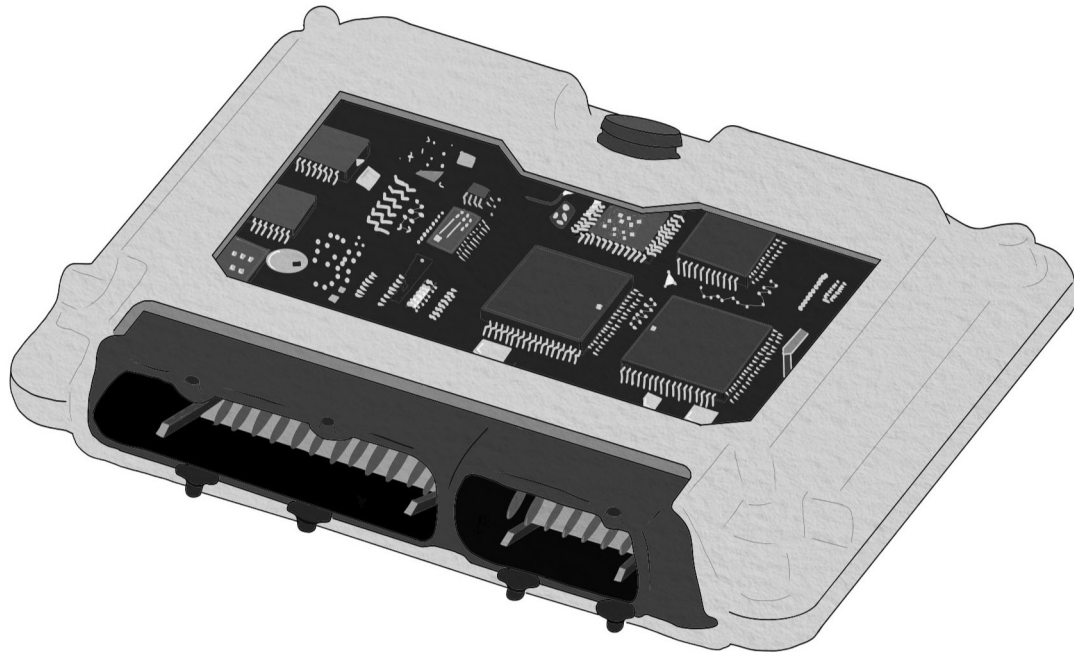




CHALMERS
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Circularity Potential in Upstream Electronic Control Unit Supply Chain in the Automotive Industry

A Case Study of the Circularity Potential of the Critical Raw Materials Gallium and Germanium

Bachelor's thesis in Industrial Economy

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Supply Chain in the Automotive Industry**

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Materials Gallium and Germanium

**Potential för cirkulära flöden i uppströms leveranskedja för
elektroniska styrenheter inom bilindustrin**

Fallstudie om potentialen för cirkulära flöden för de kritiska
råmaterialen gallium och germanium

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Cover: Illustration of an Electronic Control Unit (ECU) and its internal components.

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Abstract

The automotive industry's rapid shift towards electrification has created a widespread dependence on semiconductors. This is making the supply chain vulnerable to disruptions in the availability of Critical Raw Materials (CRMs) such as gallium and germanium. Today, China dominates the global production of these materials, while the recycling rate from End-of-Life (EoL) electronics is almost non-existent with a rate of 0% for gallium and 2% for germanium. The geopolitical risk makes it of interest for the EU to become more independent within this supply chain. An identified approach to this is implementing circular flows.

In this bachelor's thesis, the aim is to investigate the potential for circular flows of gallium and germanium in the upstream supply chain for Electronic Control Units (ECUs). Through a qualitative case study based on literature studies and semi-structured interviews with stakeholders throughout the supply chain, the current situation, and potentials regarding circular flows, have been mapped. Further, both opportunities and challenges with these have been analyzed.

The results show that current circular practices are mostly limited to recycling of production waste, but that there is significant technical potential in emerging methods such as Flash Joule Heating (FJH), AI-based sorting and recovery from industrial residues, such as red mud and jarosite residue, and End-of-Life (EoL) sources. The main challenges to large-scale implementation are the very low concentrations of material in individual components, the lack of economic viability compared to primary materials, and design choices that prioritize protection over disassembly.

Keywords: semiconductor, gallium, germanium, electronic control units, ECU, circularity, recycling, critical raw materials, supply chain, supply resilience

Sammanfattning (Swedish Abstract)

Bilindustrins snabba övergång till elektrifiering har skapat ett utbrett behov av halvledare. Detta gör leveranskedjan sårbar för störningar i tillgången av kritiska råmaterial såsom gallium och germanium. Idag dominerar Kina den globala produktionen av dessa material, medan återvinningsgraden från End-of-Life (EoL) elektronik är nästan obefintlig med siffror på 0% för gallium och 2% för germanium. Den geopolitiska risken gör det av intresse för EU att bli mindre beroende inom denna leveranskedja. En identifierad metod för detta är att implementera cirkulära flöden.

I detta kandidatarbete är syftet att undersöka potentialen för cirkulära flöden av gallium och germanium uppströms i leveranskedjan för elektroniska styrenheter. Genom en kvalitativ fallstudie baserad på litteraturstudier och semistrukturerade intervjuer med intressenter i hela leveranskedjan har den nuvarande situationen och potentialen gällande cirkulära flöden kartlagts. Vidare har både möjligheter och utmaningar med dessa analyserats.

Resultaten visar att nuvarande cirkulära metoder mestadels är begränsade till återvinning av produktionsavfall. Det finns dock betydande teknisk potential i nya metoder som Flash Joule Heating (FJH), AI-baserad sortering och återvinning från industrirester, såsom rödslam och jarositrester, samt End-of-Life (EoL) källor. De största utmaningarna med storskalig implementering är de mycket låga koncentrationerna av material i enskilda komponenter, bristen på ekonomisk lönsamhet jämfört med primärmaterial och designval som prioriterar skydd framför demontering.

Nyckelord: halvledare, gallium, germanium, elektroniska styrenheter, ECU, cirkularitet, återvinning, kritiska råmaterial, leveranskedja, leveransmotståndskraft

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List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order:

CRMs	Critical Raw Materials
CRMA	Critical Raw Materials Act
DRC	Democratic Republic of Congo
ECU	Electronic Control Units
EoL	End-of-Life
ELV	End-of-Life Vehicles
EU	European Union
EV	Electronic Vehicles
FJH	Flash Joule Heating
Ga	Gallium
Ge	Germanium
OEM	Original Equipment Manufacturer
PCB	Printed Circuit Board
STL	Société du Terril de Lubumbashi - Company Based in DRC
Tier-3	Primary producers involved in raw material extraction
Tier-2	Suppliers of PCBs and semiconductors used in manufacturing ECUs
Tier-1	Final-stage manufacturers producing ECUs
US	United States
4N	99.99% (four nines) purity
5N	99.999% (five nines) purity
8N	99.999999% (eight nines) purity
9N	99.9999999% (nine nines) purity

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1

Introduction

This chapter will introduce the topic and the background behind it, together with purpose, research questions and limitations.

1.1 Background

The automotive industry is undergoing a massive transition towards electrification, automation, and connectivity. This has made vehicles extremely dependent on semiconductors, which play a key role in many Electronic Control Units (ECUs). This growing dependency is fragile, as the supply chain of several raw materials used in semiconductors are highly complex (King et al., 2021). ECUs control everything from engine functions to advanced safety systems. In addition to this, it also manages batteries in Electric Vehicles (EVs) which is a driving factor behind semiconductors' ever increasing relevance in the current landscape (Rahman et al., 2024). With this transition towards electrification, it is estimated that electronic components will account for 45% of the manufacturing cost of a car by 2030 (King et al., 2021).

According to Andersson and Lennström (2025) the supply chain of semiconductors is characterized by a lack of transparency and limited upstream visibility. This entails that automotive manufacturers get heavily dependent on their suppliers without having clear knowledge about the actual geographical origin of the components or the underlying actors in the supply network (Andersson & Lennström, 2025). Without a broad insight into the supply chain, it becomes more challenging to assess circular opportunities and sustainable solutions such as recycling of Critical Raw Materials (CRMs).

During the semiconductor shortage of 2020-2023, many vulnerabilities in the supply chain of semiconductors were exposed. When initially, COVID-19 created a decreased demand for vehicles, Original Equipment Manufacturers (OEMs) canceled orders of semiconductors. Semiconductor producers (Tier-2) redirected this capacity to meet the rapidly growing demand for consumer electronics (Burkacky et al., 2022). The automotive demand recovered faster than anticipated, and at this stage the semiconductor capacity and supply was already committed elsewhere. This resulted in a severe supply shortage for the OEMs. Today, there are four main segments with higher demand for semiconductors compared to automotive, with wireless communication at the top. As a result, the automotive industry could be

given a lower priority in case of a future, similar crisis as semiconductor shortage in 2020-2023 (Burkacky et al., 2022).

The possibilities of circularity in the semiconductor supply chain is currently limited. In the thesis written by Andersson and Lennström (2025) it becomes clear that there is a limited amount of interest among stakeholders regarding further analysis of circularity and the supply chain overall. Where companies choose short-term solutions over long-term consideration related to sustainability and circularity and supply risk. A reason for this could be how easily lock-ins emerge in the supply chain due to inertia-related factors. (Burkacky et al., 2022). To analyze this issue, it is necessary to look upstream in the supply chain.

1.1.1 The upstream part of the supply chain

Two raw materials that play a key role in modern semiconductors are gallium and germanium (Yadav et al., 2026). Both materials appear on the European Union list of Critical Raw Materials (CRMs) (“European Critical Raw Materials Act”, 2023). Gallium and germanium are both mostly produced and refined in China which makes their supply highly concentrated (Andersson & Lennström, 2025).

According to Purchase et al. (2020), several metals used in electronics are facing a high supply risk. Despite the high supply risk of gallium and germanium, technical and economic barriers to formal recycling which entails dismantling or mechanical processing, remain formidable. Purchase et al. (2020) highlights that in developing countries, often designated as “waste-hotspots”, materials are recovered by informal recycling such as acid stripping or open-fire burning, which causes environmental contamination in the surrounding areas. As noted by Purchase et al. (2020), companies in China that try to recycle electronic waste by formal recycling have a low profit margin, making informal recycling more viable. The lack of profitable business models supporting circular economy is noted in Ribeiro da Silva et al. (2023) to be the biggest bottleneck. International Energy Agency (IEA) (2023) notes that recycled CRMs within Europe, such as gallium and germanium, are not economically competitive with primary materials. This cost disadvantage limits the market uptake for secondary raw materials and constrains the development of circular value chains.

Despite China being dependent on imports of very large portions of the bauxite that it processes, the country nonetheless has a near monopoly in regards to the refining itself encompassing around 90% (International Energy Agency (IEA), 2023). According to Center for Strategic & International Studies (CSIS), China has become the dominant supplier over raw materials needed for manufacturing semiconductors. They also claim that it is crucial to understand the supply dependency, and that the risks varies depending on the critical material. Not only should the supply risks be evaluated and calculated, but also the price sensitivity (Berg et al., 2024).

Purchase et al. (2020) calculated a Relative Supply Risk (RSR) index through a combination of: recycling rate, production concentration, political stability, reserve distribution, and abundance in the Earth’s crust. On a scale from 1 to 10 of RSR index, where 10 indicates a very high supply risk, gallium and germanium were given risk scores of 7.6 and 8.1, respectively (Purchase et al., 2020). Since August 2023, gallium has been a frequent subject of China’s export controls. The price has therefore been affected and it has doubled since July of that same year.

Gallium has the highest distribution risk compared to other materials required in manufacturing semiconductors. The risk of disruption has heightened since China has increased their investments heavily towards semiconductor industry to enhance wafers manufactured of Gallium Nitride (GaN) (Berg et al., 2024). As for germanium, it is mainly used for other purposes which could act as a risk for the automotive industry. Infrared imaging and fiber optics are the main fields in which germanium is used, making a small amount reach the manufacturing of semiconductors. Section 2.1.2 describes how germanium holds higher efficiency in semiconductors. As the industry, as a whole, reaches towards more efficiency, germanium demand could increase significantly making them compete even more for the market shares. China is a key player in this field as well since they have a strong capacity of refining zinc, which germanium is extracted from. The International Energy Agency (IEA) (2023) claims that policies and regulations need to be revised to be able to increase recycling of critical materials within the EU.

This is important to have in mind reading this thesis since it could influence the need for circularity, to thereby reduce long-term supply risks and reduce the EU’s dependency on other countries.

1.1.2 Theoretical background

The central concept of this thesis is circularity, or circular economy. Its antithesis is linear economy which approach revolves around "take-make-dispose". The latter fails to include sustainability which has led to the development of the circular economy model. This economy focuses on long-lasting products which is then reintegrated into the supply chain, creating a circular loop. When discussing circularity, the 9Rs are often mentioned. 9R is a framework prioritizing strategies to reach a more circular economy (Rashid & Malik, 2023). The strategies included are: refuse, rethink, reduce, reuse, repair, refurbish, remanufacture, repurpose, recycle and recover. (Muñoz et al., 2024)

1.2 Aim and purpose of the thesis

The aim of the thesis is to investigate and provide an overview of circularity potentials in the upstream supply chain of the critical raw materials gallium and germanium, connected to the production of ECUs. The study seeks to identify where in the supply chain opportunities and limitations for circularity exist. Through a combination of supply chain mapping, semi-constructed interviews, and literature

study, the thesis aims to evaluate the potentials and constraints associated with recycling gallium and germanium from different parts of the supply chain for ECUs. An additional objective is to identify stakeholders and assess their interest in circular flow of said CRMs.

Furthermore, the thesis examines how factors such as quality and, to a certain extent, cost influence effects the adaption of recycled materials, particularly gallium and germanium. This analysis is intended to clarify the requirements that stakeholders may have for integrating circular flows into their supply chains.

The results of the thesis will be presented as a mapping of circularity potentials and limitations for gallium and germanium connected to ECUs. The report will furthermore present an analysis of how circular strategies for critical raw materials can support stakeholders in understanding the current state of the field and future sustainable production.

1.3 Research Questions

Increased electrification in the automotive industry is resulting in an ever growing demand for ECUs and thus a reliance on a secure supply chain is pivotal. While OEMs generally have a good grasp of the products that are to be procured from Tier-1 suppliers, there seems to be a lack of understanding of the extended supply chain upstream (Andersson & Lennström, 2025). Such knowledge gaps could result in lack of preparedness for supply disruptions for the automotive industry. The problem arising is therefore the lack of mapping points where gallium and germanium currently have a circular flow in the supply chain for ECUs. It is an important step to offer alternative procurement methods. Instead of relying on extracted raw materials, the focus would be on reusing them. This in turn could result in the diversification of supply. It would also answer questions in regards to the feasibility of strategies and stakeholders that value circulation and the best practices that are presently utilized in the market. Furthermore it would lead to a more comprehensive understanding of the current state of the industry. The research questions is therefore going to be as followed:

Research Question 1: What is the current state of circularity in the supply chain for gallium and germanium in the production of ECUs, and why?

Research Question 2: Where in the supply chain is there potential for circularity practices for gallium and germanium, and what are the challenges and potentials with implementing and upscaling these?

Research Question 3: Why is it of interest for the stakeholders to invest in circularity questions pertaining to gallium and germanium?

1.4 Limitations

The project is conducted within a limited time frame, which constrains the depth of the analysis. In addition, restricted transparency and confidentiality within the supply chain of gallium, germanium and ECUs limits the access to detailed internal processes and material flows. There are also limitations within literature data, where specifically numbers regarding recycling capacity or material prices may vary due to the lack of transparency in the chain and limited consolidated information or databases. As a result, the desk research relies on public available information, which may affect the level of details in certain parts of the system mapping.

The study focuses on the materials gallium and germanium connected to automotive ECUs with a global scope, since actors engaging in these processes are geographically dispersed. The focus is however largely from a European perspective and emphasizes circularity as a method for supply resilience, thus other circular perspectives are covered less. The objective is to identify and map key processes and possibilities for circularity at each step of the supply chain which can help diversify supply for industry actors. This delimitation leads the study to prioritize how circular flows of gallium and germanium could help mitigate risk in ECU supply chains.

Another important angle regarding limitations is how the economic aspect of the thesis is approached. The economic aspect will not be reviewed in quantifiable economical variables, however economics will play a role in describing certain aspects of implementation as well as the current situation.

Due to time constraints, the study focuses only on a limited number of critical raw materials present in ECUs. Other materials and components are excluded. The study prioritizes a more detailed analysis of selected material over a broader but more superficial material feasibility of all ECU constituents. As a result, the study can provide a deeper insight into the circularity potential of strategically important resources. Additionally, the time constrained the number of conducted interviews with stakeholders.

2

Theory

This section outlines the theory that underpins this study. It introduces the key concepts and theories used to analyze the research problems. The chapter begins with an overview of the functions and architecture of the Electronic Control Unit (ECU), followed by a description of its main components: Printed Circuit Board (PCB) and semiconductors. It then presents the Critical Raw Materials (CRMs), and their theoretical context. Lastly the chapter introduces relevant policies and frameworks.

2.1 An overview of Functions and Architecture of the Electronic Control Unit (ECU)

An ECU serves as a monitor, controller and coordinator of several subsystems within vehicles (Naqvi et al., 2024). The ECU facilitates real-time decision making regarding energy distribution and manages safety parameters, for instance, it controls wheel speed to implement stability and prevent loss of traction. Due to the critical nature of these tasks, the ECU must be engineered to maintain high reliability under adverse environmental conditions. This necessitates a design capable of withstanding high temperatures, high frequency vibrations, and withstand humidity without failure. Additionally, the unit must achieve a balance between high-performance processing for safety features and low power consumption to maintain overall subsystem efficiency (Naqvi et al., 2024).

In the context of Electric Vehicles (EVs), the ECUs role extends to advanced battery management. It monitors thermal and electric stages to prevent overheating and overcharging. Furthermore, the ECU optimizes the vehicles energy efficiency through regeneration of kinetic energy to extend the driving range (Naqvi et al., 2024). EVs can possess up to 150 different ECUs today, and the numbers are increasing as the vehicles become more complex (Sugunaraj & Ranganathan, 2022). Figure 2.1 shows a simplified illustration of an ECU.

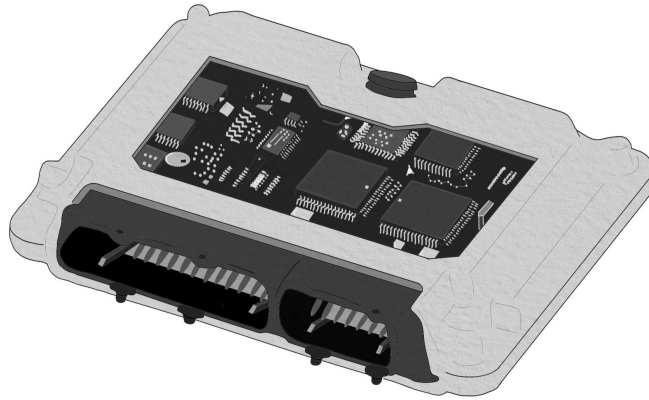


Figure 2.1: Author’s illustration of an ECU. The top part of the housing is cut-out to show the PCB. On the side, the connectors are seen which are used to plug-in the ECU.

2.1.1 Printed Circuit Boards - the Brain of the ECU

ECUs consist of a PCB. The PCB is the place where the electronic components, such as semiconductor chips, are physically attached, thus acting as the brain of the ECU (Brindley, 2011). To protect the PCB, a shell of plastic or metal is used, which together with connectors form the ECU (Kaiser, 2015).

2.1.2 Semiconductors

Materials can be divided into conductors, insulators, and semiconductors based on their ability to conduct electricity. The latter group is important since it can be utilized to transfer electrical currents in a controlled manner which is key in electrical devices. Semiconductors can be elements or compounds, and there are different types of them. Silicon is the most common, but gallium and germanium are also important alternatives. The base material of a semiconductor heavily affects its overall capability where certain variants, for example, can withstand more heat and handle higher voltages (Butcher & Brown, 2014). Germanium is, for instance, desired due to its functionality on smaller semiconductors, since it has more electron mobility compared to silicon. It allows more power on the same area. Therefore germanium occupies both a niche as well as an important role within the semiconductor industry (Berg et al., 2024).

Furthermore, these properties can be affected by changes in temperature and purity, both of which can be done intentionally. Doping, for instance, is a critical process in the creation of desired semiconductors. It entails the addition of supplementary substances to the base material, intentionally introducing impurities to alter its properties. By doing so you can enhance conductivity, precision, and create transistors, the very foundation of modern electrical engineering. The semiconductive material itself is therefore not enough, it needs to be modified for the device to have the same range of functionality that is accessible in modern technology (Paloheimo, 2020; Streetman, 2001).

When the term semiconductor is used, it is not the material itself that is being referred to. It is rather the semiconductor device as a whole. A more accurate term would be an integrated circuit. A single transistor can function like a switch that can be turned on and off and thus regulate the electrical current that is passing through. On is usually represented by the number 1 while off is 0. By creating a lot of transistors and connecting them to each other, you end up getting an integrated circuit, a network of switches where complex decisions can be made (Streetman, 2001).

2.2 Introducing the Critical Raw Materials, (CRMs)

Two of the prominent CRMs used to produce semiconductors are gallium and germanium. These are of extra interest due to their limited and vulnerable supply. This is mainly a consequence of geopolitical concerns because they are highly concentrated by extraction and refining in China (Andersson & Lennström, 2025). Both materials are by-products from other metal industries which makes them dependent on dynamics in other markets, increasing their supply risk. Both gallium and germanium are included in the list of CRMs by the European Union (“European Critical Raw Materials Act”, 2023).

2.2.1 The Critical Raw Materials Act, (CRMA)

According to Wachtmeister (2025) China has long maintained a predominant position in the production and refinement of critical materials, many of which are indispensable to global high-tech manufacturing companies. In 2023, largely in response to technology export restrictions and tariffs from the US, China began implementing its own restrictions on key elements such as gallium and germanium. The restrictions have since grown more extensive and now include elements such as graphite, antimony, and even Rare Earth Element (REE) magnet manufacturing technologies. Although these restrictions were initially meant to target the US they have caused significant disruptions in the European supply chains. This has led to price increases for several essential materials worldwide (Wachtmeister, 2025). The European Union (EU) has long recognized the strategic vulnerability in its heavy reliance on external supply. To mitigate its dependency and strengthening its position the European Critical Raw Materials Act (CRMA) was adopted in 2023, establishing a regulatory framework aimed at strengthening the EU supply of critical and strategic raw materials. The CRMA sets specific targets aimed at strengthening the EU’s supply chain. By 2030 the goal is that:

- 10% of the annual EU consumption is to be extracted within the EU.
- 40% of consumption is to be supplied through EU based processing.
- At least 25% is to be provided through recycling.
- No more than 65% is sourced outside of EU.

(European Union, 2024)

2.2.2 Gallium

Gallium (Ga) is a metallic element that normally is found as a trace element in ores, such as aluminum or zinc. As a result gallium can only be found in very small amounts, which in turn makes it uneconomic to mine as the primary subject for extraction (Butcher & Brown, 2014). Therefore, the production of gallium is dependent on other mining industries (Andersson & Lennström, 2025). Further gallium is a chemically unstable element and therefore requires specific and costly processes to produce (Butcher & Brown, 2014). Approximately 95% of gallium is produced from bauxite processing during alumina production (Andersson & Lennström, 2025), called Bayer processing (Zuo et al., 2025). Recent reductions of the Bayer process in China have raised concerns regarding future gallium availability (Zuo et al., 2025). This dependency makes the Gallium supply chain structurally tied to fluctuations in market of other raw materials. The supply chain of gallium is shown in figure 2.2.

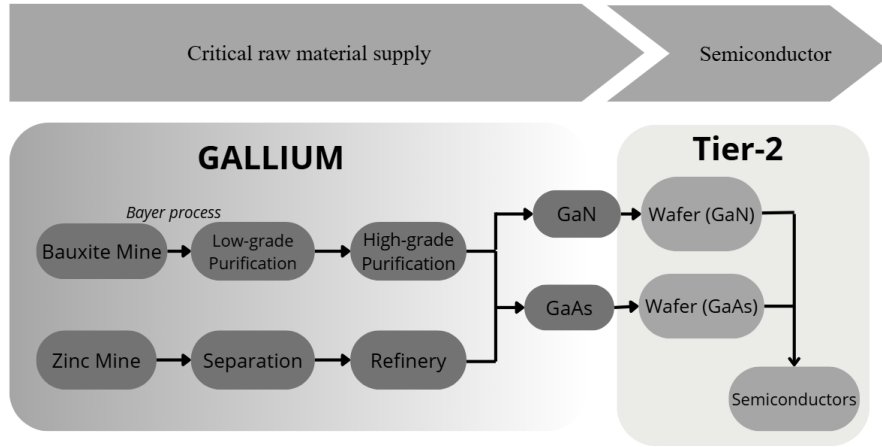


Figure 2.2: Schematic overview of the gallium supply chain, illustrating its extraction as a by-product from bauxite and zinc mining, and subsequent purification (refining) steps, and its use in semiconductor wafer production (GaN and GaAs). Author’s adaption from (Andersson & Lennström, 2025).

Gallium is found in two grades within the critical raw material supply: “low-grade gallium” (primary material) and “high-grade gallium” (refined low-grade gallium), as seen in figure 2.2. China dominates the production of low-grade gallium, with an estimated percentage of 99% of the global production. The country is also responsible for 51% of high-grade gallium production (Andersson & Lennström, 2025). Despite the fact that China has the upper-hand on the production of low-grade gallium, Andersson and Lennström (2025) notes that China is reliant on other countries such as USA, Japan and Canada for high-grade gallium.

In semiconductor applications, gallium is primarily used in compound materials such as Gallium Nitride (GaN) and Gallium Arsenide (GaAs) wafers, which enable high-performance electronic components. The chemical properties of gallium allows

it to handle higher voltages, more heat, and allows for a faster transportation of electrons and thus a higher frequency of signals (Butcher & Brown, 2014). Its very high boiling point allows it to withstand these extreme environments. GaN and GaAs are increasingly used in power electronics, high-frequency systems, battery management systems, and advanced sensing technologies in vehicles (Rahman et al., 2024). The transition toward electric vehicles is a major driver of demand, particularly for devices including GaN wafers that offer improved efficiency and thermal performance compared to conventional silicon-based solutions.

The accumulated global gallium extraction has seen a dramatic rise, growing from 100 tons in 2000 to 4,179 tons in 2019. This results in an annual growth rate of 21,7%, and it is estimated that the demand could increase by 200% by 2050 (Zuo et al., 2025). This growth trajectory strengthens concerns regarding supply security in the long term.

The infrastructure of recycling gallium is very limited. Where the global recycling rate of gallium End-of-Life (EoL) products were estimated to be between 0-1% (Royal Swedish Academy of Engineering Sciences (IVA), 2024; Zuo et al., 2025). As noted by Purchase et al. (2020), the companies in China that try to recycle electronic waste by formal recycling has a low profit margin, making informal recycling more viable. The lack of profitable business models supporting circular economy is noted in Ribeiro da Silva et al. (2023) to be a big bottleneck.

This combination of geographic concentration, dependency on other metal industries and rapidly increasing demand positions gallium as a critical material in the upstream automotive electronic supply chain. An increased circularity could therefore require interventions at multiple stages of the supply chain.

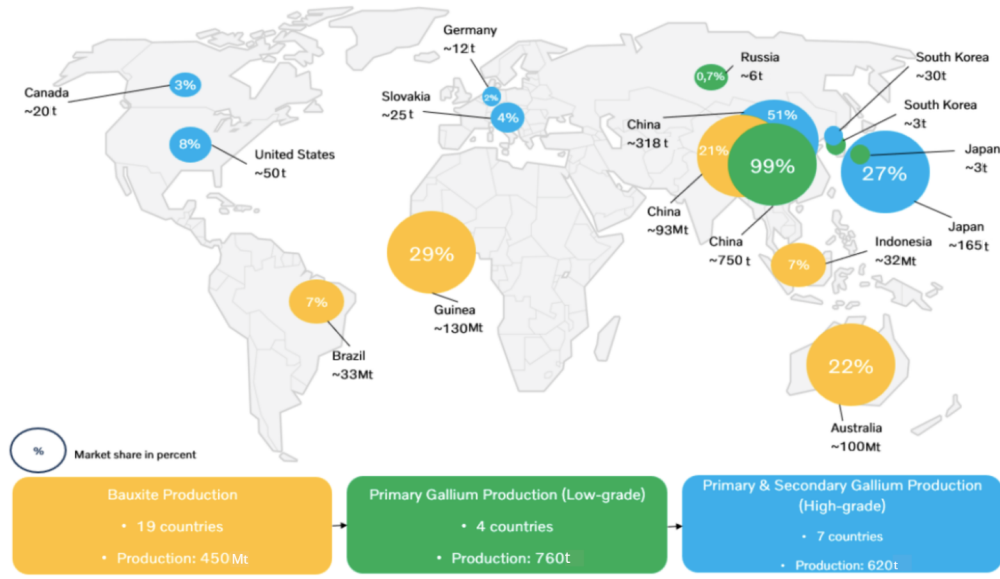


Figure 2.3: Global production of bauxite, low-, and high-grade gallium (Andersson & Lennström, 2025). *The units in this figure have been corrected. Bauxite Production is reported in megatons (Mt), Low-grade and High-grade in tons (t).

Figure 2.3 is a map disposed from Andersson and Lennström (2025) master’s thesis that shows an overview of the global reserves and production of gallium. The bauxite production is distributed over 19 countries with the main actors in Guinea, China and Australia. From Figure 2.3 it becomes clear that a major bottleneck in the supply chain of gallium is that 99% of the primary gallium production (Low grade gallium) takes place in China. The high grade gallium production occurs mostly in China with 51% but Japan is also a contributor of 27%.

2.2.3 Germanium

Germanium (Ge) is a rare metalloid with efficient electrical conductivity making it suitable for high speed semiconductor applications. The metalloid is mainly recovered as a by-product from zinc refining and coal ash which structurally limits production scalability and makes supply rigid and dependent on the output of other industries (Encyclopaedia Britannica, n.d.). It has become increasingly economically significant since the recognition of its semi-conductive properties in 1945, driven by its escalating use in electronics, fiber optics and other advanced technologies. Today infrared optics and fiber optics are still the primary applications of germanium with 36.76% and 54.59% of the market shares, respectively (Mei et al., 2024). Nevertheless, it can also be used as a dopant for semiconductors, which this thesis places greater emphasis on (Andersson & Lennström, 2025). The supply chain of germaniumF is shown in figure 2.4.

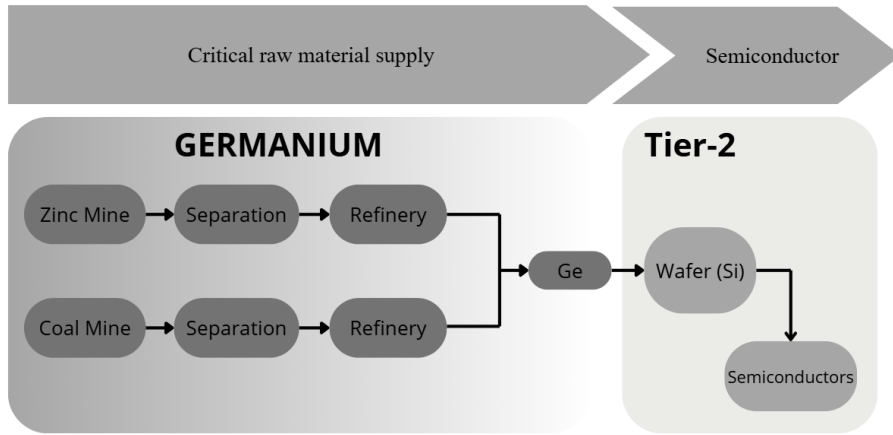


Figure 2.4: Schematic overview of the germanium supply chain, illustrating its extraction as a by-product from zinc and coal mining, and its subsequent purification (refining) steps, and its use in semiconductor silicon (Si) wafer production. Author’s adaption from (Andersson & Lennström, 2025).

The demand for germanium has grown fast the last decades. In China between the years 2002 and 2021 demand went from 19.16 to 85.87 tons. During this time frame 1086.92 tons have been extracted from coal ash, 585.27 tons from zinc concentrates and only 13.45 tons sourced from end-of-life products (Mei et al., 2024). The increase is also seen in global market demand in recent years. From 2022-2024 compound annual growth rate of germanium consumption has been 12.12%, with estimates landing at 259.27 tons in 2026. This increase is primarily driven by the solar-energy sector and would result in a supply shortage of 48.47 tons (Xun et al., 2026). However, this sector is not the only one experiencing rapid growth. The automotive industry has undergone significant development over the past 30 years, where the last years focus has been on electrification of vehicles. This also affects the germanium market (Richert & Lebkowski, 2025).

Global germanium reserves are difficult to accurately estimate, partly because it is only a by-product of other mining activities (Höll et al., 2007). Known reserves are concentrated to China, with around 41% share, and Russia, with 10% share. Europe on the other hand are instead reliant on imports due to a lack of significant reserves (Srivastava & Ilyas, 2025).

Today, recycled germanium mainly comes from new scrap, meaning leftover materials from production. Only a small fraction is recovered from end-of-life products. The reason for this is the generally small unit use in electronic components (Höll et al., 2007). Germanium has been classified as a strategic and critical raw material under the European Critical Raw Material Act (CRMA). With China being the main producer of germanium worldwide and the estimate of the European recycling rate being approximately 2% there is a significant gap between the current supply situation and the EU’s strategic targets under CRMA (Bergfald et al., 2024). There are ongoing projects initiated by the EU to diversify germanium supply by sourcing from the Democratic Republic of Congo (Andersson & Lennström, 2025).

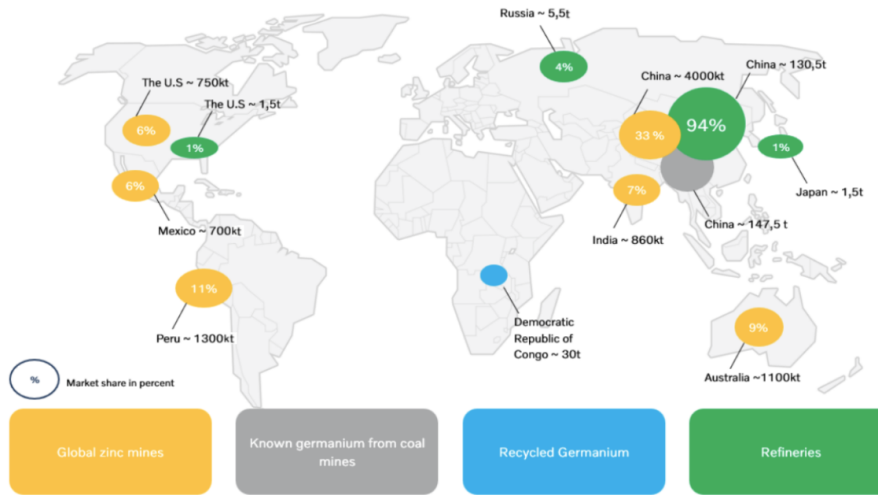


Figure 2.5: Global reserves of zinc mines and germanium refineries (Andersson & Lennström, 2025). *The units in this figure have been corrected. Russia’s Refineries have been corrected to tons (t), Mexico’s and Peru’s zinc mine units have been corrected to kilotons (kt).

Figure 2.5 is a map disposed from Andersson and Lennström (2025) master’s thesis that shows an overview of the global reserves and production of germanium. The global zinc mines are spread out over a number of different continents but the refineries and germanium extracted from coal mines are dominating in China. 94% of all refining takes place in China.

2.3 Chinese Dominance of Critical Raw Materials

The global supply of critical raw material is highly concentrated with production of materials such as germanium and gallium, often limited to a small number of countries. China’s dominance in several critical mineral supply chains did not emerge from a sudden revelation of resource abundance but rather a tactical development spanning over decades (Zhou et al., 2025).

A central factor has been the use of state led industry policy. China has implemented targeted measures to support domestic production including investment in processing capacity, support for strategic industries, as well as policies aimed at strengthening control over key segments of the supply chain (Zhou et al., 2025). China’s strategy has not been limited to resources extraction, though this has also played an important role in the development of its overall position in the supply chain. The country has also focused on developing capabilities across the entire chain, particularly in refining and processing, where much of the value creation takes place (Zhou et al., 2025). This has enabled the country to become a central actor in the global supply chain.

China has lately also expanded its influence internationally through investments in overseas mining and resource projects as well as opening up for foreign investors to

invest in the Chinese mining industry, previously one of the country's most protected sectors, mainly in the pursuit of attracting foreign technology to further develop the field (Zhou et al., 2025).

China's dominance in gallium and germanium is particularly substantial. According to Wachtmeister (2025) China accounts for more than 90 % of global production of both materials. This level of concentration significantly increases the supply risk for regions dependent on imports such as Europe. Andersson and Lennström (2025) highlights that China aims to hold this power position, since no other country will be able to catch up during the next 10 to 15 years.

China has increasingly leveraged this dominant position strategically. Chinese export controls introduced in 2023 on minerals demonstrate how control over critical materials can be used as a geopolitical tool. During 2023 China launched export controls on gallium, that drove up the global price and resulted in restricted supply (Andersson & Lennström, 2025). These export controls and the increased demand established a price divergence of gallium domestically and outside of China, in early 2024 gallium outside China was almost double the price compared to the domestic Chinese prices (Powers-Riggs et al., 2025). Germanium export restrictions also had a huge impact on global markets. European industries saw a dramatic 400 % increase in prices for germanium. While prices for gallium and germanium within China seemed to decrease within the same time frame (Wachtmeister, 2025). Although factors such as transportation cost and additional expenses likely contributed to the price divergence, China based companies maintained a particular competitive advantage over their European counterparts during this period (Wachtmeister, 2025). Although the controls were mainly aimed at the United States of America they caused huge consequences for the European markets as prices surged following the export controls.

These measures have led to substantial reductions in export volumes and price increases globally highlighting China's influence over these markets. (Wachtmeister, 2025). There are also examples of China leveraging its position within mining operations to force out international competitors. Examples being the case of cobalt and nickel, which between 2022 and 2025 fell heavily in price, around 60% for cobalt and over 70% for nickel. During this time-frame the only US cobalt mine was forced to shut down as well as several nickel operations in Australia (Baskaran, 2025). This suggest that China is aware of its hold over the markets for these materials and can manipulate these to maintain its position as the leading global distributor.

2.4 End-of-Life Vehicles (ELV) Directive

Within the European Union (EU) several regulatory frameworks have been established to promote circularity in the automotive industry. One example is the directive that addresses End-of-Life Vehicles (ELV Directive), which aims to reduce and prevent the waste arising from EoL vehicles and their components, while improving the environmental performance of stakeholders involved throughout the vehicles life

cycle (European Commission, n.d.). The directive was implemented across European countries in 2002 and has since been subject to adjustments since its implementation (European Union, 2023).

The background to the directive is closely linked to the significant material flows and waste generation associated with the automotive sector. Each year, EoL vehicles generate approximately 8-9 million tons of waste within the EU (European Union, 2023). At the same time, vehicle production is resource-intensive, with the industry accounting for a substantial share of rare metal use (30% within the EU). This highlights the importance of improving material recovery and reducing reliance as a part of a transition towards more circular systems (European Commission, 2023).

In addition to recourse intensity, challenges related to traceability and waste management remain. Approximately 3.5 million vehicles (corresponding to one third of EoL vehicles in the EU) are unaccounted for annually. These vehicles are either exported or disposed throughout informal recycling. For instance, over 800,000 used vehicles are exported annually, primarily to third world countries. Although regulations exist to control such flows, strengthened requirements regarding traceability are considered necessary to ensure that exported vehicles meet appropriate standards. One of the key goals of the ELV is to recover 95% of the weight of the vehicle, where the percentage also includes energy recovery. (European Commission, 2023).

2.5 Managing a Supply Chain

To gain a better understanding of the value that circularity can bring to supply chains, the following section is going to explore some of the fundamental goals in supply chain management. The focus will be on the economic perspective and will cover prevalent short- and long-term objectives. This will also shed light on some of the challenges that might arise and the balancing of up- and downsides.

Traditionally supply chain management focuses on sourcing the materials and managing the processes that create value until the product reaches the end customer (Pellicelli, 2023). A conventional model puts emphasis on inputs, outputs and how different points in the chain create content that is primarily needed by subsequent processes (De Angelis et al., 2018). The overall goal is economic efficiency where costs are minimized and the focus is transactional with a flow that is fairly linear and sequential in nature. This does not mean however that the processes are fixed, as adjustments have to be made based on changing circumstances such as supply risks (Pellicelli, 2023). A basic model entails the following steps:

1. **Plan:** Planning the activities and matching the supply with the demand.
2. **Source:** Creating a product starts by choosing what to source and from whom. This will be mainly driven by the necessity of the required materials and the costs associated with procurement.
3. **Make:** The flow of materials is thereafter followed from the point of extraction to the point where it becomes a finished product. This includes all the processes that handle the materials and parts.
4. **Deliver:** The finished products are delivered to the consumer fulfilling their needs.
5. **Return:** A certain retrieval mechanism can be taken into account if the product is faulty.

(Pellicelli, 2023)

The aforementioned points are in line with a conventional take, make, and dispose model. The flow is linear and has clear start and end points. Changing market requirements however, in the form of environmental regulation, demands from consumers, and economic factors are resulting in a shift that puts emphasis on a more holistic perspective (De Angelis et al., 2018). For instance, supply chains are complex and global (Pellicelli, 2023). They have to decrease waste due to environmental and financial reasons. It is also important to increase their flexibility to be able to deal with uncertainty caused by natural disturbances, price volatility, and supply risks. Strategic objectives are therefore becoming more relevant (De Angelis et al., 2018). This entails that instead of being overtly focused on transactional efficiency, more attention is paid to long-term relationships and cooperation where knowledge and rewards are shared. Rather than exclusively looking at the company's own operations, corporations shift toward seeing the value in competing as a supply chain instead (Pellicelli, 2023). Furthermore, it is a move from being overtly focused on costs to enhancing flexibility and resilience by considering product and process innovations and new technologies. Sustainable financial success is key and some of the aforementioned risks, like regulatory oversight and supply instabilities, can be turned into opportunities by increasing the scope of analysis and taking further factors into account. This in turn can benefit a company's competitiveness. Integrating circularity in supply chain management is an important step and a notable shift from the standard linear models (De Angelis et al., 2018).

2.6 The Circular Economy, 9R Framework

To understand why circularity investments can be valuable in supply chains and what they might lead to, first an introduction to circular economy is provided below.

A circular economy puts emphasis on the idea of using materials for as long as

possible, minimizing the subsequent waste, and recycling what is leftover back into the economy so that it can continue to create value. It is especially relevant in a product where a large percentage of the cost is associated with the raw materials that it consists of. The overall goal is to enact a shift from a linear model toward a circular one (De Angelis et al., 2018).

Beyond minimizing the waste of physical materials, it is also paramount to decrease the amount of energy used both in production and in potential recovery of said content. A prominent model in this field is the 9R framework that is based on the idea of integrating different kinds of circularity practices to facilitate a shift toward a circular economy. These practices are to be prioritized in sequential order, starting with R0: Refuse and ending with R9: Recover (Potting et al., 2017). The aim of this framework is to introduce methods that are environmentally beneficial while being economically viable (Potting et al., 2017).

R0: Refuse - Avoid producing new products if similar solutions already exist.

R1: Rethink - Efficient use of a product by sharing between consumers or designing a multifunctional product.

R2: Reduce - Efficient use of materials by reducing the quantity needed in a product.

R3: Re-use - Extend the use phase of a product by enabling it to be used again by another consumer if the product is still functional and in good condition.

R4: Repair - Extend the product's lifespan by repairing it when defective.

R5: Refurbish - Extend a product's lifespan by restoring the product to its original state by updating the functionality.

R6: Remanufacture - Use parts of an old product to produce a new one with the same or similar function.

R7: Repurpose - a discarded product or its parts used to produce a good with different functions.

R8: Recycle - Process waste into materials that can be used in new products. Said materials could lose a portion of their quality during the procedure.

R9: Recover - Waste that no longer can be processed into usable materials can be incinerated for energy recovery.

(Muñoz et al., 2024)

The Rs can be sectioned into functional categories to better illustrate their intent within circular economy. The main intent of R0-R2 is to reduce the amount of virgin

materials and energy needed in the development of a product. Minimizing the input of resources at the design and development stages can ease the pressure on natural resources. Moreover, well thought through designs act as a foundation for enabling the effective implementation of subsequent Rs. R3-R7 aim to extend a product's lifespan, allowing it to continue to contribute value to the customer through reusing or reworking the product. R8 and R9 purpose is to recontribute to the cycle when Rs of higher hierarchy no longer are suitable options. These may be seen as a last resort but are crucial parts for closing the loop. Improving the efficiency and quality of material recovery in R8 can reduce the need for virgin material extraction and thereby lessen the strain on natural resources. R9 makes use of the energy content so that it is not completely lost after leaving the system.

The 9R framework is a hierarchical system that can be used to evaluate the degree of circularity of different practices (Muñoz et al., 2024). The integration of a method represented with a lower R-number entails a lesser usage of materials and resources and thus an investment that is more circular in nature (Potting et al., 2017). While that should be the priority, being able to implement said system in practice requires a certain amount of compromises to be done. A company needs to match their own resources and capabilities with the appropriate circular practices. While an R that is higher up in the hierarchy is preferable, the company might lack the resources to be able to integrate it in its own operations (Muñoz et al., 2024). There might also be strategic concerns and thus lack of willingness. Issues can also arise due to a dependency on other entities in the supply chain having to do a certain part of the work. For instance, prolonging a product's lifespan might require some of the parts to be designed in a certain manner which would be outside of a single entity's control. That is more so covered by the integration of the circularity in the supply chain at large which is going to be a challenging endeavor requiring a certain amount of direct and indirect cooperation beyond the company's boundaries (De Angelis et al., 2018).

2.7 Circularity in Supply Chain Management

There are currently many companies that make use of the circular economy concept in their operations. This is accomplished by creating more durable products, offering repair services, and having recycling facilities that take care of waste. The implementation is however still lacking. Corporations are proficient at introducing sustainable solutions in a limited manner and with a certain objective in mind. For instance introducing a system to recycle raw materials at specific facilities (Du et al., 2025). However, a systematic implementation of circularity throughout the entirety of operations is lacking. In general there are knowledge gaps when it comes to theory that connects the circular economy concept to supply chain management. This is prominent when it comes to some managers' poor understanding of the subject which might affect the decision making process (Du et al., 2025).

Studies show that companies can change that by enacting a gradual shift from linear models toward sustainable and thereafter circular ones (De Angelis et al., 2018).

These are rooted in first of all increasing product durability. Repair services could be appropriate to help keep the product in use for a longer period of time. When said product is disposed of by the consumer, it is to be re-used when possible with minimal modifications or refurbished if it is not fully functional. The last step is recycling and is used to regain the raw materials included if the aforementioned steps are not suitable. The research puts emphasis on decreasing the usage of physical materials and other resources utilized in production. The methods mentioned above should therefore be used in priority order (De Angelis et al., 2018). For example, refurbishing a certain good is likely to cost less energy compared to a recycling process where the raw materials are regained. The latter is likely going to require refinement and reproduction which is going to cost considerably more and is therefore less desirable.

Systematic implementation of these steps aim at a transition toward closed loops where a minimal amount of materials and energy go to waste. This is going to require cooperation between different entities in the supply chain which might be difficult to achieve due to operational complexities, geographical limitations, and competition between the different firms resulting in secrecy. Despite the difficulties however, a more cooperative environment is needed. Products and processes have to be designed in a certain way for circularity methods to be feasible (De Angelis et al., 2018). When that is not the case, an alternative is to utilize open loops instead where waste or partially recycled materials are sold to other supply chains in a relationship that can be beneficial to both parties. The reverse can also occur as well where sourcing is done by interacting with other supply chains rather than procuring new raw materials. In this context, recycled, re-used or refurbished content can be bought in. Since sourcing is a major decision, it can play a pivotal role and such procurement strategies might end up creating demand for circularity practices. Over time these can lead to more notable consequences as to how the supply chain operates at large (De Angelis et al., 2018).

3

Methodology

This chapter presents the methodology explaining methods utilized for collecting and analyzing data to ultimately answer the research questions.

3.1 Research Design and Two Case Approach

The objective of this study is to research the potential for circularity in the automotive sector specifically in relation to ECUs. The scope was then limited to the two CRMs gallium and germanium with focus on recycling as the main circularity strategy due to the case design. However, other circular methods are examined to a certain degree as well. R. K. Yin (2014) describes a case study as a investigation into prevailing circumstances. This aligns greatly with what this report is trying to achieve. The basis of this project is tied to real world practices in the supply chain of gallium and germanium with regard to sustainability. The importance of said topic has become increasingly prominent in today's global economy, particularly within the automotive industry. The automotive sectors poor management of the recovery of EoL vehicles is not currently optimal and in some cases untraceable (European Commission, n.d.). To gain insight into the circularity potential, the study was divided into two cases:

- **Case 1:** Gallium's circularity potential throughout the supply chain.
- **Case 2:** Germanium's circularity potential throughout the supply chain.

In this way both materials could be investigated in depth within their respective contexts.

The choice of materials was based on further research derived from a previous study conducted by Andersson and Lennström (2025) who identified resource dependencies in the automotive supply chain of materials used in semiconductors. The study highlighted that further investigation of recycling as a potential to not only mitigate dependencies in the supply chain, but also create a more sustainable supply chain could be of interest to the field. Of the initial 4 materials that were studied, high-purity quartz, antimony, gallium and germanium, two were selected based on their scarcity and significance in the context of ECUs. High-purity quartz was excluded due to its lower criticality and supply risk, while antimony was excluded due to its limited use in ECU components.

3.2 Data Collection

Due to the exploratory nature of this study and the range of different types of data to be collected, a qualitative desk research was chosen as an appropriate method for data collection in addition to semi structured interviews. Figure 3.1 is intended to provide an overview of the categorical distribution of the data collected.

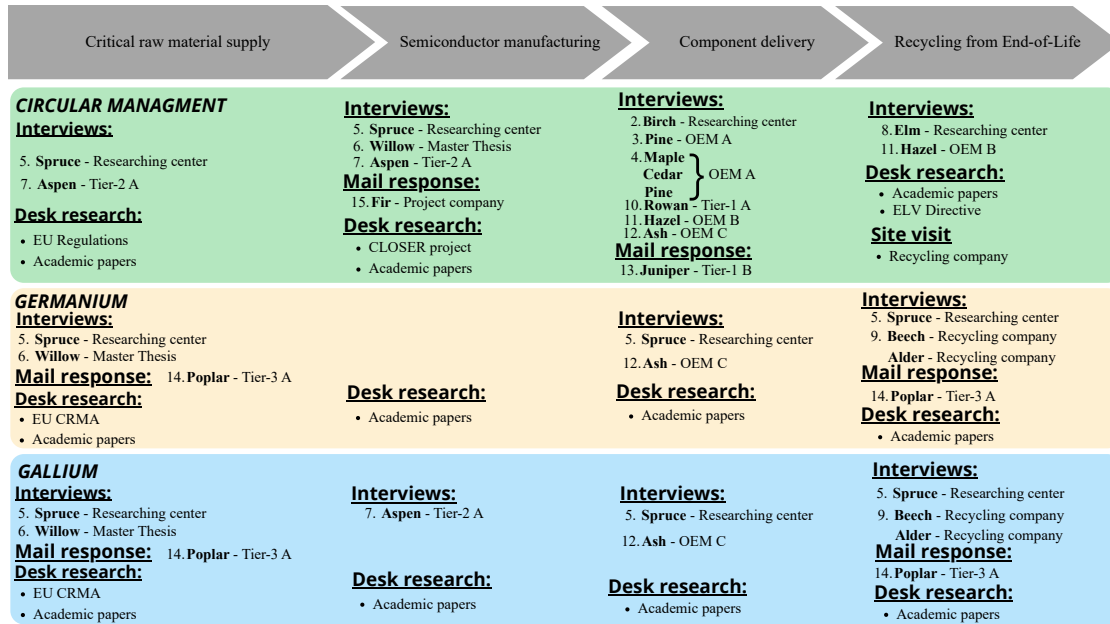


Figure 3.1: Overview of the data sources mapped across the supply chain.

3.2.1 Desk Research

Desk research includes a wide range of data collection activities including gathering and analyzing literature, reports and policies (Moore, 2006). A literature review is not just a method for presenting existing research, but also a tool for identifying patterns, knowledge gaps and guiding future research topics. It creates a strong scientific foundation for further analysis (Snyder, 2019). The literature and scientific articles provided the study with a good theoretical base and provided inspiration to relevant questions for the interviews. The literature review was mainly conducted using electronic databases such as Google Scholar, Science Direct and Scopus. Several different keywords were used to find relevant articles that were useful to the study such as ECU, circularity, gallium and germanium. The snowball method was applied to several searches to find additional relevant articles for the study. The snowball method is a way to find additional relevant literature based citations or references of literature already found (Wohlin et al., 2020). In addition, non-academic literature, such as reports from non respondent companies with valuable information relevant to the study, government and union policies like CRMA and directives such as the ELV directive. The contribution to each case as well as additional circular practices from the desk research is specified in figure 3.1.

3.2.2 Semi-structured Interviews

To observe the behavior, needs, values and practices of the subject, semi-structured interviews were conducted. Merriam et al. (2025) describe semi-structured interviews as a middle ground between structured and unstructured interviews. A semi-structured interview is based on a predetermined set of questions outlined in an interview guide, but allows for more in depth responses and deviations from the initial questions that would not normally be captured in a rigidly structured format. This particular interview style is compatible with case study research, as it allows the adaptability required to form a comprehensive understanding of the subject, which R. K. Yin (2014) emphasizes is a desired attribute to conduct a good case study. The choice of utilizing a semi-structured approach allowed for comparable interview data across interviews, which was important during the final phase of the study when all primary and secondary data were analyzed.

Prior to each interview, an interview guide was prepared based on the specific expertise and role of the interviewee to ensure relevant and informed responses. In some cases, to capture a broader organizational perspective, the interview guides were distributed in advance to allow the interviewees to prepare for topics that extended beyond their specific area of expertise but were of value to the study. During the course of the project, later interview guides contained questions derived from insights obtained in previous interviews. This progression enabled a deeper and more nuanced understanding of circularity potentials in the field.

The interviews in the early phase of the project consisted mainly of researchers in the automotive and sustainability fields, giving a broad perspective on the theoretical possibilities of circularity in the automotive supply chain. The initial interview was conducted with an aim of obtaining initial guidance and recommendations for additional participants. Subsequent interviewees were selected using a snowball sampling approach, as well as own research. Further interviews were finalized in recommendations for subsequent correspondence that could be enriching to the study. Later interviews were mainly with manufacturing companies giving practical insights and industry perspectives.

All interviewees were anonymized to ensure confidentiality, protect their identities and encourage open and honest discussions. The interviewees were given code names in the report to make the findings easier to follow. The code names were chosen to be a variety of tree species in the spirit of circularity and the positive sustainability impacts it reflects. Below is a list of all interviews in the order of which they were conducted, the respondent's positions in their respective companies, the duration and date the interviews were conducted and the bracket tier the company belongs to. The interviews contribution to each case as well as additional circular practices is specified in figure 3.1.

3. Methodology

Interview	Respondent	Job field	Length (min)	Date	Company
1	Oak	Professor, Materials Science	30	2026-02-13	Researching center
2	Birch	Professor, Electrical Engineering	15	2026-02-25	Researching center
3	Pine	Electronics & Software	15	2026-02-26	OEM A
4	Pine	Electronics & Software	30	2026-03-05	OEM A
	Maple	Electronics			
	Cedar	ECUs			
5	Spruce	Professor, Chemical Engineering	60	2026-03-11	Researching center
6	Willow	Former Master students	60	2026-03-12	Master Thesis
7	Aspen	Quality	50	2026-03-24	Tier-2 A
8	Elm	Innovation & processes	30	2026-04-01	Researching center
9	Beech	Electronics	45	2026-04-08	Recycling company
	Alder	Electronics			
10	Rowan	Quality & processes	45	2026-04-13	Tier-1 A
11	Hazel	Sustainability	50	2026-04-14	OEM B
12	Ash	Compliance	45	2026-04-27	OEM C
Email contact					
13	Juniper	Central sales	-	2026-03-30	Tier-1 B
14	Poplar	Metallurgist	-	2026-04-02	Tier-3 A
15	Fir	Management	-	2026-05-01	Project company

Table 3.1: Overview of the conducted interviews and contact via email

3.2.3 Field Research at Recycling Center

One instance of field research was conducted by visiting a recycling center to gain firsthand insight into the general recycling process of electronic waste. This recycling center did not specifically recycle the materials gallium and germanium. They did however recycle zinc which both materials derive from, thus this visit contributed to the overall circular management point of view and not directly to the 2 cases as seen in figure 3.1. Observing the process of recycling electronics contributed to developing a better practical understanding of operational practices and material flows within

a recycling facility. The visit provided additional contextual understanding and served as a compliment to the data collected through interviews and secondary sources. This enabled a broader more comprehensive perspective of the system.

3.3 Data Analysis

Data analysis was conducted using a qualitative, exploratory and iterative approach due to the nature of the study, as described earlier in this chapter. The goal was to gain an in-depth understanding of the circularity potential for gallium and germanium connected to the ECU supply chain. Therefore the analysis required the integration of both primary data obtained from the interviews and the site visit to the recycling center as well as secondary data collected through desk research.

The majority of interviews were voice recorded and later transcribed with the consent of each interviewee. In the cases where consent was denied interview notes were taken. The notes and transcriptions could not in it self be treated as evidence of the whole process, as it is based on individual perspectives thus certain biases and missing aspects of the overall scope may be overlooked. For this reason the primary data from the interviews were reviewed together with the primary data from the field research and secondary data sources gathered during the desk research.

Triangulation is a strategy used in qualitative research to strengthen credibility of the findings. According to R. Yin (2016) the strategy involves identifying multiple ways of verifying a procedure, piece of data, or finding. Evaluating the primary data from the interviews, the visit to the recycling center and secondary data together made it possible to identify patterns, similarities, and recurring themes as well as identifying gaps between theoretical circularity strategies and practical implementations within the industry. This use of triangulation strengthened the credibility of the findings, ensured consistency as well as increased the robustness of the analysis.

Insights from the secondary data were continuously brought into interviews for confirmation and clarification and vice versa, allowing for iterative refinement of the understanding. Relevant illustrative quotes from interviews were used to support and clarify key findings. A collective of a few quotes and key takeaways can be found in Appendix A. Furthermore the analysis was aimed to capture the complexity of the supply chain by considering perspective from company practices, industry dynamics, and systemic factors such as supply risk and regulatory influences. This enables a more nuanced understanding of where circularity potentials and limitation occur within the chain.

3.4 Research Quality

In qualitative research, credibility is a vital criterion referring to how well the findings reflect the reality that is being studied (Bell et al., 2022). In this study credibility was strengthened through the use of multiple sources of different varieties, including interviews, academic literature review, review of documents and policies as well as insights from a site visit. Comparing the findings with a triangulation strategy across multiple sources assisted in identifying consistent pattern and reduced the risk of misinterpretations. Throughout the data collection process a consistent and iterative approach was applied. Interview guides were developed and refined based on data from previous interviews and new insight from the ongoing desk research allowing for comparability across interviews. However, certain limitation must be acknowledged. The findings rely on the perspective of the selected interviewees to a certain extent. This may introduce biases and a result that can be an incomplete representation of the broader system. The study is also limited in scope, therefore the findings are not intended to be generalizable. Instead they might offer insights that may or may not be transferable to similar contexts.

4

Case Description

This chapter begins by presenting results from a master’s thesis by Andersson and Lennström (2025). It introduces a map of gallium and germanium supply chains and some of the prevalent stakeholders associated with them. Andersson and Lennström (2025) presents some of the supply risks and production inefficiencies that create the need for circular solutions. Thereafter it examines the current landscape of circularity and how present challenges, and solutions to them, are directly related to the purpose of this report. Understanding the context is important as this paper builds upon it and focuses on evaluating the circularity potential specifically.

4.1 The Material Flow of the Cases

A walkthrough that follows gallium and germanium from the point of extraction to refinement, and thereafter usage in electronics is presented below. This is illustrated in figure 4.1.

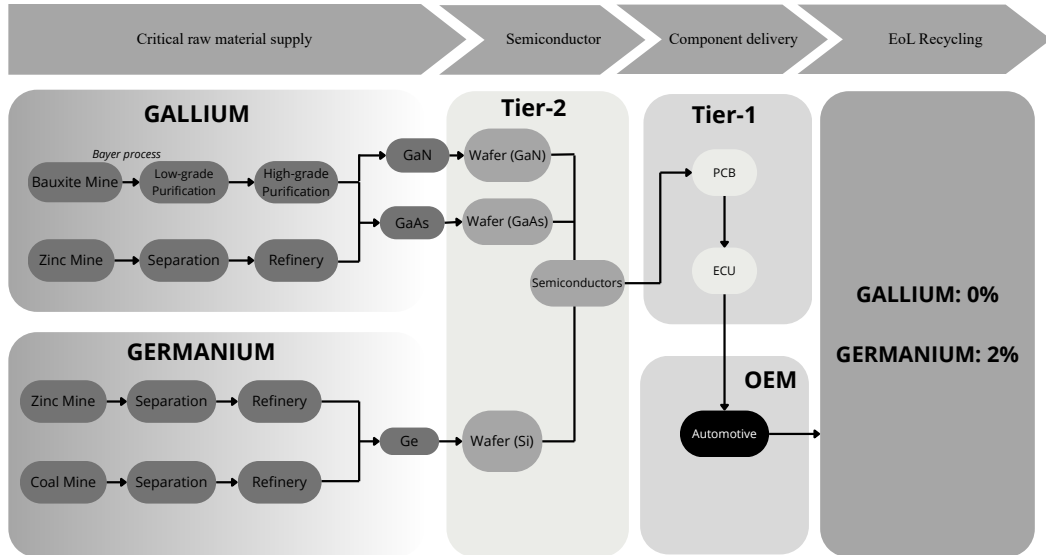


Figure 4.1: Gallium and germanium material flow, Author’s adaption from (Andersson & Lennström, 2025). The recycled content of EoL Recycling of gallium and germanium is gathered from (Royal Swedish Academy of Engineering Sciences (IVA), 2024).

Case 1: Gallium's Circularity Potential Throughout the Supply Chain

The vast majority of gallium is obtained from bauxite which is a mineral that is extracted from mines, most prominently situated in Africa, Australia, and China. Even though the points of extraction are scattered, the bauxite flow itself is transported and consolidated to facilities where it can be processed into useful materials (Andersson & Lennström, 2025). This mainly occurs in China and the refinement is done by companies, most of which are owned by the state. The country has the necessary infrastructure and competence to utilize bauxite for large-scale aluminum production and gallium is obtained as a by-product. At this stage the gallium is low-grade and China accounts for 99% of its global production. For the metal to be utilized in ECUs, it has to undergo further refinement from low-grade to high-grade. This procedure is technically different and involves another set of companies. While China plays a role in, it does not have a monopoly. Japan is also a major stakeholder in this process and China imports a portion of its high-grade gallium from there (Andersson & Lennström, 2025).

Following the supply chain beyond extraction and refinement, the material can be used now by Tier-2 companies to manufacture parts that can be utilized in electronic components (Andersson & Lennström, 2025). The vast majority of gallium is processed into GaN and GaAs wafers which are base materials for semiconductor units with the same names (Guan et al., 2025). The finished semiconductors are integrated into electronics and Tier-1 corporations produce and sell the finished parts to OEMs (Andersson & Lennström, 2025).

As far as the relevant stakeholders are concerned, they can be divided based on the mapping above into the following:

1. **Raw materials:** Companies associated with the extraction and refinement of the raw material itself. These will later be referred to as Tier-3.
2. **Tier-2:** Tier-2 corporations represent semiconductor producers that will make use of the high purity Gallium.
3. **Tier-1:** Tier-1 companies source the finished GaN and GaAs units and manufacture finished automotive parts. That is where the ECUs come together.
4. **OEMs:** OEMs buy these parts and integrate them into their products.

Case 2: Germanium's Circularity Potential Throughout the Supply Chain

Germanium, similar to gallium, is a metalloid that does not occur compounded in individual natural reserves but instead is sourced as a by-product from zinc and coal mines. A large percentage of the zinc and coal reserves that contribute to the production of germanium are situated in China. The country dominates the germanium extraction from coal as seen in figure 2.5 while the zinc mines are more dispersed. Although the country does not have a monopoly in terms of the natural resources themselves, they do account for the majority of the germanium production representing 94% of what is produced globally. Similarly to the gallium supply chain, a prominent dependency emerges where China is the important stakeholder when it comes to refinement. They are therefore pivotal in providing the purified germanium needed in electronic devices (Andersson & Lennström, 2025).

The refined metal is thereafter used by Tier-2 companies as a dopant in silicone based wafers. These are processed into finished semiconductors which are then integrated into finished parts by Tier-1 corporations. OEMs make use of said finished parts in their products. There are clear structural similarities when it comes to the flows of gallium and germanium as seen above. However, the stakeholders themselves are usually different, when it concerns the entities that own the mines as well as the refineries. Furthermore, silicone based semiconductors are usually produced by other companies as well (Andersson & Lennström, 2025). The stakeholders are as follows:

1. **Raw materials:** Companies associated with the extraction and refinement of the raw material itself. These will later be referred to as Tier-3.
2. **Tier-2:** Producers that use germanium as a dopant in silicone based semiconductors.
3. **Tier-1:** Corporations that integrate said semiconductors into finished parts. That is where the ECUs come together.
4. **OEMs:** OEMs buy these parts and integrate them into their products.

Both of the aforementioned supply chains have a flow that is fairly linear in nature. There is a dependency on the previous point in the chain relative to the focal stakeholder and cooperation is fairly limited to the closest suppliers and customers. The same can be said about visibility (Andersson & Lennström, 2025). Beyond the companies that are a part of the conventional supply chain, there are also third party entities like recycling companies. They are specialized in handling waste streams and taking in materials from different sources to recycle them. The recovered portion can thereafter be sold to entities that are either a part of the same supply chain or otherwise. In some cases, recycling can be operated by actors that also take part

in processing and refining processes. In that context, the firm in question can make use of existing infrastructure when suitable (Umbrex, n.d.). Indium Corporation is an example of that in the gallium supply chain (Indium Corporation, n.d.).

Having an understanding of the supply chains presented above is pivotal to be able to evaluate the circularity potential. Before delving deeper into that however, an examination of why circularity might be important to begin with is presented below.

4.2 The Need for Circularity

There are a lot of common themes when talking about these two cases. Gallium is a scarce resource in a world where the demand for it is ever-growing. It is also difficult to substitute and is commonly utilized in high performance semiconductors that are greatly desired in today's market. Despite the high demand however, there are complications when it concerns production. The metal is sourced as a by-product and is therefore dependent on the supply chains of other materials. This results in a lack of visibility that slows down research into the metal and its related fields (Guan et al., 2025). It also limits the stakeholders' understanding of the supply chain and makes it difficult to make appropriate decisions (Andersson & Lennström, 2025). Said convoluted production and refinement procedures also suffer from inefficiencies where very large portions of the gallium extracted end up going to waste. This is most prominent during the stage when gallium is used for manufacturing and it entails a lot of energy consumption that is not effectively utilized. It is therefore one of the driving factors behind the need for circular alternatives (Guan et al., 2025).

A similar dichotomy affects the germanium supply chain as well. A rising demand, lack of substitutes, and an important functionality in semiconductors represent the current need for the metal. On the other hand, its complex extraction and refinement processes are costly and inefficient (Kumar et al., 2025). The majority of the germanium that enters production is lost by the time the material is refined to such a degree that it can be utilized in advanced electronic devices. This goes both for the processes that extract it from zinc as well as from coal. It is also an important reason why it is pivotal to look for potential recycling methods that might be more efficient (Haghighi & Irannajad, 2022).

Beyond what is mentioned above, there is a very prominent bottleneck in the supply chains of both of the materials. The vast majority of production and early refinement take place in China, resulting in a dependency and supply risk that is pivotal to manage. China's previous trade restrictions make that point clear as it affects the price and availability of these important metals on the market (Andersson & Lennström, 2025). Beyond the uncertainty itself, it is also resulting in the introduction of new laws by the EU. These concern certain requirements in regards to CRMs, where gallium and germanium are included. A certain portion of the extraction, refinement, and recycling of said materials have to take place within EU countries (European Union, 2024). This presents yet another reason to invest in circularity initiatives and apply them in practice.

4.3 Current Landscape and Challenges

The automotive industry is showing a notable amount of interest in circularity investments that beyond being environmentally beneficial can also strengthen supply resilience and offer opportunities for value creation (Du et al., 2025). Companies want to position themselves in a strategic manner that can benefit their businesses. This can be done by introducing a number of circular practices like re-use, remanufacture, and recycle which are to be integrated in a financially viable way. Some of the prominent incentives that are driving such investments forward are regulatory frameworks that companies have to follow and technological developments that can facilitate the creation of sustainable solutions (Du et al., 2025). Introducing circular practices in this context helps fulfill legal obligations while creating possibilities for cost reductions which are greatly desired by companies. It can also offer strategic competitive advantages like more efficient material and energy usage that in turn can generate a positive impact on supply chain management (Du et al., 2025).

Many barriers remain prevalent however. Information, for instance, is lacking due to poor coordination between different entities in the supply chain. This is partially driven by fear of security risks when sharing sensitive information but also due to a lack of willingness to share knowledge to begin with (Du et al., 2025). This in turn can result in difficulties to coordinate with other corporations in the supply chain which is pivotal for circularity. Furthermore, there are also organizational issues where managers might lack the expertise in this field. This could increase the difficulty to make the appropriate decisions and might affect the attitude toward circular practices (Du et al., 2025). Beyond information gaps, there are also concerns when it comes to the economic viability of such investments. In some waste streams the quantity of the products might be too low or the design overtly complex for practices like remanufacturing or recycling to take place efficiently. A comprehensive analysis of costs and benefits is important for the long-term sustainability of these initiatives (Du et al., 2025). This goes for the automotive industry itself but is also a general consideration for regulatory frameworks with sustainability or circularity aims. Financial viability is paramount to corporations and similar initiatives should take into account the feasibility of such systems when applied in an industrial context (Baldassarre & Carrara, 2025).

A similar situation is prevalent when examining the CRMs gallium and germanium themselves. The demand for both of the materials is expected to grow and there is an interest in finding circular solutions. Presently 30% of the germanium supply stems from recycling where the production scrap is a very pivotal source (Yadav et al., 2026). There are also promising results when it comes to gallium recycling where the manufacturing stage is also the focus (Pereira, 2026). Many issues persist nonetheless. To begin with,, there is a lack of information in regards to the practical application of recycling methods. While there is a lot of research about gallium for instance, it mostly focuses on controlled laboratory settings. There is a lack of insight into industrial applications and how feasible it is from an economic standpoint to integrate such practices and upscale them (Pereira, 2026). The same

can be said about germanium where there are knowledge gaps in regards to analysis that combine technical methods with their economic viability (Yadav et al., 2026). Cost can be a major barrier as well as many methods might be promising when examining the techniques themselves, but in practice they might be too demanding when it comes to energy consumption and the costs involved (Yadav et al., 2026) (Pereira, 2026).

The aim of this report is to bridge the gap concerning many of the challenges that are presented above. This begins with visibility issues as to how circularity investments are sustainably integrated in an industrial context. Another major problem is the cost of such practices and their financial feasibility. Furthermore, how a lack of understanding of the subject by some managers could inhibit appropriate decision making.

To be able to accomplish the aforementioned, the report is going to follow the supply chains of gallium and germanium. It is going to map out where in the supply chain effective circularity practices are established and what methods are used. It is also going to explore where the potential for the future is while pointing out the associated challenges. To conclude, the report is going to examine the incentives that drive circularity investments to be able to give insights that can help managerial decisions. While the supply chain as a whole is going to be examined, there is a larger focus on the upstream portion and on recycling activities specifically as they pertain more to the CRMs.

5

Result

This chapter aims to present the findings from the conducted desk research and semi-structured interviews. The chapter begins with a technical description of different common and relevant recovery methods identified in section 5.1. The state of these methods, recovery from alternative sources and circular initiatives will then be presented in 5.2. The final section 5.3 showcases the opportunities and challenges of implementing circularity in the supply chain.

An overview of the findings and which section of the supply chain they fall under is presented below in figure 5.1. The figure depicts the processes that gallium and germanium go through from extraction to EoL:

- **Critical raw material supply:** The part of the supply chain that consists of the extraction and production of the critical raw material.
- **Semiconductor:** The part of the supply chain where Gallium Nitride (GaN), Gallium Arsenide (GaAs) and germanium is used as a dopant in silicon (Si) wafers, are manufactured. These are later utilized in the production of semiconductors in Tier-2 factories.
- **Component delivery:** The part of the supply chain where the semiconductors and other components are integrated into the PCB and the complete ECU is constructed by Tier-1. The complete units are subsequently delivered to the OEMs, and installed within an automotive.
- **EoL Recycling:** The part of the supply chain where the recovery processes after use are implemented. It is within this section the electronic waste is transformed into recycled materials. These can then be looped back to critical raw material supply where it is refined and thereafter used again throughout the supply chain.

Furthermore the figure presents a mapping of circularity potential throughout the supply chain. Green rhombs represents established circular flows in the supply chain and will focus on answering **Research question 1**. Red ovals represents where materials exist but is not implemented in circular flows commercially. Orange rectangles represents where investments have been made recently. The red ovals and orange rectangles aims to answer **Research question 2**. Section 5.3 will focus on answering **Research question 2** and **Research question 3**.

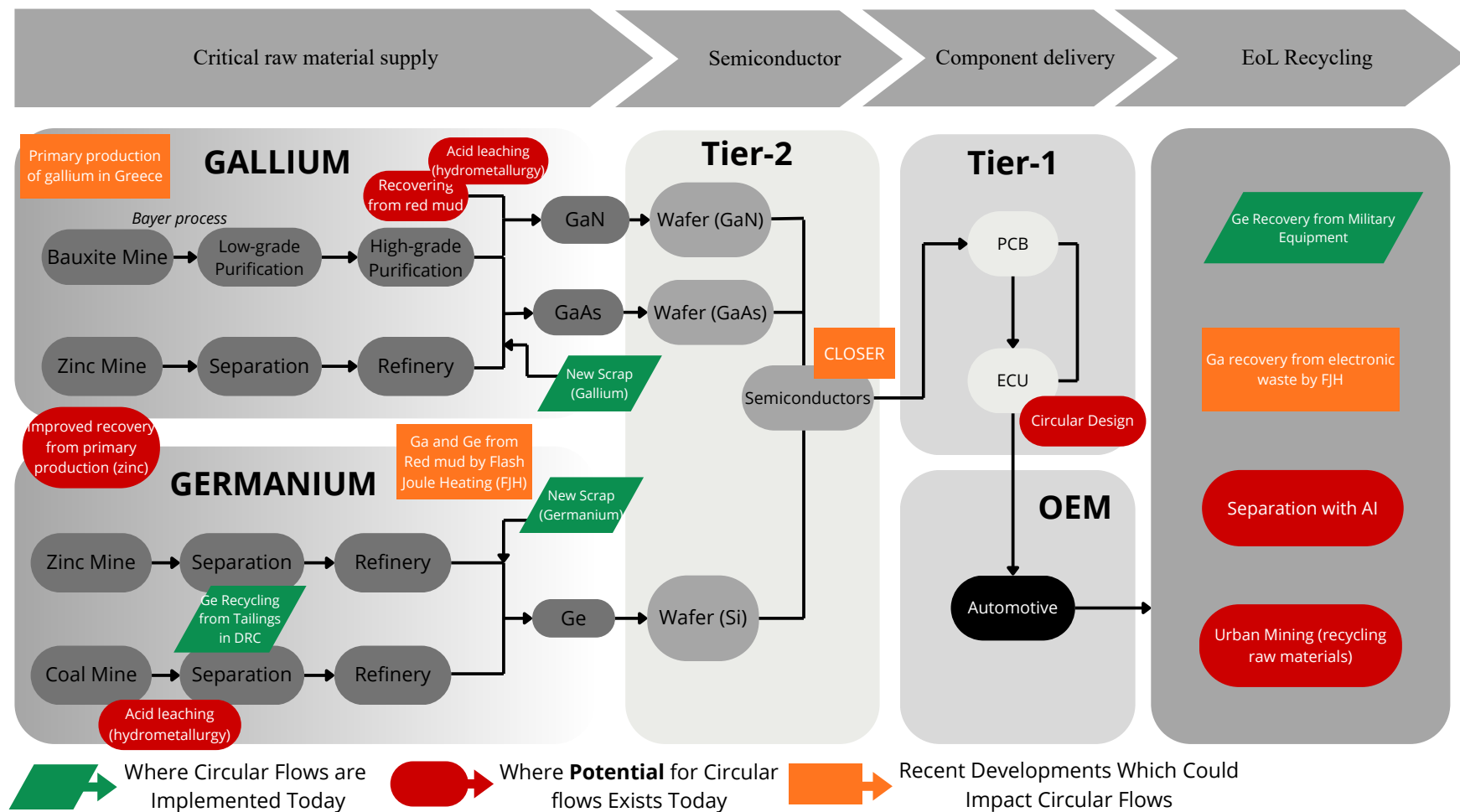


Figure 5.1: Overview of the findings. **Green rhombs** represents established circular flows in the supply chain. **Red ovals** represents where potential for circular flows exist today. **Orange rectangles** represents where investments have been made recently.

5.1 Description of Methods for Gallium and Germanium Circular Flows

In the following section, a technical description of relevant and common methods for circular flows within the supply chain will be explained. The methods mentioned are applicable for gallium and germanium, except for 5.1.1 of which describes mechanical pre treatment of electronic waste. In section 5.2 these methods and their state and potential of circular flows in figure 5.1 will be explained.

5.1.1 Mechanical Pre-treatment of Electronic Waste

A traditional process of recycling PCBs from ECUs is by shredding or grinding. The protective case surrounding the PCB is removed, and hazardous materials are disassembled from the circuit board. After this step the PCB is turned into a powder by mechanical processes such as shredding or grinding. The powder is then separated into metal and non-metal powders for refining or disposal purposes (Cucchiella et al., 2016).

This can be compared to a general strategy for recovering valuable metals from electronics. The first step is a mechanical pre-treatment, starting with disassembly, followed by crushing and then sorting. Crushing the materials into smaller particles ensures more efficient recovery. In the second step the metals need to be separated. There are several methods of doing this, with the most common ones being hydro-, bio- and pyrometallurgy (Teng et al., 2025).

5.1.2 Hydrometallurgy

Hydrometallurgy is a common method used in the extraction and recovery of metals from ores, concentrates, and other recycled materials. According to interviewee *Spruce*, hydrometallurgical recycling of electronic waste begins with mechanical separation of materials not of interest for this process. The material is then shredded, followed by leaching where metals are dissolved in a controlled chemical environment. Then, they are separated using techniques such as pH-controlled precipitation or solvent extraction. These processes allow for the selective recovery of highly pure metals, while organic materials, ceramics and other non-metallic fractions are left behind and handled separately, *Spruce* says. Advantages with using hydrometallurgy is that it is efficient, has the ability to be selective and is easy to operate, but it produces wastewater which increase costs (Teng et al., 2025).

5.1.3 Pyrometallurgy

Pyrometallurgy is a method to separate metals using high temperatures, and is often used as a pre-treatment process for metal recycling (Teng et al., 2025). A disadvantage of using pyrometallurgy is that it is energy-intensive (Teng et al., 2025).

5.1.4 Biometallurgy

Biometallurgy uses microorganisms, for example bacteria and fungi, to extract metals. Advantages include being an energy effective and environmentally friendly method, but the process is slow, and lead times are long (Teng et al., 2025).

5.1.5 Flash Joule Heating (FJH)

By utilizing electrical resistance within materials, Flash Joule Heating (FJH) can generate high intensity bursts that result in near instantaneous temperature increases reaching over 3,000 Celsius within milliseconds (Metallium Ltd, n.d.). This makes it feasible to modify the characteristics of a substance or separate different materials from each other. This emerging technology resolves some of the primary issues associated with the methods, utilized for the same purposes. Those traditional procedures usually consume a lot of energy and might take a long time for the chemical reaction to be completed. Additionally, FJH allows for higher precision in the process which increases the efficiency of the desired task (Xiao et al., 2025).

5.1.6 AI-Based Method for Separation of Semiconductor Waste

Hadj (2025) introduces an advanced, AI-powered framework for the precise sorting and separation of semiconductor waste. The system begins with a multi-modal imaging process, where High-Resolution RGB Cameras, Near-Infrared and Hyper-spectral Imaging and X-ray Imaging capture detailed information about each waste item which is necessary data for further steps. The combination of these tools allows the system to detect surface features as well as internal structures, which is essential when dealing with complex components such as GaAs wafers or multilayer PCBs.

After this, Hadj (2025) mentions a combined AI model used to identify the materials. Convolutional Neural Networks (CNNs) and Vision Transformers (ViTs) will together recognize details and be able to give a very precise identification of the raw materials. CNNs excel at identifying fine-grained textures and edges, while ViTs capture global patterns and relationships within the image. Together, they enable highly accurate classification of semiconductor materials, reaching a reported accuracy of 98.5% in the study. This is important in the automotive sector, where components may contain mixtures of silicon, ceramics, and various other metals Hadj (2025) points out.

When the materials are identified, a Random Forest based decision support is used to determine the best recycling method for the material. Random Forest is a learning algorithm that uses many decision trees to make better predictions. This includes selecting technical process, estimating environmental impact and maximizing economic value (Hadj, 2025).

5.2 Mapping of Implemented Circular Flows, Potential for Circular Flows and Recent Developments

In the previous section 5.1 a technical description of common and relevant methods were provided. In this section, the current implementation (green rhombs), potential (red ovals) and recent development (orange rectangles) for circular flows of gallium and germanium will be presented of figure 5.1. This section is aimed to answer **Research question 1** and **Research question 2**.

5.2.1 Green Rhombs – Where Circular Flows are Implemented Today

In this section, the green rhombs in figure 5.1 will be explained. They represent where circular flows are implemented today and aims to answer **Research question 1**.

5.2.1.1 Recycling Gallium

A Canadian company, NEO Performance Materials, is currently recycling gallium from, for example, new-scrap from semiconductor manufacturing and are able to produce gallium reaching 8N (99.999999%) purity (Neo Performance Materials, n.d.).

Another example is Indium Corporation which is an American company that offers recycling services for gallium scrap that they take in from customers. The recycled material can either be bought by Indium or sent back to the client (Indium Corporation, n.d.). The US Department of Energy announced in 2026 investments in companies that extract and recycle gallium locally to strengthen supply resilience and increase autonomy. Indium Corporation is one of the entities involved in the project and is to focus on the development of gallium recycling methods (U.S. Department of Energy, 2026).

In general gallium recycling is more so affected by the flow of materials rather than the choice of technical procedure itself, even though the latter still has an impact. GaN and GaAs production scrap and residues represent the most prominent stream that can be utilized (Pereira, 2026). This includes production chamber waste, sludge from processing, and waste resulting from cutting wafers. In this context, the gallium concentration is high and there are less substances mixed together. The semiconductors are not integrated yet into complex products and therefore are easier to handle. Furthermore, the process commonly uses hydrometallurgy and is not as energy intensive which is important in regards to the cost of implementation. It is therefore more financially feasible to integrate and upscale on an industrial level (Pereira, 2026).

5.2.1.2 Recycling Germanium

Currently, it is estimated that 30% of the total supply of germanium is sourced from recycled content and that manufacturing scrap is very prominent in this context (Yadav et al., 2026).

Umicore, a Belgian company, is actively recycling germanium waste, with over 50% of their stock coming from scrap from their own production or scrap from their customers. Umicore refines and recycles, and both these activities use largely the same processes, being pyro- and hydrometallurgy. They are able to handle materials and waste containing germanium contents of at least 0.5% (Umicore, 2026).

In 2024 *Société du Terril de Lubumbashi* (STL) made its first batch of recycled germanium from the Big Hill Tailings Site, which is a large pile of mining waste, in The Democratic Republic of Congo (DRC) (Umicore, 2024). This was made through a partnership between Umicore and STL, where Umicore provided support through its expertise in germanium. The germanium was processed by hydrometallurgy and the project is intended to up-scale further at STL's plant in Lubumbashi (Umicore, 2024).

The US Department of Defense (now Department of War) initiated a program in 2022 for recovering germanium from EoL sources. Around 3,000 kg of pure germanium ingots were procured, mainly from night-vision lenses and turret windows from Bradley Fighting Vehicles. This is equal to about 10% of US domestic demand for refined germanium (Blackwood & DeFilippo, 2024).

5.2.2 Red Ovals – Where Potential for Circular Flows Exists Today

In the following section, the red ovals in figure 5.1 will be described. They represent where potential for circular flows exists today and aims to answer **Research question 2**.

5.2.2.1 Recovery of Gallium from Red Mud

Red mud is a by-product from alumina production and is normally dumped in landfills. As of 2016 an estimated 1-1.5 billion tons of red mud has accumulated in landfills (Dhiman et al., 2024). Another source claims that 4 billion tons of red mud are stored globally in 2023 (Allen, 2024). According to Dhiman et al. (2024), reported content of gallium in red mud is 20-80 ppm, compared to gallium in zinc residue and bauxite residue being reported at 430 and 115 ppm respectively (Huang et al., 2024). Annually about 150 million tons of red mud is created from aluminum production globally, and around 7 million tons is created within Europe (Allen, 2024).

It is possible to extract gallium through hydrometallurgy from red mud (bauxite waste), and it is estimated that as much as 79% of the gallium mined ends up there or in the aluminum cycle (Robla et al., 2024).

A study suggests gallium extraction from red mud together with scandium (Sc), iron (Fe), aluminum (Al) and titanium (Ti) (Dhiman et al., 2024). The study made an economic analysis of such a plant and concluded that stable revenue would come from Fe, Al and Ti, based on their higher volume, while gallium and Sc would provide a boost to profitability based on their high prices. The method used in the study suggests gallium recovery from red mud by acidic leaching (hydrometallurgy), and reached a recovery rate of 80% of gallium. The target recovery rate for such a process to be profitable were calculated to be 75%, 75%, 50% and 50% for gallium, Sc, Fe and Al respectively (Dhiman et al., 2024).

5.2.2.2 Gallium & Germanium Recovery from Zinc Slag/Residues

Gallium and germanium rarely occur in mineable ores of their own. Instead they occur as trace elements in, for example, Sphalerite (ZnS) and therefore enter the supply chain as a by-product of zinc production. Interviewee *Poplar* says that in hydrometallurgical zinc plants, both elements end up almost entirely in the jarosite residue which is a solid waste produced during the iron removal process in zinc hydrometallurgy plants.

According to *Poplar*, hydrometallurgy is the most common industrial route because it integrates naturally into zinc refineries. Hydrometallurgy uses acid-based leaching to dissolve gallium and germanium from zinc residues, but 20-30% of germanium is lost because it becomes trapped in silica gel during conventional leaching. Modern improvements, like pressure leaching and controlled pH, greatly increase extraction efficiency, achieving up to 98% gallium and 94% germanium recovery, *Poplar* says.

There are other methods for extracting gallium and germanium from zinc slag as well. Pyrometallurgy for example uses high-temperature smelting or volatilization to concentrate gallium and germanium. *Poplar* mentions that today, pyrometallurgy is mostly used with the goal of recovering zinc, lead (Pb), silver (Ag) while gallium and germanium come as a bonus. Some possible future techniques are according to *Poplar* bioleaching (technique within biometallurgy) and electrochemical approaches. Bioleaching can with specialized microorganisms dissolve part of the germanium from jarosite, although gallium recovery remains very low. Electrochemical approaches are being explored to selectively deposit gallium or germanium from process solutions, but these remain at lab-scale without industrial application yet.

According to *Poplar*, the concentration of gallium and germanium in their company's zinc concentrates are typically, 10-100 ppm for both gallium and germanium, globally. In jarosite residue, which is the main sink, the typical values are 50-100 ppm gallium and 80-100 ppm germanium, according to *Poplar*. Within the EU there is 0.6 million tons of jarosite residue created each year (Ali & Khan, 2023).

5.2.2.3 AI-Based Method for Separation of Semiconductor Waste

In today's automotive industry, electronics and CRMs are more and more integrated into vehicles. This creates new challenges for recycling, as modern components contain complex semiconductor materials that are difficult to separate using traditional methods. According to *Beech & Alder* at a recycling company:

"It makes it more difficult. You cannot extract the metals in a classic car fragmenter. You have to manually disassemble, which is a cost that the buyers have to pay for".

Traditional waste management methods are often manual, expensive and inefficient (Hadj, 2025).

The study by Hadj (2025) mentioned in section 5.1.6 resulted in a 99.0% recovery rate of gallium from GaAs substrates and LED waste streams, producing material with 5N-9N purity grade (99.999-99.9999999%) and 94.0% recovery for germanium from optical fiber and infrared optics waste streams. These recovery levels significantly exceed those of conventional recycling methods and demonstrate the potential of AI-driven sorting to support a circular economy in both the semiconductor and automotive industries. *Beech & Alder* sympathize with that this is a method that is not implemented in larger scale yet but has potential in the future.

5.2.2.4 ECU Design for Circularity

An aspect to consider when designing for circularity potential of ECUs is the joining method between the PCB and casing. The method of choice can have an impact on the rate of undamaged PCBs when disassembling. A study conducted on headlight-ECUs found that the best designs for damage-free recovery are tool-free insertions or joining by standardized screws (Peitzmeier et al., 2025). These methods resulted in damage rates when disassembled of 0% and 55.45% respectively. Joining by glue or both glue and rivets are more prone to damage during disassembly, resulting in damage rates of 80.43% and 100% respectively (Peitzmeier et al., 2025).

Spruce described a previous attempt to standardize battery design, as a parable for a uniform design of PCBs. The aim of the attempt was to assign different colors to different battery types. This would have made it easier to identify the chemical recycling process once the components reached EoL. However, the initiative was never implemented:

"The producers never agreed on that. Because they had their vision of the design. And then this also would stop the development, because you would have new ideas of the design of the components, and this would stop this progress." Spruce says.

5.2.2.5 Urban Mining of Gallium

The in-use stock of gallium has seen a stark increase between 2000 and 2021, with a factor of 19. Urban mines, which means "mines" of discarded waste, contain valuable materials, although the majority of gallium is not in EoL products yet. (Han et al., 2024).

There are challenges that concern the recycling of gallium from mixed electronic waste. The concentration of the metal is low, products have complex structures, and too many substances are integrated together. While potential exists in controlled laboratory environments, unexpected reactions are likely to occur in practical applications which would complicate the procedure. Furthermore, pyrometallurgical processes might be needed for separation of materials and those tend to be energy intensive. The aforementioned results in economic difficulties in introducing and upscaling such processes in an industrial context (Pereira, 2026).

While the need exists for sustainable solutions to match the rising demand, recycling gallium from EoL products faces economic difficulties. At present, it is notably cheaper to buy gallium that is produced through primary production and a decrease in energy costs for EoL recycling is needed to change the situation (Yadav et al., 2026). For instance, recovering gallium from LEDs that use GaN semiconductors is considered uneconomic. This is due to low concentrations of the metal and high processing costs. There is therefore a need for streams with greater volumes and more efficient procedures (Wu et al., 2025).

5.2.3 Orange Rectangles – Recent Developments Which Could Impact Circular Flows

The following section will explain the orange rectangles in figure 5.1, which represents recent developments that could impact circular flows in the supply chain. It aims to answer **Research question 2**.

5.2.3.1 Implementing FJH for Gallium Recovery from Electronic Waste and Red Mud

In early April 2026, Metallium received green light from the US Department of War (previously Department of Defense) for further funding regarding their FJH technology to recover gallium from semiconductor and electronic waste, as well as from steel or alloy scraps (Argus Media, 2026).

Metallium is also partnering with the company ElementUSA to recover gallium and scandium from red mud in the US. The implementation of Metallium's FJH technology here is in early stages and will need to reach certain agreed performance benchmarks for further development (Hadrian, 2025).

5.2.3.2 New Primary Production Plants in the EU

Metlen Energy & Metals have received funding through the European Investment Bank to start primary production of gallium in Greece (European Investment Bank, 2026). The plant is planned to produce around 50 tons of gallium annually and has been deemed by the EU as a Strategic Project connected to CRMA (METLEN Energy & Metals, 2025).

5.2.3.3 CLOSER

CLOSER stands for “Circular raw materiaLs for european Open Strategic autonomy on chips and microlEctronics pRoduction” and is a European Union initiative aimed at establishing a closed loop system for semiconductor materials within Europe (CLOSER, n.d.). The CLOSER project is specifically focused on the materials gallium and germanium, together with silicon and indium (European Commission, 2024). Today, Europe remains heavily dependent on Asia and the United States for electronic components. This reliance originates both from Europe’s limited natural reserves of important elements (such as gallium and germanium) and from the economic advantages of sourcing them elsewhere. The CLOSER project launched officially on October 17, 2024 and will span 36 months (CLOSER, n.d.).

The goal of CLOSER is to build an EU-based supply chain capable of recovering and reusing secondary semiconductor raw materials from electronic waste and industrial by-products for the production of chips and related technologies (European Commission, 2024). The project is 70% funded by the EU and brings together 32 partners across Europe, each contributing from different stages of the supply chain. During the interview with *Aspen*, it became clear that EU funding is essential not only to make the research possible but also to act as a signal that the EU believes this ambition is both achievable and important.

5.3 Opportunities and Challenges Concerning the Implementation of Circularity in Supply Chains

In this section, opportunities and challenges with implementing circular flows to the supply chain will be brought up. These are based on interview findings and the perspectives from the different participating actors. The focus of the following sections is to answer **Research question 2** and **Research question 3**.

5.3.1 Opportunities and Challenges in Critical Raw Material Supply

Interviewee *Elm* talks about that it is just within the recent years that we have understood the greatness of gallium and germanium in electronics. Therefore, there is still a lot of ongoing research regarding this topic.

Hydrometallurgy is, as mentioned in section 5.2.2.2, naturally integrated into zinc refineries. According to *Poplar*, hydrometallurgy can theoretically extract almost all gallium and germanium, but that requires expensive equipment, complex chemistry, handling of large volumes of liquid, and is not practical for enormous solid waste piles.

In metal production and recycling there is also a big focus on material purity. *Spruce* says no one wants to start having trouble with their products because of lower purity, and producers therefore focus on high purity materials to attract customers. *Spruce* says that:

"...(okay say) we are okay with 99.2% purity, and then we find out the product is not working, that is why the primary mining or metal producers try to sell as pure as possible, because they know it will attract the costumer."

Spruce further states that material purity is crucial in the costs related to metal recycling, higher purities incur higher production costs, so companies need to strike a balance between the right purity and price.

Beech & Alder points out the role of EU to promote local production:

"One alternative is that you finance to create a market, that is one way. You can also regulate it with legislation, that production should be domestic. There are different strings to pull, financing is one, legislation is another."

The material's purity is especially important in the production of semiconductors. According to *Fir* when said units are recycled, the recovered material has to undergo further refinement to reach the specified requirements.

5.3.2 Opportunities and Challenges in Semiconductor Manufacturing

Aspen mentions that there are currently no known widespread methods within wafer-manufacturing for circularity. If there was someone who had progressed in such research it is unlikely it would be known to others, since they are competitors on the same market.

A challenge with promoting circular commitments within the semiconductor industry is according to *Aspen* that:

"How many tons become hazardous waste or how much can be recycled we have not seen. Cardboard, for example, has a clear number for recycling."

On the other hand, *Aspen* also brings up that:

"Yes, there is an interest from Europe to solve that problem...The goal is to source more from European partners - a more sustainable flow within Europe."

5.3.3 Opportunities and Challenges in Component Delivery

With the rising electrification and increased amount of ECUs in vehicles, the ECUs become more and more integrated in the construction. Interviewee *Juniper* mentions that this, as well as that it is hard opening the control units, are two of the main reasons for why it is hard to recycle an ECU. Another thing *Juniper* brings up is that the components in the ECUs usually are compounded with adhesives, instead of using for example screws, which makes the disassembling much more challenging. This aligns with section 5.2.2.4.

These designs are mainly because of safety or convenience reasons. For example an argument for using glue is according to *Beech & Alder* that it makes the ECU more water and dustproof, which is a benefit in many other aspects. When *Spruce* got the question if companies work or prioritize design for recycling, *Spruce* says:

"No, not at all, we are very far from there."

Interviewee *Hazel* brings up that if you take it a step further, you should be able to take everything out and have standardized designs. In the best of worlds everyone would have had the same design, where they would have made the same type of cover, one type of circuit board etc. *Hazel* says. In addition *Hazel* states:

"[At Hazel's company] we talk a lot about designing modular, for instance, an ECU you should be able to take apart and easily replace broken parts. And we all win on this."

Spruce says that a uniform design of a PCB will not happen. The reason of a similar case is mentioned in section 5.2.2.4.

Aspen mentions that they can extend their life-span of their products in the future, but they have not seen this request from costumers yet. *Aspen* further talks about that a vehicle engine prototype previously was designed to run indefinitely, but for some reason today, the design approach has moved away from this.

5.3.4 Opportunities and Challenges in EoL Recycling

Interviewee *Elm* has a positive view of the future for recycling of CRMs itself. They bring up that the problem is not that it cannot be done, because it can. It is possible to create processes where you extract one substance at a time and then recycle. The question is how to make it economically sustainable. Connected to this, *Beech & Alder* said the following about if they have knowledge of gallium and germanium in

their material flows:

"Absolutely, but it is such small amounts that it is not payable, there is really no customer that pays for it today. That is the case with really all CRM metals, if you are going to extract them at larger scale you need more energy in the smelters, and then the smelters cannot achieve their climate targets when it comes to their emission allowances. They are a bit contradictory, CRMA versus emission allowances."

When asked if the price is what is the main factor for why gallium and germanium is not recovered compared to something like gold, *Beech & Alder* had the following statement:

"Yes, but the amounts as well, there is significantly more gold, copper and silver in the material than there is gallium and germanium, which makes it worth it to create a process for these [gold, copper, silver]."

From another interviewees perspective, *Rowan* discusses that a big challenge with recycling gallium and germanium is that:

"We count in tons, if we look specifically at your materials in question [gallium and germanium], they are irrelevant as they are not included."

Rowan further says that the materials appear in a small weight in the final product compared to other materials. *Beech & Alder* confirms this by saying:

"There is no market for germanium or gallium."

They also comment on that there are such small amounts that it is not payable and that no customer wants to buy it.

Spruce further states regarding software secrecy on recycling PCBs:

"...they are so secretive of their products that they don't want them to end up in the recycling where the design can be copied. But then they would have to have a system where they can collect it back."

Another thing *Spruce* points out are the high investment costs of starting hydrometallurgy plants. Operational costs are lower, but a big problem is the waste stream which is often heterogeneous and irregular. Another important aspect of using hydrometallurgy processes is its scalability compared to pyrometallurgy.

Spruce also explains another important aspect regarding the mix of materials and the impact on hydrometallurgy recovery. Each combination of elements needs different conditions to be separated effectively. This is something that interviewee *Elm* also points out. *Elm* explains that we understand very well how materials go together in ores and which elements are found together in mining activities. Electronics are however man-made and contain a much bigger variety of materials which complicates recovery *Elm* says.

5.3.5 Opportunities and Challenges Between Different Actors Within the Supply Chain

There are a lot of questions regarding where in the supply chain the most potential for recycling takes place. *Elm* means that today, electronic waste is handled by extracting substance by substance. *Elm* notes that this might not be the best system and a component by component type of recycling would be more effective. *Elm* also mentions that we have to stop talking about waste. In a circular economy there is no waste.

Interviewee *Ash* mentions that geopolitical issues have a huge impact on the supply chain and notes that major issues such as natural disasters and pandemics are difficult to guard against. However deep-rooted conflicts that sometimes lead to war make managing the supply risk comparatively less complex as these conflict often develop over a longer period of time. Interviewee *Aspen* speaks about the importance of local sourcing in times of conflict. *Aspen* highlights that it is of special importance for military equipment manufacturers during periods where supply may be throttled:

"During times of war and conflict you need your own supply chain so other countries cannot throttle production. The surrounding world is the main driver of this industry."

Ash also points out that supply resilience is a consideration as a driving force in their circularity projects. They further explain that a lot of the geopolitical issues stem not only from China but the US nowadays. Some materials face restrictions because of tariffs. This might result in a number of devices being sourced in a different way, *Ash* says.

Rowan means that EU does not have the perspective of the industry and that their initiatives are very good from an environmental or societal perspective, but that you cannot introduce laws that makes it even more expensive to manufacture in the EU:

"EU cannot engage in its own regulations if China does not follow these anyway, then everybody is not competing under the same conditions."

According to *Hazel*, EU regulations are created in consultation with the industries. If they want to set new directives, industries can come together and say that they cannot cope with them. Then the EU listens to not put the economy out of balance.

Visibility in the entire supply chain is essential to *Ash*. *Ash* states that in order to create resilience in their supply chain they prefer to have visibility from extraction of materials to delivery of products to their customers.

Ash mentions the importance of close relationships within the supply chain and touches on their cooperations with suppliers especially during times of elevated supply risk and how they sometimes help their suppliers to secure their supply. *Ash*

identified periods of shortages, such as COVID-19 and regulations such as CRMA, as driving forces to secure their current supply chain and also relevant projects.

When asked about whether there are difficulties in cooperating in the supply chain, *Ash* replied that there is a good amount of interest to deal with these supply challenges from different stakeholders.

A recurring trend in the interviews has been the question about price. Many of the interviewees mentions this as one of the most important aspects, both for the manufacturers and customers.

In section 5.2.2.3 *Beech & Alder* mentions that the buyers has to pay for the manual disassembly, which is expensive.

Rowan also considers the price a crucial aspect in the question. They bring up an example with aluminum:

"Recycled aluminum is more expensive but we have come a long way and prices are getting closer."

Interviewee *Spruce* talks about how electrical waste is often treated by several different companies. Usually a company takes care of collection and mechanical-pretreatment, and then sends the material powders out to different refineries. It is unusual for someone to take care of all processing steps of the recovery of electronic waste.

Regarding challenges with take back systems, *Rowan* emphasizes that:

"A third party cannot guarantee that the components have the same function as new."

6

Discussion

The discussion chapter aims to discuss findings from literature, interviews and academic papers. Firstly this chapter will address **Research question 1** on the current state of circularity in the supply chain for gallium and germanium. Next it will discuss **Research question 2**, on where there is potential and challenges for circularity practices. Lastly, the chapter will address **Research question 3**, why it is of interest for stakeholders to invest in circularity questions.

6.1 What is the current state of circularity in the supply chain for gallium and germanium in the production of ECUs, and why?

As stated in figure 4.1, the EoL recycling rate of gallium and germanium is 0% and 2%, respectively. A possible reason for this could be that there is currently no established market for recycled gallium and germanium, which is addressed by *Beech & Alder* in section 5.3.4. The impression gathered from most interviews is that there is a limitation in knowledge concerning gallium and germanium, as well as their potential. This could be closely associated with the market situation. As mentioned in section 5.3.1, *Elm* conveyed that the importance of gallium and germanium in electronic applications has only recently been recognized. This awareness is also linked to the statement of *Beech & Alder*. Additionally, a key explanation for this lies in the small quantities of gallium and germanium present in EoL products. As further emphasized by *Beech & Alder*, the quantity of material plays a decisive role in enabling both the development of recycling processes and the establishment of viable markets. For other metals such as gold, copper and aluminum, larger quantities have supported the creation of established recycling infrastructures. As pointed out by *Rowan*, the price of recycled aluminum is getting closer to primary material.

Outlined in section 2.1, the ECU carries an important role within vehicles, for instance managing safety parameters. Therefore, it is essential for the ECU to keep a high standard. As a result, mining companies want to sell metals as pure as possible to ensure not being the reason for low quality products. This is also supported by *Spruce* in section 5.3.1. However, there is ongoing projects regarding recycling both gallium and germanium. This shows that there is an existing interest for development in this field. Section 5.2.1 mentions Umicore, STL, NEO Performance Materials, STL, Indium Corporation and US federal agencies as stake-

holders investing in, and managing the field of gallium and germanium recycling. As for NEO Performance Materials, they are already able to produce gallium with the high purity that is needed (8N). This indicates that the earlier mentioned uncertainty addressed by *Spruce* is a result of lingering inertia rather than technical limitations. This is seen when the streams are suitable in regards to their volume, the concentrations of the metals, and the mix of substances not being overtly complex. The aforementioned is prominent when gallium and germanium are recycled during manufacturing processes which is presently utilized on an industrial level.

It should be underscored that the ELV directive and CRMA is, and has been, vital for the green rhombs to exist, as they accelerate development. One of the main reasons for the implementation of the two regulatory frameworks is the intent to reduce import reliance, particularly towards China. As mentioned in section 2.3, China accounts for more than 90% of the global production of both gallium and germanium. It also points out that this dominance can be used as a geopolitical tool, which it already has been. These factors likely influenced the concerns within EU and contributed to the implementation of ELV directive and CRMA. This reflects the significance of competition within the industry, especially concerning international technological development. Conflicts and war are also underlying causes for this competition. As mentioned in section 5.2.1, the US Department of Defense/War is one of the leading stakeholders in the scaling of gallium and germanium recycling. They have already achieved one of the goals of CRMA, "10% of the annual EU consumption is to be sourced within the EU", but for germanium in the US.

6.2 Where in the supply chain is there potential for circularity practices for gallium and germanium, and what are the challenges and potentials with implementing and upscaling these?

According to concepts from circular economy and the 9R-framework, the priority should be to make use of circularity practices that can minimize the amount of materials and energy consumed. This is in line with prominent views held in supply chain management that aim to reduce costs while maximizing the value generated. These principles should be taken into account when considering the flows that are presented below.

The flow of materials and its content is a pivotal consideration when evaluating circularity potential. This entails examining factors like the concentration of gallium and germanium in said flow, its overall volume, and the amount of other substances that are mixed in. A further consideration is whether the materials are a part of products with complex designs, which might make it difficult to remanufacture or recycle. Beyond the flows themselves, the technology utilized is of great importance as well. Untapped flows where established technology with high efficiency can be used

are to be prioritized. Emerging technologies that can decrease energy consumption are pivotal as well and should be taken into consideration.

6.2.1 Circular Potential in the Upstream Supply Chain

A number of flows seem to be interesting in the upstream supply chain. On one hand, recovery of gallium from red mud, together with other materials, could provide an important secondary source with great potential. There exists large masses of red mud within Europe. With a lower gallium content estimates of 20 ppm and using current European red mud creation of 7 million tons annually results in 140 tons of gallium being lost in landfills each year in Europe. Annually this is almost three times that of Metlen's planned gallium plant in Greece, showing that there is huge potential from this source. A similar calculation can be done for germanium and gallium waste in jarosite residue. Using the lower estimates provided by *Poplar* with 50 ppm gallium and 80 ppm germanium, and annual jarosite residue creation within the EU at 0.6 million tons will result in losses of 30 tons and 48 tons each year for gallium and germanium respectively. If compared to figure 2.5, China annually refines 130.5 tons of germanium, which covers 94% of global supply. In relation to this the amount lost within the EU to residue waste seems an enormous source for supply resilience. Utilizing these streams can be advantageous due to the concentrations of gallium and germanium and the large volumes processed. Furthermore, there are not as many substances mixed in which makes it easier to use methods like hydrometallurgy. It is also a method that is already established which makes it easier to integrate on an industrial level.

Recycling plants for handling gallium and germanium could benefit from being closely linked to plants for primary production or refining as well. Hydrometallurgy for instance is already used for primary production during the Bayer process and zinc refinement. The problems of uneven and heterogeneous waste-streams would be mitigated by having established supply streams from mining operations. This could stabilize operations and help smooth out revenue streams. Furthermore, it would ensure a practical implementation of recycling that is more feasible due to existing infrastructure. More concretely, recovery from red mud could be tried out alongside a new gallium production plant by Metlen in Greece. Investments here for infrastructure to support gallium production could hopefully also be utilized for a reverse flow, promoting circularity and diversifying supply for European markets.

6.2.2 Circular Potential for EoL Flows

There are alternatives for extracting gallium and germanium from EoL electronics today, and thus urban mines could prove a useful source of gallium and germanium. Both materials are implemented in different emerging technologies, such as increasingly electrified vehicles, which means a recent increase in in-use products, many of which have not reached their EoL yet. Urban mines could therefore prove an important secondary source in the future. Currently, the utilization of EoL waste for recycling is limited due to cost constraints and high energy consumption. On

one hand, the concentrations of gallium and germanium in such products is very low and the substance mix is complex, as mentioned by *Beech & Alder*. Beyond that, the materials tend to be included in products with complex designs that might be difficult to process. Furthermore, the infrastructure to support urban mining activities is not prevalent at present and would probably take years to establish.

While EoL flows are more difficult to handle, changes in the nature of the streams or the technology used for recycling can be paramount for their future potential. Emerging technologies can offer an increase in efficiency which might improve financial feasibility. AI-based separation, for instance, could help improve recovery from EoL sources by being able to more clearly distinguish between materials. This method is however not implemented yet at larger scale. FJH is another development which could prove useful in the future for EoL purposes, as well as recovery from higher up in the supply chain. These emerging methods could solve some of the problems of traditional material recovery facilitating an easier separation of materials, being less energy intensive, and offering opportunities for cost reductions.

Beyond the technology itself, changes to the flow can play a pivotal role in increasing the efficiency of circularity practices. Through design choices EoL electronics, such as ECUs, could be built in a way that makes them easier to recycle, refurbish, or remanufacture. This can be accomplished by applying standardized designs that simplify separation and disassembly. The aforementioned is important to consider as it is directly related to theories concerning circularity. From an energy efficiency perspective circular practices should be integrated in a manner that minimizes material and energy consumption. In this context products containing gallium and germanium should preferably be R3: Re-used or R5: Refurbished before considering R8: Recycling, as is concluded from the 9R framework in section 2.6.

However, there are a number of issues. Mentioned further by *Spruce*, taking care of EoL electronics is handled by several different companies. This together with the fact that *Rowan* mentions a third party cannot guarantee functionality of take-back products probably makes R3: Re-use and R5: Refurbishment more difficult. By not being able to implement these Rs the only other alternative becomes R8: Recycling which is not as optimal from an energy and environmental perspective. In a best case scenario all EoL electronics and ECUs that are still functional at disposal should be refurbished and reused, as is suggested by the 9R hierarchy. Furthermore the standardization itself could be difficult to implement due to the fact that it could hinder innovation, as mentioned by *Spruce*.

Another angle to consider about recycling from EoL products for gallium and germanium is that it might not be positive from an environmental perspective, as was discussed with *Beech & Alder*. A conclusion from this could be that energy and emissions needed to recycle, might be greater than what is environmentally justifiable for industry actors. By analyzing the 9R framework, the tier R8: Recycle could therefore be excluded if focus is just on environmental impact. If this is the case focus should instead be on Rs of higher tiers, such as R3-R7 (Re-use, Repair,

Refurbish, Remanufacture and Repurpose).

6.2.3 Geopolitical Challenges for Circular Flows

Rising tensions in the world and recent export regulations from China regarding strategic metals such as gallium and germanium have caused the prices of these materials to skyrocket. With ever increasing demand the prices are likely to continue to rise.

Rising prices and tensions could promote recycling efforts which is currently seen throughout the west, with the US and the EU promoting and funding projects regarding circularity and ways to diversify supply. Due to the fact that China controls such a majority of the primary production, and probably sit at an excess of materials, these undertakings would probably need to be commercially viable at much lower gallium and germanium prices. This is due to the risk of price dumping of Chinese materials. Due to the price divergence for gallium in China and the global market it can be assumed that the Chinese market has an oversupply of the materials which could flood the market if a serious investment was made to produce gallium and germanium outside of China. This means that plants focusing on these materials need to be planned with long-term strategic goals and collaboration in mind and probably need non-private funding to motivate an investment. This would be crucial to not be forced to shut down operations based on much lower, or negative, profit margins.

There are several examples of China leveraging its position as a large scale producer of crucial materials for green transition to make competitors go out of business or close down operations. Price drops of 60-70% for materials such as cobalt and nickel shows China's strong strategic position regarding raw materials, where they are able to operate at much lower margins due to state backing. Serious European efforts to source and recycle materials, such as gallium and germanium, within Europe would probably need to be backed by import regulations or non-private investments to not go out of business.

Primary production of gallium by Metlen in Greece could also have an impact on developing circular flows within the EU. While the infrastructure might support more circular undertakings, the diversified supply might give European actors less incentives for circular practices regarding gallium. A simple conclusion from more supply, and less risk associated with supply, the price of gallium should stabilize, something that would push recycling alternatives out of range for commercial implementation.

Germanium recovery by STL in DRC seems to in contrast focus on more traditional circular flows, where germanium material is procured from mining tailings. By having a more clearly defined partnership with Umicore there is probably less risk with this kind of investment. Both parties benefit, STL get improved facilities and are able to enter a new market for strategic materials, while Umicore are able

to diversify their germanium supply to mitigate risk.

6.3 Why is it of interest for the stakeholders to invest in circularity questions?

One of the current main drivers for implementing circular flows of gallium and germanium appear to be geopolitical risk and fear of supply shortage, particularly for military applications. One example that strengthens this assumption is the US Department of War's focus on these materials in recent times, both from EoL sources and production scraps. This development could be in reaction to the intensified trade wars between China and the USA as briefly mentioned in section 2.3. Further it can be viewed as an attempt to strengthen their national supply and mitigate dependencies on foreign import.

This also supports that the Chinese dominance, discussed in section 2.3, can be viewed as one of the main factors of geopolitical risk. For instance, the export controls introduced in 2023 caused the global prices of gallium to rise significantly and lead to supply constraints. China holds such a strong position that by controlling prices, they effectively shape the market and can influence growth within Europe. If China then were to leverage its position to force out competitors similar to the cobalt and nickel case mentioned in 2.3 there might be little opportunity for investments in new infrastructure to become financially profitable during current conditions.

That global conflicts heighten the risk of supply shortages when the supply is concentrated is a fact, however there seems to be mitigating processes in place to lessen the impact of these noted by *Ash*. Nevertheless it seems that these processes are in some cases not very effective as dependencies still exist within the supply chain. Therefore a more locally sourced alternative could arguably be preferable, this is corroborated by *Aspen's* statement. Resilience can be viewed as a key factor in a well designed supply chain and circularity practices can be the answer to strengthening resilience through out the chain. *Ash* mentions the resilience is considered to be a driving force in their circularity projects. According to *Ash*, visibility and good working relationships between stakeholders are also noted to be key component in strengthening the supply chain. One could argue that these are also key components in increasing circularity in the supply chain and it is a reason to why directives such as ELV and projects like CLOSER are the chosen course of action by the EU. CLOSER exemplifies the existing dedication and commitment to establishing a closed loop system for semiconductor materials in Europe. Such initiatives could lead to an increase of European resilience in this area. Collaborations between stakeholders similar to CLOSER could also be utilized to bridge the information gaps within the supply chain and may therefore lead to easier implementation of circular practices.

Throughout the results, the price and quantity of gallium and germanium have been highlighted as two of the major factors shaping the current situation. Firstly, it is seemingly not profitable for manufacturers to recycle gallium and germanium as

electronic waste is valued by weight. As EoL vehicles seem to contain overall comparably small amounts of gallium and germanium the cost of specifically recycling these materials might outweigh the profits. Additionally it might result in recycled material having to be sold at a higher price-point than virgin material. Since cost is such a vital determiner in production this might lead to a situation of little change in the system as EU companies might be likely to continue to source more cost efficient materials outside of the EU. Secondly, many of the methods mentioned in the result might need to be implemented on a larger scale. Meaning that new infrastructure would be needed. This would likely come with additional costs which will be added on along the supply chain, ultimately increasing the price for end customers. All this is in line with *Elm*'s statement that the question is not whether it can be done, but how to make it economically sustainable.

With sustainability and circularity becoming increasingly relevant topics in today's society, decision making authorities have begun to act. Through the CRMA, the EU has acknowledged current vulnerabilities in the supply chain of CRMs, alongside directives such as the ELV. This emphasizes the importance of treating waste as a resource to support a circular transition. Growing public awareness of environmental issues has also increased consumer attention to sustainability, leading to greater consciousness around these topics.

The combination of the very small amounts of gallium and germanium in vehicles and the generally low awareness of these materials does pose a challenge. One can argue that there is unlikely to be a significant demand for cars containing recycled gallium or germanium if they come at a higher price point. Aluminum for example, occurs in larger quantities and is more familiar to customers. This could lead to a higher willingness to pay for a vehicle with recycled aluminum than for gallium and germanium. An increase of awareness of the criticality and importance of these materials could possibly lead to public demands of increasing recycled content. This could be the necessary push for manufactures throughout the supply chain to overcome the cost barrier of recycled materials.

Design for recycling, stated as one of the potentials for circular flows in the result, could in some ways be economically profitable for recycling companies. A modular design could not only make recycling of the ECUs less complicated and more cost efficient. It could also create possibilities of R4: Repair, R5: Refurbish and R6: Remanufacturing. If one component in the ECU stops working, it can just be plucked out and replaced with a new working one or used in production of a new unit. *Hazel*'s statement in 5.3.3 does corroborate this and according to *Hazel* this would be a winning concept for all companies. This would help the companies decrease their EoL waste and create another opening towards a circular flow leading to an economic profit.

7

Conclusion

The purpose of this thesis has been to explore the current circularity of gallium and germanium, as well as its potential. These materials have been identified as parts of the upstream supply chain of ECUs in vehicles which makes the automotive industry of main focus. By a combination of desk research and semi-structured interviews across the whole supply chain, a broad perspective has been provided.

7.1 Answering Research Question 1

This thesis identified knowledge gaps regarding circularity in the supply chain of gallium and germanium, highlighting recycling and circular strategies. This circularity has been established as a possible approach to reduce the EUs dependency on other countries regarding CRMs. By developing a clearer understanding of existing practices for circular flows, the study establishes a foundation for evaluating future opportunities and potentials related to Research question 2.

Current circular flows for gallium and germanium is limited mainly to higher up in the supply chain. There has been recent success in recovering germanium from mining tailings in DRC, and production scrap is recycled and re-used in larger scale by industry actors, while EoL sources are largely unused. The identified reason seems to be the knowledge of how the materials are connected to one another upstream, and that the mix of materials gets more complicated further down. An exception is germanium recovery from EoL military equipment for strategic stockpiling by the US.

As in all industries, price and costs are main focal points connected to this issue. Everything must be economical justifiable. It is also shown that a clear customer is what is needed to succeed. As for STL, they have an established customer with Umicore. Given that the importance of gallium and germanium is relatively newly understood, the knowledge base surrounding them is still developing, and the market is currently premature regarding circularity, compared to other metals such as gold and aluminum.

This lays the foundation for Research question 2 and therefore answers Research question 1.

7.2 Answering Research Question 2

The information below builds upon the foundation presented in the answer to Research question 1. It expands on the bridging of knowledge gaps by looking at tangible areas that can help decrease the EU's dependency in gallium and germanium supply chains. Furthermore, the financial feasibility of future investments are discussed as cost is presently a major issue.

Areas with high potential sources for gallium and germanium recycling today are landfill waste points like red mud (bauxite residue) and zinc waste (jarosite residue). These are more preferable due to high volumes and concentrations of gallium and germanium and a lower mix of materials. Another important secondary source could be urban mining for electronic waste, although it is more difficult to exploit due to low concentrations and a complex mix. Established extraction techniques such as hydro- and pyrometallurgy can be used but are not utilized for recycling on a large scale currently. Ongoing projects for primary production can thus be useful to make use of their existing infrastructure for gallium and germanium recycling.

New technologies like FJH and AI-based sorting can furthermore be used to decrease energy consumption and costs while increasing separation efficiency. They do offer advantages but lack industrial application currently. Beyond the techniques themselves, applying design for recycling could also be used to simplify circular practices and strengthen supply resilience. In this context, focusing on R3-R7 from the 9R framework is preferable but faces challenges such as the fact that a lot of different companies are involved in EoL flows and it is therefore difficult to apply standardization while maintaining quality. Another challenge by establishing circular flows for supply resilience is the geopolitical risk. The EU has been dependent on other actors regarding these materials for a long time, and attempting to become less dependent will probably be met with resistance. Non-private financing or legislation for gallium and germanium sourcing is probably needed for long term viability for circular flows.

This answers Research question 2. Further evaluation of incentives is explored in Research question 3.

7.3 Answering Research Question 3

The following part of the conclusion is primarily based on the interviews conducted, as well as insights from Research question 1 and Research question 2. Together, these findings provide a clearer picture of the landscape in which supply chain stakeholders operate and the conditions under which they would be willing to invest.

Resilience is a key characteristic of a secure supply chain, and strengthening circularity offers an important opportunity to enhance this resilience. A more independent Europe would therefore be better equipped to manage disruptions and reduce exposure to geopolitical risks, such as China's export controls and the semiconduc-

tor shortage during COVID-19. As mentioned in the introduction, semiconductor production is not always prioritized for the automotive sector, which further underscores the need for resilience within the semiconductor supply chain for automotive applications. To foster both circularity and resilience under current conditions, investments of both financial and intellectual capital will be required to develop the necessary technologies, processes, and infrastructure.

Sustainability and circularity are becoming increasingly relevant topics in today's society, particularly in the EU. Public awareness of environmental issues is growing and new regulations arise as research progresses. Both regulatory framework such as CRMA and investments like CLOSER are initiatives by EU to, in the future, secure the supply of CRMs within Europe. These developments are likely to continue further beyond the perceivable future which makes it even more relevant for stakeholders joining this transition. Companies should therefore position themselves to be front runners or at least participants in this transition and invest early in circularity questions. With an increasing amount of incentives and regulations, companies will also be expected to account for sustainability. In the future, it might be seen as an advantage to have joined this transition at an early stage.

This section answer Research question 3.

7.4 Limitations and Future Research

The encountered limitations during the data collection were mainly linked to the time constraints as well as supply chain transparency. A consequence of the set time frame was, although numerous stakeholders were contacted, all desired interviews were not feasible to carry out. Certain interviewees had limited availability which led to constraints regarding the iterative process of interviews, where new information emerge that would be interesting to investigate further. Most interviews ended by the question *"Who would you recommend us to contact next?"* which provided an oversight of what the industry wanted to know. This could have been taken further given more time.

During the early stage of the project, it became clear that the studied industry is characterized by a lack of transparency. This posed challenges in two ways. Many interviewees had limited knowledge of parts of the supply chain beyond their own, and much of the relevant information is considered sensitive by companies. As a result, several actors were hesitant about what they were allowed to disclose. The interviews conducted were also constrained by the knowledge of the interviewee, creating a degree of information asymmetry. The interviewee's position on the company may have influenced their perspective on the topic. While this provided valuable diversity in viewpoints, it may also have resulted in responses that were shaped by their specific roles and responsibilities.

A possible direction for future research is to further expand the sustainability perspective beyond the scope of this study. While this thesis primarily focuses on

supply risk and circular flows, future studies could investigate the economic sustainability of different technologies by including detailed cost analyses. Such analyses could help determine which strategies are economically viable. It would also be valuable to execute research concerning the environmental impacts associated with the identified technologies. Although circular solutions may reduce dependency on primary sources, the methods themselves could generate disadvantageous emissions or by-products. In addition, this thesis did not investigate the social sustainability aspects. Future research could therefore examine, for example, labor rights, health and safety. Including these social dimensions would provide a more comprehensive sustainability assessment of circular supply chains for CRMs such as gallium and germanium.

Bibliography

- Ali, A., & Khan, R. A. (2023). A feasibility assessment on the use of industrial waste jarosite in concrete construction [UKIERI Concrete Congress – ‘Sustainable Concrete Infrastructure’]. *Materials Today: Proceedings*, 93, 302–309. <https://doi.org/https://doi.org/10.1016/j.matpr.2023.07.260>
- Allen, M. (2024, April 12). *The riches in Europe’s mountains of metals waste*. Horizon Magazine, European Commission. Retrieved April 10, 2026, from <https://projects.research-and-innovation.ec.europa.eu/en/horizon-magazine/riches-europes-mountains-metals-waste>
- Andersson, F., & Lennström, M. (2025). Dependence dynamics in the upstream of semiconductor supply chain to the automotive; a case study with four embedded cases.
- Argus Media. (2026, April 7). *Metallium advances US gallium recovery project*. Argus Media. Retrieved April 9, 2026, from <https://www.argusmedia.com/en/news-and-insights/latest-market-news/2810804-metallium-advances-us-gallium-recovery-project>
- Baldassarre, B., & Carrara, S. (2025). Critical raw materials, circular economy, sustainable development: Eu policy reflections for future research and innovation. *Resources, Conservation and Recycling*, 215, 108060. <https://doi.org/https://doi.org/10.1016/j.resconrec.2024.108060>
- Baskaran, G. (2025, June 12). *Building a new market to counter Chinese mineral market manipulation* [Critical Minerals Security Program]. Center for Strategic and International Studies. Retrieved April 9, 2026, from <https://www.csis.org/analysis/building-new-market-counter-chinese-mineral-market-manipulation>
- Bell, E., Bryman, A., & Harley, B. (2022). *Business research methods* (6th). Oxford University Press.
- Berg, R. C., Ziemer, H., & Polo Anaya, E. (2024). *Mineral demands and supply chain vulnerabilities* (CSIS Brief, published May 2024, accessed 2026-03-20). Center for Strategic and International Studies (CSIS). https://csis-website-prod.s3.amazonaws.com/s3fs-public/2024-05/240515_Berg_Mineral_Demands.pdf
- Bergfald, B., Kristensen, K., & Lystad, H. (2024). *Recycling of critical raw materials in the nordics*. Nordisk Ministerråd. <https://doi.org/10.6027/temanord2024-513>
- Blackwood, M., & DeFilippo, C. (2024, March). *Germanium and gallium: U.S. trade and chinese export controls* (Executive Briefing on Trade) (The views expressed solely represent the opinions and professional research of the authors and do not represent the views of the U.S. International Trade Commission)

- or the United States government.). U.S. International Trade Commission, Office of Operations. Retrieved April 9, 2026, from https://www.usitc.gov/publications/332/executive_briefings/ebot_germanium_and_gallium.pdf
- Brindley, K. (2011). Chapter 12 - soldering. In K. Brindley (Ed.), *Starting electronics (fourth edition)* (Fourth Edition, pp. 205–257). Newnes. <https://doi.org/https://doi.org/10.1016/B978-0-08-096992-3.00012-3>
- Burkacky, O., Deichmann, J., Pflingstag, P., & Werra, J. (2022). Semiconductor shortage: How the automotive industry can succeed. *McKinsey & Company*.
- Butcher, T., & Brown, T. (2014). Gallium. In G. Gunn (Ed.), *The critical metals handbook* (pp. 150–176). John Wiley & Sons. <https://doi.org/10.1002/9781118755341.ch7>
- CLOSER. (n.d.). *About* [LinkedIn page]. Retrieved March 27, 2026, from <https://www.linkedin.com/company/closereuproject/about/>
- Cucchiella, F., D’Adamo, I., Rosa, P., & Terzi, S. (2016). Automotive printed circuit boards recycling: An economic analysis. *Journal of Cleaner Production*, 121, 130–141. <https://doi.org/https://doi.org/10.1016/j.jclepro.2015.09.122>
- De Angelis, R., Howard, M., & Miemczyk, J. (2018). Supply chain management and the circular economy: Towards the circular supply chain. *Production Planning & Control*, 29(6), 425–437. <https://doi.org/10.1080/09537287.2018.1449244>
- Dhiman, S., Fuloria, N., Ghosh, A., Chaudhary, S., Ziauddin Ahammad, S., Tsushima, S., Kelly, N., & Jain, R. (2024). Gallium recovery from red mud: Integration of solvent extraction and siderophore assisted technologies. *Journal of Environmental Management*, 370, 122374. <https://doi.org/https://doi.org/10.1016/j.jenvman.2024.122374>
- Du, B., Bryson, J. R., & Qamar, A. (2025). Aspiring towards automotive circularity: A critical review and research agenda. *Journal of Environmental Management*, 380, 125150. <https://doi.org/https://doi.org/10.1016/j.jenvman.2025.125150>
- Encyclopaedia Britannica. (n.d.). Germanium [Accessed: 2026-02-10].
- European Commission. (2023). *End-of-life vehicles regulation* [Accessed: 2026-03-18]. Retrieved March 18, 2026, from https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles/end-life-vehicles-regulation_en
- European Commission. (2024). Circular raw materials for European Open Strategic autonomy on chips and microelectronics production (CLOSER) [Status: Ongoing; Duration: 1 October 2024–30 September 2027; <https://ec.europa.eu/info/funding-tenders/opportunities/portal/screen/opportunities/projects-details/44416173/101161109/I3>].
- European Commission. (n.d.). *End-of-life vehicles* [Accessed: 2026-03-17]. https://environment.ec.europa.eu/topics/waste-and-recycling/end-life-vehicles_en
- European critical raw materials act [Published 16 March 2023]. (2023). *European Commission*. https://commission.europa.eu/topics/competitiveness/green-deal-industrial-plan/european-critical-raw-materials-act_en
- European Investment Bank. (2026, January 15). *Eib backs Europe’s first gallium production investment with €90 million financing to METLEN in Greece* [Press release 2026-011-EN]. European Investment Bank. Retrieved April 7, 2026, from <https://www.eib.org/en/press/all/2026-011-eib-backs-europe-s-first>

- gallium-production-investment-with-eur90-million-financing-to-metlen-in-greece
- European Union. (2023). *End-of-life vehicles* [Summary of Directive 2000/53/EC, last updated 30 March 2023]. <https://eur-lex.europa.eu/EN/legal-content/summary/end-of-life-vehicles.html>
- European Union. (2024). Regulation (EU) 2024/1252 of the European Parliament and of the Council on critical raw materials [Accessed: 2026-02-19]. <https://eur-lex.europa.eu/legal-content/EN/TXT/?uri=CELEX:32024R1252>
- Guan, T., Guo, M., Wang, L., & Liu, J. (2025). Production and recycling of the cutting edge material of gallium: A review. *Science of The Total Environment*, 971, 179046. <https://doi.org/10.1016/j.scitotenv.2025.179046>
- Hadj, G. (2025). An ai-based method for sorting and separation of semiconductor waste: An environmentally friendly method for implementing a circular economy in the semiconductor industry. *The Eurasia Proceedings of Science, Technology, Engineering and Mathematics*, 38, 296–306. <https://doi.org/https://doi.org/10.55549/epstem.1228>
- Hadrian, W. (2025, December). *Metallium Ltd critical metals partnership secures \$10.1M funding*. Discovery Alert. Retrieved April 27, 2026, from <https://discoveryalert.com.au/metallium-critical-metals-partnership-usa-2025/>
- Haghighi, H. K., & Irannajad, M. (2022). Roadmap for recycling of germanium from various resources: Reviews on recent developments and feasibility views. *Environmental Science and Pollution Research*, 29(32), 48126–48151. <https://doi.org/10.1007/s11356-022-20649-5>
- Han, Z., Liu, Q., Ouyang, X., Song, H., Gao, T., Liu, Y., Wen, B., & Dai, T. (2024). Tracking two decades of global gallium stocks and flows: A dynamic material flow analysis. *Resources, Conservation and Recycling*, 202, 107391. <https://doi.org/https://doi.org/10.1016/j.resconrec.2023.107391>
- Höll, R., Kling, M., & Schroll, E. (2007). Metallogenesis of germanium—a review. *Ore Geology Reviews*, 30(3), 145–180. <https://doi.org/https://doi.org/10.1016/j.oregeorev.2005.07.034>
- Huang, Y., Wang, M., Liu, B., Su, S., Sun, H., Yang, S., & Han, G. (2024). The extraction and separation of scarce critical metals: A review of gallium, indium and germanium extraction and separation from solid wastes. *Separations*, 11(4). <https://doi.org/10.3390/separations11040091>
- Indium Corporation. (n.d.). *Metals and compounds reclaim and recycle program*. Retrieved May 3, 2026, from <https://www.indium.com/products/reclaim-and-recycle/metals/>
- International Energy Agency (IEA). (2023). *Clean energy supply chains vulnerabilities* [Part of: Energy Technology Perspectives 2023, accessed 2026-03-20]. <https://www.iea.org/reports/energy-technology-perspectives-2023/clean-energy-supply-chains-vulnerabilities>
- Kaiser, M. (2015). Electronic control unit (ecu). In K. Reif (Ed.), *Gasoline engine management: Systems and components* (pp. 254–259). Springer Fachmedien Wiesbaden. https://doi.org/10.1007/978-3-658-03964-6_16
- King, I., Wu, D., & Pogkas, D. (2021). How a chip shortage snarled everything from phones to cars. *Retrieved June, 1, 2021*.

- Kumar, A., Dhiman, S., Kumar, R., & Gupta, H. (2025). Recovery of germanium from waste optical fibres using phosphonium ionic liquid. *Journal of Cleaner Production*, 505, 145466. <https://doi.org/https://doi.org/10.1016/j.jclepro.2025.145466>
- Mei, Y., Geng, Y., Chen, Z., Xiao, S., & Gao, Z. (2024). Ensuring the sustainable supply of semiconductor material: A case of germanium in china. *International Journal of Production Economics*, 271, 109231. <https://doi.org/https://doi.org/10.1016/j.ijpe.2024.109231>
- Merriam, S. B., Tisdell, E. J., & Stuckey-Peyrot, H. L. (2025). *Qualitative research: A guide to design and implementation* (5th ed.). Jossey-Bass. <https://research.ebsco.com/linkprocessor/plink?id=073836bb-67f6-37e7-a224-0689affd0fa8>
- Metallium Ltd. (n.d.). *FJH: What is flash joule heating?* [Technology overview page]. Metallium Ltd. Retrieved April 10, 2026, from <https://metalliuminc.com/flash-joule-heating>
- METLEN Energy & Metals. (2025, March 26). *METLEN's investment in gallium production is officially included in the EU's selected strategic projects for critical raw materials*. METLEN Energy & Metals. Retrieved April 9, 2026, from <https://www.metlen.com/news/press-releases/metlen-s-investment-in-gallium-production-is-officially-included-in-the-eu-s-selected-strategic-projects-for-critical-raw-materials/>
- Moore, N. (2006). Desk research. In *How to do research: The practical guide to designing and managing research projects* (pp. 106–111). Facet.
- Muñoz, S., Hosseini, M. R., & Crawford, R. H. (2024). Towards a holistic assessment of circular economy strategies: The 9r circularity index. *Sustainable Production and Consumption*, 47, 302–316. <https://doi.org/https://doi.org/10.1016/j.spc.2024.04.015>
- Naqvi, S. S. A., Jamil, H., Faseeh, M., Iqbal, N., Khan, S., & Kim, D.-H. (2024). A comprehensive review on development strategies of integrated electronic control units in ioevs for energy management. *Internet of Things*, 25, 101085. <https://doi.org/https://doi.org/10.1016/j.iot.2024.101085>
- Neo Performance Materials. (n.d.). *Gallium*. Neo Performance Materials. Retrieved April 20, 2026, from <https://www.neomaterials.com/rare-metals/gallium/>
- Paloheimo, J. (2020). Properties of silicon crystals. In M. Tilli, T. Motooka, V.-M. Airaksinen, S. Franssila, R. L. Puurunen, & T. Kajartton (Eds.), *Handbook of silicon based mems materials and technologies* (3rd, pp. 61–92). Elsevier. <https://doi.org/10.1016/B978-0-12-817786-0.00003-7>
- Peitzmeier, H., Tebruegge, C., Bouattour, G., & Seibel, A. (2025). Circularity in automotive electronics design: A comparative evaluation of headlight control units [32nd CIRP Conference on Life Cycle Engineering (LCE2025)]. *Procedia CIRP*, 135, 900–905. <https://doi.org/https://doi.org/10.1016/j.procir.2024.12.096>
- Pellicelli, M. (2023). Chapter one - toward a new way of thinking. In M. Pellicelli (Ed.), *The digital transformation of supply chain management* (pp. 3–33). Elsevier. <https://doi.org/https://doi.org/10.1016/B978-0-323-85532-7.00006-2>

- Pereira, A. C. (2026). Electronic waste and semiconductor-related residues as secondary sources of gallium: Occurrence, processing routes, separation challenges, and circular supply perspectives. *REMUNOM*, 13(07). <https://doi.org/10.66104/c6qq5978>
- Potting, J., Hekkert, M. P., Worrell, E., & Hanemaaijer, A. (2017). *Circular economy: Measuring innovation in the product chain* (tech. rep. No. 2544) (Accessed: 2026-05-07). PBL Netherlands Environmental Assessment Agency. The Hague. <https://www.pbl.nl/en/publications/circular-economy-measuring-innovation-in-product-chains>
- Powers-Riggs, A., Hart, B., Funaiolo, M. P., Thomsett, S., Zieleniewski, S., & Rose, T. (2025, July). *Beyond rare earths: China's growing threat to gallium supply chains* (CSIS Brief). Center for Strategic and International Studies (CSIS). Washington, D.C. Retrieved April 7, 2026, from <https://www.csis.org/analysis/beyond-rare-earths-chinas-growing-threat-gallium-supply-chains>
- Purchase, D., Abbasi, G., Bisschop, L., Chatterjee, D., Ekberg, C., Ermolin, M., Fedotov, P., Garelick, H., Isimekhai, K., Kandile, N. G., Lundström, M., Matharu, A., Miller, B. W., Pineda, A., Popoola, O. E., Retegan, T., Ruedel, H., Serpe, A., Sheva, Y., ... Wong, M. H. (2020). Global occurrence, chemical properties, and ecological impacts of e-wastes (iupac technical report). *Pure and Applied Chemistry*, 92(11), 1733–1767. <https://doi.org/10.1515/pac-2019-0502>
- Rahman, K. F., Falina, S., Mohamed, M. F. P., Kawarada, H., & Syamsul, M. (2024). The role of gallium nitride in the evolution of electric vehicles: Energy applications, technology, and challenges. *Applied Physics Reviews*, 11(3), 031322. <https://doi.org/10.1063/5.0215799>
- Rashid, S., & Malik, S. (2023). Transition from a linear to a circular economy. In *Renewable energy in circular economy* (pp. 1–20). Springer.
- Ribeiro da Silva, E., Lohmer, J., Rohla, M., & Angelis, J. (2023). Unleashing the circular economy in the electric vehicle battery supply chain: A case study on data sharing and blockchain potential. *Resources, Conservation and Recycling*, 193, 106969. <https://doi.org/10.1016/j.resconrec.2023.106969>
- Richert, M., & Łebkowski, P. (2025). Development of automotive industry trends and demand for critical raw materials worldwide. *Journal of Entrepreneurship & Sustainability Issues*, 12(4).
- Robla, J. I., Alonso, M., & Alguacil, F. J. (2024). Recovery of lesser-known strategic metals: The gallium and germanium cases. *Processes*, 12(11), 2545. <https://doi.org/10.3390/pr12112545>
- Royal Swedish Academy of Engineering Sciences (IVA). (2024, November). *Roadmap for metals and minerals* (tech. rep.) (Accessed: 2026-04-14). Royal Swedish Academy of Engineering Sciences (IVA). <https://sustainability.unesco-floods.eu/wp-content/uploads/2024/12/202411-iva-vagval-for-metaller-och-mineral-rapport2-english-h.pdf>
- Snyder, H. (2019). Literature review as a research methodology: An overview and guidelines. *Journal of Business Research*, 104, 333–339. <https://doi.org/10.1016/j.jbusres.2019.07.039>

- Srivastava, R. R., & Ilyas, S. (2025). Harnessing germanium from industrial residues and electronic waste for a sustainable energy future [Cited by: 0; All Open Access, Green Open Access, Hybrid Gold Open Access]. *Green Chemistry*, 27(46), 14744–14768. <https://doi.org/10.1039/d5gc03018h>
- Streetman, B. G. (2001). Semiconductors and transistors. In M. E. Van Valkenburg & W. M. Middleton (Eds.), *Reference data for engineers: Radio, electronics, computers and communications* (9th). Newnes. <https://doi.org/10.1016/B978-075067291-7/50020-0>
- Sugunaraj, N., & Ranganathan, P. (2022). Electronic control unit (ecu) identification for controller area networks (can) using machine learning. *2022 IEEE International Conference on Electro Information Technology (eIT)*, 1–7.
- Teng, D., Wu, J., Ma, Q., Wang, W., Zhou, G., Fan, G., Cao, Y., & Li, P. (2025). Advances in the recovery of critical rare dispersed metals (gallium, germanium, indium) from urban mineral resources [PMID: 39829574]. *ACS Omega*, 10(1), 76–92. <https://doi.org/10.1021/acsomega.4c08689>
- Umbrex. (n.d.). *How the recycling industry works* [Accessed: May 3, 2026]. Umbrex Resources. <https://umbrex.com/resources/how-industries-work/waste-management-sustainability/how-the-recycling-industry-works/>
- Umicore. (2024, October). *First “Made-in-DRC” germanium concentrates due for export to Umicore for high-tech applications*. Umicore. Retrieved April 21, 2026, from <https://www.umicore.com/en/media/newsroom/first-made-in-drc-germanium-concentrates-due-for-export-to-umicore-for-high-tech-applications/>
- Umicore. (2026). *Recycling & refining*. Umicore. Retrieved April 3, 2026, from <https://www.umicore.com/en/markets-products/metals/germanium/germanium-refining/>
- U.S. Department of Energy. (2026, April). Doe’s office of critical minerals and energy innovation selects five organizations to restart domestic primary gallium recovery [Accessed: 2026-05-02]. <https://www.energy.gov/cmei/articles/does-office-critical-minerals-and-energy-innovation-selects-five-organizations>
- Wachtmeister, H. (2025). *China’s mineral export restrictions: Market impacts and implications* (Report No. NKK-2025-04). Swedish National China Centre (NKK), Swedish Institute of International Affairs (UI). <https://kinacentrum.se/en/publications/chinas-mineral-export-restrictions-market-impacts-and-implications/>
- Wohlin, C., Mendes, E., Felizardo, K. R., & Kalinowski, M. (2020). Guidelines for the search strategy to update systematic literature reviews in software engineering. *Information and Software Technology*, 127, 106366. <https://doi.org/10.1016/j.infsof.2020.106366>
- Wu, X., Roy, V., Liu, Y., Shakelly, N., Ghosh, T., Yang, X., Sutherland, J. W., & Zhao, F. (2025). Transforming e-waste into strategic resources: Techno-economic analysis of gallium and by-products recovery from LEDs via bioleaching. *Research Square (Preprint)*. <https://doi.org/10.21203/rs.3.rs-7436577/v1>

- Xiao, J., Cheng, L., Wu, H., Hou, M., Chen, X., & Wong, C.-P. (2025). Flash joule heating: A transformative non-equilibrium strategy for next-generation advanced materials. *Small Methods*. <https://doi.org/10.1002/smtd.202501678>
- Xun, D., Sun, M., Shen, Z., Ding, B., Lin, Z., Zheng, T., Zheng, L., Zhao, K., Li, Q., Zhou, B., Qin, S., Zeng, J., Sun, Y., Zhong, Y., & Liu, J. (2026). A review of preparation methods, product specifications, detection techniques, and production environments for high-purity rare and scattered metals. *Journal of Materials Science & Technology*, 268, 189–220. <https://doi.org/https://doi.org/10.1016/j.jmst.2025.12.023>
- Yadav, S., Yadav, J., Bruckard, W., Haque, N., & Pramanik, B. K. (2026). Gallium and germanium: Comparing demand and supply with consideration of electronic waste as a secondary source. *Separation and Purification Technology*, 398, 138270. <https://doi.org/https://doi.org/10.1016/j.seppur.2026.138270>
- Yin, R. (2016). *Qualitative research from start to finish*. Guilford Publications. <https://books.google.se/books?id=DvpPCgAAQBAJ>
- Yin, R. K. (2014). *Case study research: Design and methods* (5th ed.). SAGE Publications.
- Zhou, W., Crochet, V., & Wang, H. (2025). Demystifying china’s critical minerals strategies: Rethinking ‘de-risking’ supply chains. *World Trade Review*, 24(2), 257–281. <https://doi.org/10.1017/S1474745624000193>
- Zuo, L., Huang, Z., Song, H., Achari, G., & He, P. (2025). Global and regional gallium recycling potential and opportunities: Based on historical material flow analysis. *Sustainability*, 18(1), 255. <https://doi.org/10.3390/su18010255>

A

Appendix 1

Key takeaways and extracted quotes from conducted interviews could be find in appendix.

A. Appendix 1

Theme	Respondent	Company	Key takeaways
Critical raw material supply	Poplar	Tier-3 A	[Regarding zinc mining] ● Gallium and germanium occurs at trace levels in sphalerite (ZnS) and is therefore only extracted as by-products in the zinc industry. ● Hydrometallurgy can provide very high yields, but requires advanced process control and expensive facilities. ● Pyrometallurgy is attractive for emptying large jarosite piles and creating circular material flows, but is energy-intensive.
Semiconductor manufacturing	Aspen	Tier-2 A	● It is technically possible for Tier-2 As products to have longer lifespan than they currently do; however, there is limited or no market demand for extending use. ● Critical raw materials are recovered in-house within production facilities to improve efficiency. In some cases, less purified materials are purchased and refined internally. ● There is currently limited visibility into upstream supply chain, but there is an ambition to improve transparency.
Component delivery	Pine	OEM A	● There is no negative attitude towards ECUs with recycled material, provided there is a proof of concept showing the same lifespan as others and no negative consequences. ● A company that produces its own ECUs or batteries and can establish a recycled flow can increase its market share. ● The companies need to be competitive in the market and provide a product to a good price to our end customer herefore, price is one key aspect. ● If the Critical Raw Material Act enters into force completely, more European suppliers of raw materials will be of interest, but so far this is not main track.
	Hazel	OEM B	● Refurbishment could be a proactive approach to resilience. ● There is a need to design for disassembly. Modular design is discussed extensively. ● Operations are in line with the ELV Directive. ● Automotive overall constitutes a very small part of the market. Therefore, it is difficult for an individual OEM to influence the supply chain.
	Ash	OEM C	● China dominates the supply of gallium and germanium and there is a wish to avoid being dependent on China. ● Due to that anything can happen in the next couple of months, strengthening of supply chain resilience is necessary. Covid was a driving factor for this. Securing REEE is a key. ● CRMA is a driving force in projects regarding looking into the supply chain upstreams. ● Companies, including Chinese ones, need to classify different kinds of products and parts. Specific materials but not all require classification and in turn a certificate needed for export to certain places.
	Rowan	Tier-1 A	● Normally, it is such that legislation and customer requirements determine the level of compliance that a product should have ● Components often contain milligrams of certain materials (gallium and germanium) and such amounts do not drive recycling systems, Low mass = low economic incentive = low circularity ● Gallium and germanium are not mentioned very often in electronics, there are other things that affect much more, e.g. lead.
	Juniper	Tier-1 B	● The company is working with design for recycling but ECUs are hard to recycle. This is because of the wide variety of materials used, that ECUs are usually highly integrated into the vehicle and that it is hard opening the control units (e.g., using screws instead of adhesives) ● The company sets high standards on the suppliers regarding transparency and the proportion of recycled materials (if applicable)
Recycling from End-of-Life	Beech & Alder	Recycling company	● Recycled materials can match the performance of virgin materials, but the need for quality assurance and additional processes inevitably adds costs. ● If bonding of materials is avoided, they are easier to separate in the recycling process. ● Several companies realize that circular economy offers both goodwill and a solid business case. ● Technical innovations linked to recycling are sensor technology and AI
	Spruce	Researching center	● Towards the transition of green technology, there is not enough rare earth metals to cover the demand. ● Europe have found rare earth metals in crust and landfills back in the time during export limits from China. ● Historically Europe have invested in long term solutions during increased prices of rare earth metals, but the longterm solutions goes lost when rices decreases.
	Elm	Researching center	● Extensive research is still being conducted on the properties of gallium and germanium. In recent years, we have started to realize their importance in the field of electronics. ● We are moving towards a circular economy, and in the future, we will no longer talk about materials as waste.

Table A.1: Key takeaways from the conducted interviews categorized depending on the companies position in the supply chain.

A. Appendix 1

Theme	Respondent	Company	Example quote
Critical raw material supply	Poplar	Tier-3 A	-
Semiconductor manufacturing	Aspen	Tier-2 A	"Basic research usually begins with government funding or project grants, at national or EU level."
Component delivery	Pine	OEM A	"Since we in most cases do not manufacture the ECU ourselves, we can only place demands on suppliers and then these demands are subject to negotiations to find a cost effective and quality part - it is rare that we buy a completely unique developed ECU just for us that is not some kind of adjusted 'off the shelf' solution."
	Hazel	OEM B	"What is needed is that as soon as an idea is hatched, we should be thinking about sustainability." "I think everything can be solved, but there is a lot of inertia in these kinds of changes. It takes time to change."
	Ash	OEM C	-
	Rowan	Tier-1 A	"A third party cannot guarantee that the components have the same function as new." "Preferably, there would be no requirements at all for an as reliable product as possible that has a competitive price."
	Juniper	Tier-1 B	-
Recycling from End-of-Life	Beech & Alder	Recycling company	"There is no market for germanium or gallium."
	Spruce	Researching center	[regarding rare earth elements case] "But there was a company who invested in this in France because the price was so high, so they built plant, price went down, and plant was closed. But if you have a metal which is in high demand for many years, and there is no replacement, and not much production, if you start recycling, you should be able to survive"
	Elm	Researching center	-

Table A.2: Some example quotes from the conducted interviews categorized depending on the companies position in the supply chain. Quoting was only done when allowed by the interviewee.



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