The United States has already done this—they have invested money, time, and effort to revive the chain that was allowed to deteriorate. Finland and Sweden preserved their expertise—that is why we are an interesting and capable player in enrichment and refining. The only way to compete with China is through a centralized European effort—shared ownership and risk distribution. Should a joint venture be established at the European level—a shared refinery that spreads the risk?" RTO2
>
> “A system-level examination is needed: what kinds of metrics can be set for sustainability? How can the tightening sustainability requirements of regulation be balanced with strengthening competitiveness?” O2

4.2. Activities related to circular innovations in semiconductor industry

In relation to the second research question, circularity activities associated with multiple R Strategies (see Table 2) were identified through application of the framework

This paper was presented at the XXXVII ISPIM Innovation Conference, held in Granada, Spain on 07 June to 10 June 2026. ISBN 978-952-65771-2-8.

established by Potting et al. (2017). The interviewees stated that electronics recycling is well established in Europe, covering especially waste electrical and electronic equipment, (WEEE) and increasingly also in manufacturing processes such as silicon side stream recycling. Also, close-loop recycling of certain process chemicals has begun to emerge on small scale.

> "Amount of outcome improves, resulting in more production with fewer resources... this also reduces supply risk." I3
>
> “Silicon side streams have long been separated and recycled, rather than disposed of as waste. Measures recorded in responsibility reports include the goal to increase internal reuse of processes.” I5
>
> “Chemicals are being recovered and recycled from cleaning processes—but it is still on a small scale.” I6
>
> "We have large amounts of precious metals waiting for a decision – data security is a challenge, with IP stored on the wafer…. Discussion about technologies for recovering critical raw materials and closing the loop in Finland.” I8
>
> "The Netherlands and Germany are advanced in recycling. Semiconductor boards are priced according to their precious metal content." O4
>
> "Recycling is possible, alternative materials can be developed... the business case becomes real in the face of a crisis... EU funding for these themes is increasing... new solutions are being developed related to existing mining sites." O3

However, it was also noted that recycling solutions may require competences that are out of core of the organisations at semiconductor sector. Regional networks were noted as a crucial factor for the Finnish semiconductor industry's competitive advantage.

> "We have a recycling company involved; the next step relies on their expertise, because we are not a recycling company." I2
>
> “Heat recovery has been developed for a long time in Finland…there could be demand for this type of expertise because the processes are very energy intensive.” I3
>
> "Finland would also be an attractive location for specialized manufacturing—thanks to clean electricity, water resources, and infrastructure." O3

Additionally, it was pointed out that in global business environment, OEMs often lack visibility into the circumstances of their products and materials after their end-of-life, complicating CRM recycling.

> "Products are sent around the world – it is hoped that they end up being properly recycled… the products are designed to be dismantled." I8
>
> "Complex value chains and the long lifecycle of products make it difficult to recover raw materials at the end." RTO1

However, interviewees noted that *repurposing* components and materials is addressed during end-of-life and maintenance phases.

> “During the dismantling phase, valuable components are recovered, but their quantity is so small that utilizing them is challenging.” I7
>
> “Small valuable components are extracted from manufacturing devices, but there is no recycling system for them.” RTO1

The potential for *remanufacturing* was noted by some interviewees, highlighting that production lines and equipment represent considerable investments.

> “Could the frames or casings of manufacturing devices be reused, in a remanufacturing-type manner?” I7

> “The devices are physically large, contain replaceable parts, and require recycling—this is closer to the traditional circular economy of mechanical engineering.” O3

Similarly, *refurbishment* was mentioned as an opportunity to utilise production investments for a longer period.

> “Instead of acquiring a new product equipment or line, upgrades can be made to add more features.” I7

The *repair and maintenance* of production equipment were recognised as essential for extending operational life, even though these activities are not commonly classified as circular innovation practices.

> “The devices are long-lasting and undergo frequent maintenance… it isn’t branded as circular economy, but in practice, that’s what it is.” I4

> "A capital-intensive sector: production equipment must be kept for at least 10 years, often longer, to ensure a return on investment." I7

> “Our products are very long-lasting… maintenance and calibrations keep their lifespan extended. A new service improves the circular economy business model.” I8

> "The hardware does not wear out, but software updates may force replacements—which is problematic from a circular economy perspective." RTO1

Then, *reuse* was mostly addressed at the material level, requiring collaboration with external partners or other industrial value chains.

> “The semiconductor industry focuses on core processes; the full potential of recycling is not being utilized. A more thorough review of material flows could yield significant benefits.” O4

Similarly, strategies for *reduce* were considered at the material level, emphasizing the need for innovative solutions such as complementary chemicals.

> “For example, by optimizing processes, it would be possible to reduce chemical consumption.” I2

> “Alternative chemicals are being sought, but finding options is difficult and expensive.” I5

> “There is a need for process solutions and methods to reduce and eliminate harmful substances …Water consumption… PFAS is a major issue….” I4

Finally, the interviewees associated the concept of *rethinking* strongly with innovative solutions that involve technological development and research beyond industrial borders.

> “Greener chemicals are needed, but external funding is required to advance this.” I2

> "Biodegradable materials are under development, but the quality is not sufficient yet. Additive manufacturing would save copper and wastewater." I8

> "New technologies create a need for environmental information. A lot of discussion has taken place with companies… regarding their footprint – how many resources and rare metals are used." RTO1

> "The biggest obstacle is that fractions cannot be transported for testing – restrictions on transporting hazardous substances halt development. To establish a centralized refinery or circular economy facility, it must be possible to transport these material flows." RTO2

The interviewees did not clearly outline the *refuse* strategy, though they emphasized that avoiding hazardous or rare materials is important and partially guided by regulations. The analyses confirmed also that 3Rs (reduce, reuse and recycle) are the most adopted and accepted strategies of circular economy. The identified circular innovation activities and their contribution to narrowing, slowing and closing resource loops are summarized at the table below (Table 2). The table indicates also linkages to the three layers of the preliminary research framework (Figure 1).

Table 2 Summary of data analyses based on R strategies, i.e.

R Strategy	*Identified Circular Innovation Activities*	*Key actors and layers*
R9, Recover	Energy recovery → closing the loop	Internal processes and/or regional (cross-sectoral) users
R8, Recycle	Material recycling (including CRMs) → closing the loop	Material circularity solutions or RDI partnerships for novel materials
R7, Repurpose	Components and materials during end-of-life and maintenance phases → slowing or closing the loop	Service providers for material or component circularity solutions
R6, Remanufacturing R5, Refurbish	Upgrading, refurbishing or remanufacturing production lines and equipment →slowing the loop	Semiconductor production machine providers and local maintenance service networks of production equipment
R4, Repair	Maintenance and repair of production equipment and lines for extended lifetime → slowing the loop	Semiconductor production machine providers and local maintenance service networks of production equipment
R3, Reuse	Material (including water) reuse → slowing or closing the loop	Internal processes and/or regional (cross-sectoral) users of materials and chemicals
R2, Reduce	Complementary chemicals and materials → narrowing the loop	RDI partnerships for novel materials and chemicals
R1, Rethink	Technological development and research beyond industrial borders → narrowing or closing the loop	RDI partnerships and novel business networks (data sharing)
R0, Refuse	Avoiding hazardous or rare materials	RDI partnerships for novel complementary solutions, materials, process technologies and equipment

Source: Data sources.

4.3 Collaboration for circular innovation within semiconductor industry ecosystems

Through our empirical research, we have delineated multiple models of collaborative circular innovation networks within semiconductor industry ecosystems, as shown in Figure 2, thereby providing insight into the third research question. The industry is starting to view circularity as a core design principle, integrating it from innovation through the entire value chain instead of managing waste only after production. As indicated in the table 2 this requires involvement of different actors as well as networks with different objectives and collaboration structures.

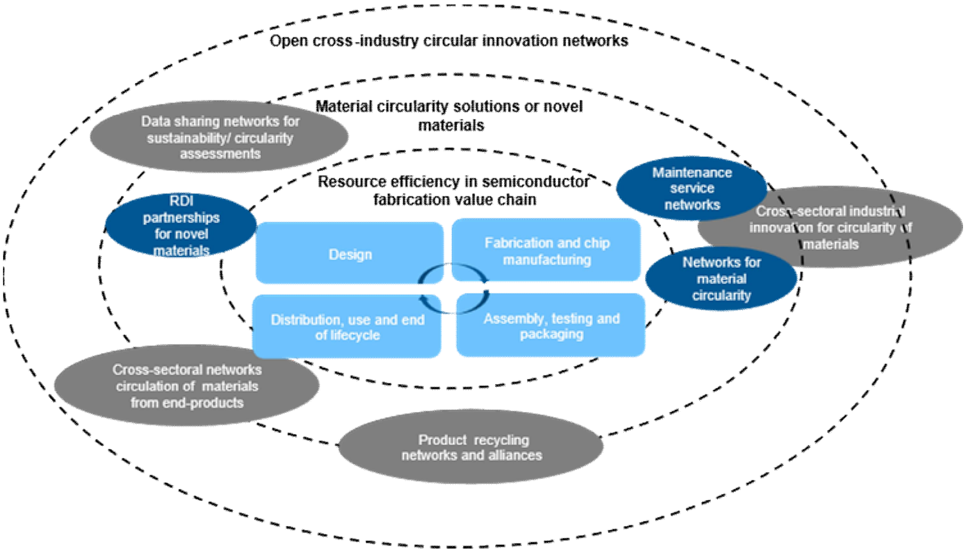

Figure 2 Collaborative circular innovation networks within three layers of semiconductor industry ecosystems.

At the core value chain, the R strategies for narrowing and closing resource loops for chemicals, energy and materials are considered.

> "Recycling is one aspect when it comes to materials – it is important to bring more reusable material into the beginning of the value chain. It is possible for many materials, but it is not yet cost-effective – technological development is needed. We can introduce new materials, for example biodegradable ones... if recycling is not possible, they could be sent to landfill with a clear conscience." O1

Some essential activities and capabilities fall outside the core value chain, so networks are necessary to improve material circularity or develop novel substituting materials. For instance, the interviewees stated that research organisations could provide science-based understanding on technological solutions, whereas companies should engage their value chain actors.

> “EU projects provide additional information and help to understand the issue better through partners.” I2

> “It would be beneficial to have a more extensive study on the development of materials—so that a small team doesn't have to search for the same things.” I8

This paper was presented at the XXXVII ISPIM Innovation Conference, held in Granada, Spain on 07 June to 10 June 2026. ISBN 978-952-65771-2-8.

Therefore, advancing circular innovations in semiconductor industry ecosystems calls for a fundamental rethinking of how materials, processes, and partnerships are designed and managed.

> "Device manufacturers, operators, and material suppliers need to be involved—a big project, ecosystem-level. A startup could be possible, but the scale of funding and product development is so large that established players are in a better position." RTO1

> "Building a process line can cost €10 million... capturing small side-streams is not always worthwhile. Value-based allocation doesn't work... side-streams can have negative value..." RTO2

> “Technological solutions are needed, along with actors who know how to connect and build the ecosystem. Innovations can also be exported globally, there is a regional example of innovations related to unique refining system that would be a significant benefit for Finland’s industry.” O4

The need for cross-sectoral collaboration was identified as it was noted that reuse of CRMs within semiconductor value chain is not practical due to the small quantities of the materials, demanding environmental requirements, and long validation processes. Consequently, it was stated that strengthening regional collaboration and clusters could enhance circularity towards industrial symbiosis and decrease environmental impacts of logistics:

> "A sufficient amount of industry is needed in the same area; cargo planes will not be running on biofuel in the near future → geographic co-location brings environmental benefits." I7

> Materials are flown by airplane... transportation has a significant impact on the footprint." I4

> “Data is needed from hotspot locations. Major players should be involved, and commercial technologies should be available at reasonable prices." I8

> ”Shared facilities and equipment bring resource benefits." RTO1

> "The quantities are physically small; the market can be managed by a small, specialized operator." O3

The interviewees also pointed out that data sharing within and across value chains can enhance sustainability assessments and create new opportunities for addressing environmental impacts.

> "It's difficult to access data networks unless you're part of the value chain... it's hard to obtain information about waste streams. Sustainability reporting obligations do not provide detailed enough information to be useful." O3

> “Device consumption data is needed for carbon footprint calculation; without visibility, calculation is impossible.” I1

It was highlighted that the long lifetime and intensive maintenance of the production equipment create significant circularity activities. Thereby, it was mentioned as a concrete example of circular innovation opportunity that dismantling and maintenance work of semiconductor fabs produces as a side-stream CRMs, but there is no recycling chain for them. Therefore, small amounts remain in warehouses because no one takes them for processing. It was stated that concrete examples that demonstrate business opportunities of circular innovation would support the engagement of actors. Thereby, it is important to note that identified circularity activities can focus on materials used in fabrication process, production equipment or end-products. Finally, it was pointed out that there are conflicting interests that may hinder the transition towards circular innovation.

> "Devices can remain in the field for decades; they are serviced and parts are replaced. This is circular economy activity that has been practiced for ages. There is expertise in extending the lifespan, but it's a double-edged sword: how much should it be promoted, when new products always sell better." O3

5 Discussion and conclusions

Our study revealed how circular innovation for the CRMS often means moving beyond the existing semiconductor value chain, as different R strategies demand new activities and actors. The layered structure of our research framework completes the current understanding on circular innovation ecosystems (Brown et al., 2019; Konietzko et al. 2020; Eisenreich et al. 202; Hansen & Schmitt, 2021; Runiewicz-Wardyn, 2023; Dorrego-Viera et al., 2025) by highlighting the variety of collaboration opportunities. As such, the findings illustrate various ways in which the activities of other actors in the ecosystem have a major impact on how value is created, captured, or destroyed, with significant potential to ensure security of supply of CRMs.

Furthermore, such strategies built on regional strengths may provide niche strategies that ensure competitiveness and enhance resilience against geopolitical disruptions. Semiconductor production relies on a range of materials, many of which are subject to supply constraints and geopolitical risk. Therefore, aligning considerations with strategic resource security goals reframes circularity as not only an environmental imperative but also a geopolitical and economic one. This view completes previous studies highlighting the production efficiency as a driver for circularity (Cho et al., 2021).

However, circular innovation demands actions and leading roles by multiple actors at the three layers as the required activities vary from regional collaboration practices to global trade policies. Thereby, parallel innovations from material science to business models and policy instruments occur within the diverse networks with multiple decision-makers or scattered decision power among various actors. This three-layered structure completes the previous study by Thakur and Wilson (2024) and provides an illustrative case study on the context where global and local circumstances are highly dynamic and competitive.

Practical implications

The findings benefit professionals and managers interested in understanding antecedents of circular innovation in the semiconductor industry by illustrating the key players in the emerging ecosystems and their roles in circular value creation. For companies involved in the ecosystem, the findings provide understanding which actors are important in their local ecosystem for advancing circular innovation and support for designing ecosystem activities that are viable. Governmental representatives can take advantage of our study to understand the complexity of the topic and need of multidisciplinary approach to advance circularity of CRMs in the European semiconductor industry through collaboration. For them, the findings are important for designing policy tools that support the transition toward more sustainable semiconductor industry, consumption, and recycling. By integrating insights of CRMs into industrial and innovation strategies, particularly within Europe, policymakers can strengthen supply resilience, reduce external dependencies, and support the development of a more self-sufficient semiconductor ecosystem.

Avenues for future studies

Therefore, further research on this topic is needed as circularity of CRMs in the context semiconductor industry requires insights beyond semiconductor value chain and novel ecosystems can be built by understanding the regional strengths and opportunities for secondary use of these valuable materials. This may enhance industrial symbiosis and challenge the entire competitive logic of the industrial sectors. However, further studies are needed to provide the depth of analysis in specific areas, those bridging together detailed industry context and regional aspects.

Acknowledgements

We want to thank Business Finland for financial support for this study under the ZeroChip project. In addition, thanks to consortium members as well as other interviewees for their time and their support.

References

Adams, R., Jeanrenaud, S., Bessant, J., Denyer, D. and Overy, P. (2016) Sustainability-oriented Innovation: A Systematic Review, International Journal of Management Reviews, 18(2), 180–205.

Adner, R. (2016). Ecosystem as Structure: An Actionable Construct for Strategy: An Actionable Construct for Strategy. *Journal of Management*, *43*(1),39–258. https://doi.org/10.1177/0149206316678451 (Original work published 2017)

Archibald, M.M. (2016)). Investigator triangulation: A collaborative strategy with potential for mixed methods research. Journal of Mixed Methods Research, 10(3), 228–250. https://doi.org/10.1177/1558689815570092

Baldassarre, B., Buesa, A., Albizzati, P., Jakimów, M., Saveyn, H., & Carrara, S. (2023). Analysis of circular economy research and innovation (R&I) intensity for critical products in the supply chains of strategic technologies. European Commission and Joint Research Centre.

Bocken, N.M.P., Pauw, I. Bakker, C. & van der Grinten, B. (2016). Product Design and Business Model Strategies for a Circular Economy. *Journal of industrial and production engineering*. 33(5) 308–320.

Brown, P., Bocken, N., Balkenende, R. (2019) Why Do Companies Pursue Collaborative Circular Oriented Innovation? *Sustainability*, 11(3), 635. https://doi.org/10.3390/su11030635

Creswell, J. W. & Poth, C. N. (2016). *Qualitative Inquiry and Research Design: Choosing Among Five Approaches*. SAGE Publications.

Dorrego-Viera, J. I., Urbinati, A., & Lazzarotti, V. (2025). Tailoring collaborations with stakeholders for open circular innovation ecosystems. *Industry and Innovation*, 1–24. https://doi.org/10.1080/13662716.2025.2563678

ECS SRIA (2025). Electronic Components & Systems Strategic Research and Innovation Agenda 2026. Available at https://ecssria.eu/ECS-SRIA-2026.pdf

Eisenreich, A., Stuchtey, M., Füller, J. (2021). Open Circular Innovation: How Companies Can Develop Circular Innovations in Collaboration with Stakeholders. *Sustainability*, 13(23). https://doi.org/10.3390/su132313456

Hansen, E. G., & Schmitt, J. C. (2021) Orchestrating Cradle-to-Cradle Innovation Across the Value Chain: Overcoming Barriers through Innovation Communities, Collaboration Mechanisms, and Intermediation. *Journal of Industrial Ecology* 25 (3): 627–647. https://doi.org/10.1111/jiec.13081.

Huggins, R., Johnston, A., Munday, M. & Xu, C. (2023). Competition, open innovation, and growth challenges in the semiconductor industry: the case of Europe's clusters, *Sci. Public Policy*, 50(3), pp. 531-547, 10.1093/scipol/scad005

Jacobides, M. G., Cennamo, C. and Gawer, A. (2018) Towards a theory of ecosystems, Strategic Management Journal, 39(8), pp. 2255–2276.

Konietzko, J., Bocken, N., Hultink, E.J. (2020). Circular Ecosystem Innovation: An Initial Set Of Principles, *Journal of Cleaner Production* 253(20). https://doi.org/10.1016/j.jclepro.2019.119942

Konstari, P. & Valkokari, K. (2025). Value creation and capture from sustainability-oriented innovations in a shared semiconductor infrastructure, *Sustainable Technology and Entrepreneurship*, 4 (2), https://doi.org/10.1016/j.stae.2025.100104.

Kumar, A. Thorbole, A & Gupta, R. K., (2025). Sustaining the future: Semiconductor materials and their recovery, Materials Science in Semiconductor Processing, 185, https://doi.org/10.1016/j.mssp.2024.108943.

Ku, A.Y., Loudis, J. & Duclos, S. J. (2018). The impact of technological innovation on critical materials risk dynamics, Sustainable Materials and Technologies, 15, 19-26, https://doi.org/10.1016/j.susmat.2017.11.002.

Lafortune, G., Fuller, G., Bermont-Diaz, L., Kloke-Lesch, A., Koundouri, P. & Riccaboni, A. (2022) Achieving the SDGs: Europe's compass in a multipolar world. Europe Sustainable Development Report 2022. SDSN. [Accessed 20 March 2024]

https://s3.amazonaws.com/sustainabledevelopment.report/2022/europe-sustainable-development-report-2022.pdf.

Ministry of the Environment (2021) Resolution 8 April 2021. Ministry of Employment and the Economy. Government resolution on the strategic programme for circular economy. https://ym.fi/en/strategic-programme-to-promote-a-circular-economy.

Paasi, J., Wiman, H., Apilo, T. and Valkokari, K. (2023) Modeling the Dynamics of Innovation Ecosystems, International Journal of Innovation Studies,

Paben, J. (2023). New firm provides chip 'recovery as a service.' *E-Scrap News*, 15 June 2023. https://resource-recycling.com/e-scrap/2023/02/01/new-firm-provides-chip-recovery-as-aservice/

Pascucci, S. Alexander, A. Charnley, F. & Fishburn, J. (2023). The circular economy: landscape, dimensions and definitions, Handbook of the Circular Economy: Transitions and Transformation, Walter de Gruyter GmbH & Co KG.

Patrahau, I., Singhvi, A., Rademaker, M., Van Manen, H., Kleijn, R., & Van Geuns, L. (2020). Securing Critical Materials for Critical Sectors Policy options for the Netherlands and the European Union. The Hague Centre for Strategic Studies.

https://hcss.nl/wpcontent/uploads/2021/01/Securing-Critical-Materials-for-Critical-Sectors.pdfPaben, 2023

Potting, J., Hekkert, M., Worrell, E., Hanemaaijer, A. (2017) Circular Economy: Measuring Innovation in Product Chains. The Hague. PBL Publications 2544.

Runiewicz-Wardyn, M. (2023). Linking Circular Innovation with 'Open Innovation' Paradigm. *Journal of Circular Economy*, 1(1), https://doi.org/10.55845/UTDS4006

Schröder, P. Charter, M. & Barrie, J. (2024). Circularity of Semiconductor Chip Value Chains: Advancing AI Sustainability Amid Geopolitical Tensions, *Journal of Circular Economy*, 2(2) https://doi.org/10.55845/MNTS1778

Thakur, P. & Wilson, V.H. (2024). Circular innovation ecosystem: a multi-actor, multi-peripheral and multi-platform perspective. *Environ Dev Sustain* **26**, 14327–14350 (2024). https://doi.org/10.1007/s10668-023-03196-y

Triguero, Á., Cuerva, M. C., & Sáez-Martínez, F. J. (2022). Closing the loop through eco-innovation by European firms: Circular economy for sustainable development. Business Strategy and the Environment, 31(5), 2337–2350. https://doi.org/10.1002/bse.3024

Yin, R. (2018) Case study research and applications: design and methods. Sage Publications, Los Angeles