Journal of Circular Economy
https://doi.org/10.55845/MNTS1778 Volume 2, Issue 2

Research paper

Circularity of Semiconductor Chip Value Chains: Advancing AI Sustainability Amid Geopolitical Tensions

Patrick Schröder[1*], Martin Charter[2], Jack Barrie[3]

Handling Editors: Brian Baldassarre and Benjamin Sprecher

Received: 09.01.2024 / Accepted: 23.03.2025

Abstract

Semiconductor chips are the foundational hardware driving the capabilities of artificial intelligence (AI) systems. This paper explores the potential of circular economy strategies to address key challenges in semiconductor chip value chains, including environmental impacts, resource constraints, and geopolitical risks. The study fills a gap in existing literature by focusing on an industry that remains largely underexplored in circular economy research. The key research questions the paper explores are: 1. How can circular economy practices transform the semiconductor value chain to reduce environmental impact and improve resource security? 2. How can these circular practices strengthen the value chain against geopolitical risks and supply chain disruptions? Using a value chain approach and complex systems perspective, informed by a narrative literature review of academic and grey literature, the paper examines how circular practices across five key stages of the semiconductor value chain can mitigate environmental pressures, reduce dependency on critical raw materials like silicon and gallium, and enhance supply chain resilience against geopolitical disruptions. Existing initiatives by leading companies such as TSMC, ASML, and Intel are reviewed, alongside emerging technological innovations in semiconductor chip materials and manufacturing processes. The paper concludes by identifying critical future research questions and providing actionable insights for policymakers, industry and researchers.

Keywords: Semiconductors · AI · Circularity · Environmental Feedback Loops · Value Chains · Critical Raw Materials · Geopolitical Risk

1. INTRODUCTION – CIRCULARITY POTENTIALS, ENVIRONMENTAL CHALLENGES AND GEOPOLITICAL RISKS

Semiconductor chips, sometimes referred to as integrated circuits or microchips, are crucial components of electronics. Semiconductor chips are the foundational hardware driving the capabilities of artificial intelligence (AI) systems, enabling everything from data processing to machine learning algorithms (Suleyman & Bhaskar, 2024). However, the rapid expansion of AI comes with significant sustainability challenges, as the energy-intensive processes and increased demand for hardware place pressure on resource use including critical raw materials (CRMs). Addressing these concerns requires integrating circular economy principles into semiconductor chip value chains to ensure AI's growth aligns with long-term environmental goals.

Semiconductor value chains are highly complex and involve different geographical regions and groups of companies – wafers and chemicals are produced mainly in Japan and South Korea, while Taiwan Semiconductor

[1] Environment and Society Centre, The Royal Institute of International Affairs, Chatham House, 10 St James's Square, London, SW1Y 4LE, UK
[2] The Centre for Sustainable Design, University for the Creative Arts, Farnham Campus, Falkner Road, Farnham, Surrey, GU9 7DS, UK
[3] Environment and Society Centre, The Royal Institute of International Affairs, Chatham House, 10 St James's Square, London, SW1Y 4LE, UK
[*]Corresponding author: pschroeder@chathamhouse.org

Manufacturing Company (TSMC) in Taiwan is the top manufacturer for chips at ten nanometers or below. Intel dominates the global market for desktop and laptop central processing units (CPUs) and the production of lithography equipment is dominated by ASML in the Netherlands (McKinsey & Company, 2020). Driven by new developments in generative AI, the global semiconductor industry revenue grew 18% in 2024 to a total of $626 billion (Gartner, 2025), compared with $140 billion market size in 2000.

At the same time, the global semiconductor industry is one of the most resource-intensive industries in the world with significant energy consumption, growing greenhouse gas emissions and toxic pollution. The need for a circular economy approach to reduce environmental impacts of high-tech products and value chains such as electronics, solar photovoltaic (PV) panels and electric vehicle (EV) batteries, all of which contain semiconductors, has been moving up on the agenda of governments, businesses and standardization bodies (Schumacher & Green, 2023). Circularity is also increasingly realized as a key solution not only to address environmental concerns, but also to ensure resilient supply of CRMs and mitigate vulnerabilities in strategic value chains. The interlinking semiconductor and CRM supply chains are the foundation of the global economy. For example, titanium metal and increasingly titanium scrap is essential for the aviation industry (Jakimów et al., 2024) and for hydrogen electrolysers and fuel cells (Axt et al., 2023), which are in turn essential for the energy transition. So far, circular innovations for semiconductors have yet to be explicitly included in foresight studies about circularity and innovation potentials for critical products in strategic technologies (Baldassarre et al., 2023).

To address this gap, the main research question the paper aims to addresses is: 1. How can circular economy practices transform the semiconductor value chain to reduce environmental impact and improve resource security? A secondary research question is: 2. How can these circular practices strengthen the value chain against geopolitical risks and supply chain disruptions?

By leveraging a supply chain approach and integrating insights from both academic and grey literature, this research fills a critical gap in the existing body of knowledge. It offers an overview of circularity potentials and interactions of environmental, political and technological factors across semiconductor supply chains. The paper argues that circularity is an important part of the solution, not only to address environmental concerns, but also to geopolitical challenges that are posing risks to the semiconductor industry and value chains.

The remainder of the introduction provides further details on the environmental impacts and geopolitical risks associated with semiconductor chip supply chains. Section 2 describes the research methods applied. Section 3 is the main section of the paper, covering the five stages of semiconductor value chains. Section 4 presents an overview of semiconductor value chains as a complex system, explaining interlinkages between environmental system feedback and geopolitical dynamics. Section 5 serves as the discussion, offering recommendations and outlining future research questions, followed by Section 6 as the conclusion.

1.1 Impacts on Climate and Environment

In 2021, Scope 1 and 2 carbon emissions of the semiconductor manufacturing industry worldwide were estimated to be 76.5M tons of CO2 equivalent, an increase of 13 percent compared to 2020 (Pelcat, 2023). Furthermore, roughly 79 percent of CO2 equivalent lifecycle emissions of a semiconductor in 2021 are scope 3, with 16 percent from the supply chain and 63 percent from the use phase (SEMI, 2023). Over the last decade, industrial-level carbon emissions from manufacturing of semiconductors as key components of computing hardware have become the largest share of the carbon footprint of computing systems (Gupta et al., 2022).

The environmental and health impacts from semiconductor component manufacture have been known since the 1990s. The semiconductor industry uses large amounts of hazardous chemicals including hydrochloric acid, arsenic, various toxic metals and gases, and ozone-forming volatile solvents all of which have adverse human health impacts, while impacts on the environment include groundwater and air pollution and generation of toxic waste as a by-product of the semiconductor manufacturing process (Chepesiuk, 1999; Boyd, 2012). The wafer fabrication stage has been identified as the manufacturing phase with the highest environmental impact, requiring huge quantities of raw materials, water, energy, and generation of waste and emissions. Increasing company size, higher value-added per wafer, and advancements in technological capacity do not consistently lead to better environmental performance, nor do they always lead to reductions in water, energy, waste, wastewater and GHG emissions per unit of wafer production (Ruberti, 2023).

1.2 Geopolitical Risks to Semiconductor Supply Chains

The challenges for the semiconductor industry are also geopolitical, as intensifying tensions between countries are threatening the stability and resilience of semiconductor value chains, particularly in the context of the global AI race, where nations are vying for dominance in AI innovation and technological leadership (Krebs, 2024). As a result, potential disruptions and the need to secure access to semiconductor chips has become critical technological vulnerabilities and a potential national security threat for all major economies alike including the United States, China, and Europe (Carrara et al., 2023). All countries and many electronics industries rely on TSMC in Taiwan for cutting-edge semiconductor chips. A potential regional naval war in the East China Sea between China and the US (potentially involving US allies Japan and South Korea) or an invasion of Taiwan by the China are increasingly regarded as high-impact events that would have wide ranging disruptive impacts across global technology supply chains (Teer et al., 2022).

The semiconductor chip industry also depends heavily on CRMs, which are in limited supply and controlled by a small number of actors and suppliers. For example, Russia has been major supplier of neon and palladium which are key materials for semiconductor manufacturing equipment (Lu & Gramer, 2022). Neon supply first became critical in 2014 with the occupation of Crimea by Russia and again in 2021 with the invasion of Ukraine – 70% of the gas is made by Ukraine and Russia. Some 45% to 54% of the world's semiconductor-grade neon gas, needed for the lasers used to make semiconductors, came from two Ukrainian companies which halted production in 2022 when Russia intensified its attack on the country (Alper, 2022).

In August 2023, China introduced new restrictions on exports of critical raw materials used in semiconductor manufacturing - exporters of gallium and germanium will be required to get a license to ship the metals. In December 2024, China banned the export of gallium, germanium and antimony to the United States, as part of a directive on dual-use items with both military and civilian applications citing national security concerns (Lv & Munroe, 2024). Gallium, in particular, is important for semiconductors due to its use in compounds like gallium arsenide (GaAs) and gallium nitride (GaN), which enable faster electron mobility, higher power efficiency, and operation at higher frequencies and temperatures compared to traditional silicon (Athow, 2022). In May 2023, China stopped buying products from the US chipmaker Micron Technology, stating that the company's products carry security risks for information networks that pose hazards to China's national security and infrastructure (Milmo & Wearden, 2023).

These measures can be seen as China's response to the United States imposing export restrictions to cut China off from key technology to manufacture semiconductors. The US tightened restrictions in November 2023 with the 'Advanced Computing Chips Rule', limiting China's access to U.S. semiconductor technology, a critical component of supercomputers used to build AI platforms. The restrictions cover semiconductor integrated circuits and semiconductor manufacturing equipment (Walsh et al., 2023). Geopolitical tensions have also affected ASML, the leading producer of lithography equipment, which has cancelled the shipment of some of its most advanced lithography machines to China in January 2024 after a request was made by the Biden administration (Simpson, 2024).

2. RESEARCH METHODS

To answer the research questions, we applied a qualitative systems mapping method, a set of approaches that is used in sustainability science to address increasingly complex problems (Hanger-Kopp et al., 2024). This systems mapping is combined with the value chain approach, a well-established framework in circular economy research (e.g. Johansen et al., 2022), which enabled mapping of circularity potentials across the semiconductor value chain.

The study employed a clustered notes approach to integrate and analyze existing literature. In this approach, individual notes were extracted from a wide array of sources and then grouped based on thematic similarities, allowing for the emergence of distinct clusters. Specifically, five clusters were identified, each corresponding to a distinct stage of the semiconductor chip value chain. The literature was scanned and analysed to pinpoint circular economy solutions relevant to one or more of these stages. An iterative process was used to refine these clusters, which ultimately led to the creation of Figure 1 that visually maps the relationships between the circular economy solutions and the value chain stages. This approach not only facilitated a broad horizontal insight into the subject matter but also ensured that the synthesis of information was both systematic and transparent.

Furthermore, to visualize some of the complex systems dynamics of environmental and geopolitical factors, the paper presents a causal loop diagram that shows networks of variables and causal influences (Barbrook-Johnson & Penn, 2022), showing positive and negative feedback loops of different types that are built around the core semiconductor value chain (see Figure 2). Based on the literature review, key variables and qualitative factors relevant to the semiconductor value chain were identified and then iteratively organized into the diagram. Initial diagrams were refined based on further literature insights and validation of causal links until a robust representation of the core semiconductor value chain was achieved, illustrating how certain processes reinforce or counteract each other. While this semiconductor systems map does not cover the full complexity and size of the value chain, it combines different qualitative factors including environmental factors, geopolitical issues and circularity solutions into a cohesive model that highlights key system dynamics.

The development of the value chain map and the systems map involved a comprehensive narrative review of both academic and grey literature (see Blomsma & Brennan, 2017). The literature search, review and selection were conducted by using both keyword searches and a snowballing approach. Literature sources were identified through searches in academic databases (Google Scholar, Scopus and IEEE Xplore) using keyword combinations of general terms of semiconductors, circular economy, recycling, wastewater, critical raw materials. In addition, more specific keyword searches were conducted with terms distinctive to the semiconductor industry such as silicon wafer recycling, acid recovery, bio-based chip design, lithography equipment remanufacturing, and so on. This iterative process included several stages to ensure a thorough understanding of the existing knowledge on circularity in semiconductor value chains and to identify gaps that this research could address.

Sources that were directly relevant to circular economy principles and sustainable value chain approaches in the semiconductor industry were considered. Grey literature including industry sustainability reports and company websites, including summaries of commercial industry reports, public policy reports and white papers, articles from reputable sources and industry-specific news portals and online tech platforms were included to capture recent trends, processes innovations and practical insights not yet covered in academic literature. Furthermore, literature and sources recommended by the anonymous reviewers were reviewed and included. Key concepts, findings about circularity aspects of semiconductor chip manufacturing, and recommendations provided in papers and reports were extracted from each source. Common themes, challenges and opportunities related to circularity in the semiconductor value chain were identified and summarised. The method provided a robust foundation for identifying five key stages in the semiconductor value chain and developing the semiconductor causal loop diagram that visualizes the circularity potentials in the semiconductor industry.

Table 1. Summary of Literature Review Sources Types and Search Methods

Source type	Description	Search methods	Objective	Literature examples
Academic literature	Includes peer-reviewed papers and articles retrieved from academic databases like Google Scholar, Scopus, and IEEE Xplore.	Keyword searches and snowballing approach; general terms (e.g., semiconductors, circular economy) and specific industry-related terms (e.g., silicon wafer recycling, closed-loop water use).	To understand existing knowledge on circularity in different semiconductor value chain stages and identify knowledge gaps.	Boyd, 2012; Ferella et al. 2021; Gupta et al., 2022; Lee et al. 2024; Ruberti, 2023; Sysova et al., 2022; Tang et al. 2023; Wang et al. 2023; Zhan et al., 2020;
Grey literature	Industry reports, company websites, white papers, reputable news articles, industry-specific news portals and online tech platforms.	Direct search for recent trends and practical insights; inclusion of sustainability reports and semiconductor process innovations not covered in academic literature.	To capture recent trends, innovations and insights not covered in academic sources.	Athow, 2022; Cheng, 2021; Irwin-Hunt, 2023; McAleese, 2021; Li, 2023; Meixner, 2023; Milmo & Wearden, 2023; Sloan, 2024; Zambonin, 2024
Government reports and policy documents	Reports from government agencies on sustainability, semiconductor policies (e.g. EU Chips Act, US Advanced Computing Chips Rule), or circular economy initiatives.	Direct search on government agency websites.	To identify authoritative insights on semiconductor policy and regulatory frameworks.	Bertuzzi, 2022; European Commission, 2023; US EPA 2006;
Market research reports	Commercial research reports providing trends, forecasts, and analyses on the semiconductor industry.	Search on market research firm sites for summary reports or databases providing industry insights.	To capture recent industry trends and understand competitive landscapes and future outlooks.	Global Info Research, 2024; McKinsey & Company, 2020; Paben, 2023;
Conference proceedings	Papers and presentations shared at industry or	Review of proceedings from	To gather cutting-edge research and innovative	Axt et al., 2023; Bleier et al., 2022;

	academic conferences.	relevant conferences and symposiums.	practices presented at events.	Lippert et al., 2024;
Technical standards and guidelines	Documents from standards organizations like ISO and IEEE on best practices and guidelines.	Consultation of standards and guidelines published by industry bodies.	To ensure alignment with established best practices and technical standards.	IEEE, 2020; ISO, 2015
Industry blogs and websites	Blogs, company websites (e.g. Intel, ASML, TSMC), and podcasts discussing emerging trends and practical challenges in the industry.	Search and review of online content from credible industry sources.	To include practical, real-time insights from industry experts and practitioners.	ASML, 2023; Intel, 2022, 2024; Micron, 2022; Nikon, 2023; Pragmatic Semiconductors 2023; Samsung, 2024; SEMI, 2024; Wafer World, 2022;
Reviewer-recommended sources	Sources recommended by anonymous reviewers, including key papers and reports directly relevant to the topic.	Reviewed and included as part of an iterative process to identify gaps and key concepts.	To integrate additional insights and recommendations relevant to circularity.	Baldassare et al., 2023

3. CIRCULARITY SOLUTIONS ACROSS THE SEMICONDUCTOR VALUE CHAIN

The following section is structured around circularity solutions across five different stages of the semiconductor value chain and the key actors. Given the complexity of the semiconductor chip value chain, a simplified version is used to highlight generalized insights and visualize the five stages:

1. The design stage for semiconductor chips conducted by electronics companies and design companies (‘fabless companies”) that underpins the circularity potential for the other four stages.
2. Production and manufacturing of the equipment that is needed to produce semiconductor chips.
3. Front-end manufacturing and silicon wafer fabrication taking place in foundries or semiconductor fabrication plants (also referred to as ‘fabs’).
4. Back-end manufacturing where semiconductors are tested, assembled and mounted onto integrated circuits and packaged.
5. End-of-life stage of recovery of semiconductors from electronic waste (see Figure 1).

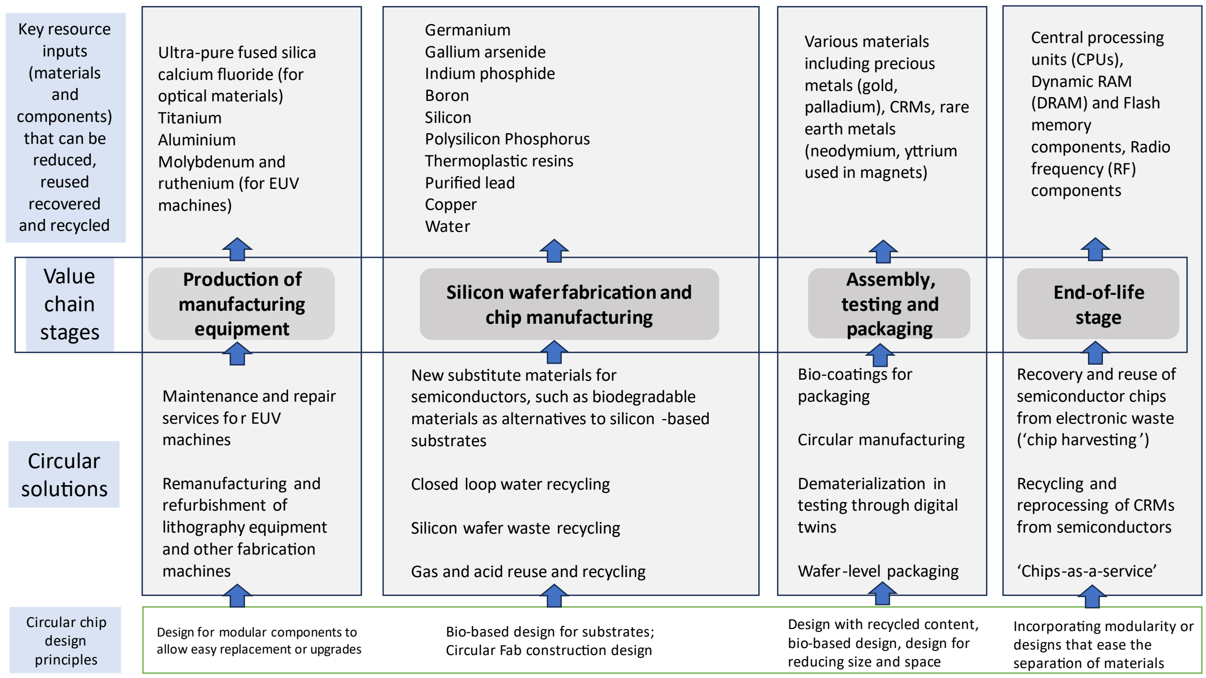

Figure 1. Simplified Semiconductor Value Chain Mapping. Five stages beginning with the design stage showing the existing and potential circular solutions together with a range of key resource and material inputs that can be reduced, reused, recovered and recycled (source: authors' original figure based on (Wallach, 2021; Zhan et al., 2020; Burkacky et al., 2017)

3.1 Semiconductor Microchip Design – Enabling Circularity Across the Value Chain

To enable circularity across the various stages of the value chain, circular principles need to be applied during the design stage. We have identified opportunities for design for modular components to allow for easy replacement, refurbishment, repair and upgrades for the semiconductor chip manufacturing equipment. The design of biodegradable semiconductors, although still in its infancy, offers the use of organic semiconductors as a potential alternative to traditional inorganic semiconductors, which require rare earth metals in their production. Promising future biodegradable materials and polymers and organic substrates are being explored (Gan et al., 2023). An example is the use of regenerating biomass such as dried birch leaves as the raw material for organic semiconductors (Tang et al., 2023). Furthermore, introducing sustainable or non-toxic alternatives to semiconductor components like chitosan-based photoresists (a sugar that is derived from shellfish exoskeletons) and non-toxic water-based developers offers new perspectives for semiconductor design (Sysova et al., 2022). Another area is the design and development of more energy-efficient and high-performance semiconductors. This can be achieved through the development of new materials and designs that reduce energy consumption and increase performance. For example, graphene semiconductors (Zhao et al., 2024) are many times more sensitive and energy efficient than established silicon technology, due to the unique electrical properties of graphene.

New innovative start-up companies like Pragmatic Semiconductors have optimized existing design and developed a type of thin-film semiconductors to create a type of flexible integrated circuits (FlexiCore) that are significantly cheaper and faster to produce than silicon-based semiconductors. The FlexiCore semiconductors are not silicon-based and power consumption can be reduced considerably by 45-56% compared to the original base design (Bleier et al., 2022). Despite these promising design innovations, as the semiconductor supply chain uses almost all the available chemical materials (Baumann & Pioch, 2021), replacing most of them with "green" and "non-critical" alternatives will not be an easy task, at least not in the short term. Design innovations are also key to enable recovery and reuse of chips at the end-of-life stage. Incorporating design for modularity and design that ease the separation of components and materials are key to enable reuse, refurbishment and recycling.

3.2 Semiconductor Chip Production Equipment – Remanufacturing Lithography Equipment

The manufacturing of semiconductor chips requires a large number of high-tech machines and equipment which are highly capital intensive. The global market for refurbished and remanufactured semiconductor chip manufacturing equipment is already a mature industry and the estimated global market size is expected to reach $ 10.7 billion by 2030, rising at a market growth of 8.6% CAGR during the period from 2024-2030 (Global Info Research, 2024).

Lithography equipment, used to create the fine patterns on printed circuit boards, is a key candidate for remanufacturing due to its high cost and critical role in semiconductor production. The production of lithography equipment involves several key resource inputs, for example, the high-purity optical materials include ultra-pure fused silica and calcium fluoride for lenses and mirrors. For the extreme ultraviolet (EUV) machine systems, molybdenum and rubidium are critical for the multilayer mirrors that reflect EUV light (Saedi et al., 2020).

For lithography equipment producers, circular practices such as maintenance, repair and upgrading are key aspects of the business model. For the company ASML, the service business is subscription-like and maintenance and repair represent a 20+ year annuity. As a result, 95% of lithography machines are still in service (Tulloch, 2024), offering not only reductions in materials use, but also cost savings. In addition to maintenance services, companies such as ASML and Nikon have been advancing remanufacturing and reuse practices, potentially making circularity a key driver of future competitiveness of the semiconductor chip industry (McAleese, 2021). ASML's Return4Reuse programme states "We believe the circular economy is vital to ensure the future success and competitiveness of the semiconductor industry". ASML seeks to reuse and remanufacture old equipment such as the PAS 5500 system that can be used to produce less sophisticated microchips, while ensuring progressively sustainable use of materials across processes and the value chain via refurbished and remanufactured products (ASML, 2023).

Nikon has promoted the reuse of semiconductor lithography equipment to reduce waste. Lithography systems have grown larger in size with advancements in semiconductor products, so their reuse and remanufacturing of components has become increasingly important for reducing waste of components and materials. After customers finish using these systems, Nikon buys them back, restores their parts and components, and resells them. Since the launch of the initiative in 2000, by March 2023, 449 systems had been resold, reducing waste materials that would have been disposed of by about 4,100 tonnes (Nikon, 2023).

3.3 Silicon Wafer Fabrication and Chip Manufacturing Stage

The biggest environmental impacts stem from energy and water consumption, and chemical pollution generated during the front-end manufacturing stage of semiconductors which takes place in semiconductor 'fabs' – short for fabrication – in which raw silicon is turned into wafers. The process involves large numbers on individual steps including wafer processing, wet cleans, photolithography, ion implantation, various etching and thermal treatment processes. Manufacturing sites are generally certified to the ISO 14001:2015 Environmental Management international standard (ISO, 2015) and other environmental certifications. The leading players in the semiconductor industry including Intel, Samsung, TSMC, Micron Technology, and others have already started implementing a range of circular solutions in their manufacturing processes to increase resource efficiency and reduce waste. For example, the reuse of process water, production waste reduction, and recycling of materials such as silicon wafers are some of the circular solutions that have been adopted.

3.3.1 Circular solutions to wastewater can enable closing the water loop of chip fabrication plants

For the chip manufacturing stage, circular fab construction design that enables closed loop water recycling, gas and acid reuse and metal recovery are emerging solutions (Meixner, 2023). Water circularity as a strategy is pursued not only for environmental reasons, but is becoming essential to simply maintain manufacturing processes. For example, future water supply to the Hsinchu Science Park in Taiwan, which plays a vital role in the chain of semiconductor production, is emerging as a serious concern for stabilizing the manufacturing processes and hence the global semiconductor component supply (Lee et al., 2024). To address this issue, TSMC in Taiwan have implemented circular solutions to reduce water consumption in their manufacturing processes. During Taiwan's drought and water shortages in early 2021, TSMC built upgraded industrial water treatment plants so water can be reused in the semiconductor manufacturing process (Cheng, 2021).Taiwan suffered from droughts again in 2023 when record low rainfall impacted water availability for chip manufacturing (Li, 2023).

Other manufacturers also have set water savings, recycling and reuse targets for 2030. For example, Micron aims to reuse, recycle, and restore 75% of the water used in its operations (Micron, 2022). Similarly, Intel has implemented a water recycling programme that treats and reuses wastewater generated by their manufacturing processes. The stated company goal is to accomplish ‘net-positive water use’ through water conservation by 2030 (Intel, 2022). Both TSMC and Intel are facing challenges in Arizona, a part of the Unite States increasingly prone to drought, where dwindling water supplies have raised questions about the viability of the planned semiconductor manufacturing plans - Intel is expanding existing campus in Chandler and TSMC is investing $40bn to build two large chip fabrication facilities with high water consumption (Irwin-Hunt, 2023).

One of the key environmental issues in semiconductor manufacturing is water use and chemical pollution. Effluent discharges from chipmaking facilities are heavily contaminated with organic solvents and cutting residue, metals, silicon, acids, and salts. Water recycling and reuse are key circular economy strategies that can be adopted. Membrane technologies such as reverse osmosis already play a dominant role in water treatment and reclamation of many manufacturing facilities (Wang et al., 2023). Emerging technologies include novel electrochemical cell designs can be used to achieve selective copper removal and recovery from semiconductor wastewater streams (Lippert et al., 2024). Specific chemical pollutants in wastewater from semiconductor manufacturing include tetramethylammonium hydroxide (TMAH). There is significant concern about the presence of TMAH in wastewater streams in semiconductor manufacturing countries such as Japan, China, South Korea, and Taiwan and many factories carry out only preliminary treatment. Pilot studies suggest that novel wastewater solutions using microorganisms in aerobic bioreactors can eliminate TMAH from wastewater and could provide a solution to the issue and enable water reuse (Ferella et al., 2021).

3.3.2 Addressing industrial waste from semiconductor manufacturing through circular solutions

Silicon wafers are a key component in semiconductor chip manufacturing, requiring raw materials such as highly pure semiconductor silicon, silicon carbide and germanium. Recycling semiconductor wafers is a circular solution that can been implemented to reduce the amount of waste generated during the manufacturing process. Waste from silicon wafers is gathered, the silicon sludge is ground into tiny particles and subjected to a self-propagating high-temperature synthesis (SHS) reaction [1] to create a ceramic material called SiAlON (Wafer World, 2022). This process involves removing the layers of the wafer and polishing the surface to make it ready for reuse. Back in 2006, during wafer production process, about 60% of silicon from cutting and polishing was scrapped (US EPA, 2006). The recycling of wafers can reduce the amount of waste generated by the industry. Companies like Intel and Samsung have implemented silicon wafer recycling programmes to reuse the wafers in their manufacturing processes.

Intel has adopted a circular strategy to manage waste from its manufacturing processes. Intel has increased its recycling rate from 25% to 90% since the 1990s and total waste generation has decreased. The company claims it has transitioned from traditional disposal methods of incineration and landfill to materials recovery and reuse methods, resulting in circular economy solutions that reduce costs and environmental impact (Fiehrer et al., 2019). Similarly, in 2018, TSMC launched an "Action Plans to Turn Waste into High Value Products" for waste sulphuric acid recycling, ammonia-nitrogen wastewater treatment, turning cobalt sulfate waste into industrial-grade recycled products, and other waste product recovery. Samsung set a goal in 2018 to become zero-waste and has achieved a Platinum of Zero Waste-to-Landfill certification at its semiconductor manufacturing sites for the first time in the industry in 2021 and reached 97% waste recycling rate at all semiconductor manufacturing sites. Various processes and technologies are used to recycle Epoxy Molding Compounds (EMCs) and extract metals such as gold and tungsten from the clean vacuum dust captured in semiconductor process equipment (Samsung, 2024). Another circular solution is the recycling of gases used in the manufacturing process. This process involves collecting and purifying the gases used in the production process and reusing them. Gas recycling is another potential solution for

[1] Self-propagating high temperature synthesis (SHS) is used to describe a process in which the initial reagents (usually powders), when ignited, spontaneously transform into products due to the exothermitic heat of reaction.

enhancing sustainability in the semiconductor lithography industry. This can be done by capturing unused process gases and refining them for other uses or reuse. Several manufacturers have developed new gas recycling systems that purify up to 85 percent of used neon gas for reuse in lithography lasers (Yashiro et al., 2017).

3.4 Assembly and Back-End Manufacturing – Circular Solutions for Semiconductor Packaging

The back-end manufacturing process includes various steps to prepare and mount wafers and packaging of integrated circuits. The packaging of integrated circuits is the last stage in the manufacture of semiconductor devices. The package is a case that surrounds the circuit material and is mounted and connecting to the printed circuit board. This process is critical for circularity, ensuring microchips to be easily removed at the end-of-life. Furthermore, there are several possible recyclable direct materials such as alloys and bonding wire that can be used in semiconductor memory packaging (Gan et al., 2023). Future innovative sustainable materials in semiconductor packaging could include biodegradable materials for printed circuit boards, organic substrates, and die attach films (specialized adhesive materials) used in memory packaging.

3.5 End-of-Life Stage - Semiconductor Recovery From Electronic Waste and Refurbishment

For the companies involved in the various stages of semiconductor design and manufacturing, the end-of-life remains a major challenge with no scalable sustainable solutions yet developed. One emerging option is so-called 'chip harvesting', which involves extracting functional semiconductor components from discarded electronics, testing them for functionality, and refurbishing and reusing them in other applications (Stoddard et al., 2024). Some companies are beginning to offer semiconductor chip 'recovery as a service' and 'chips harvesting', with new methods to remove higher-value chips from CPUs. The recovered chips are certified and returned to the client for either reuse or to sell them (Paben, 2023).

There are potentially significant reductions in CO2 emissions associated with the recovery and reuse of semiconductor chips. Companies like IC Recovery exemplify this potential, as their process of recovering and reusing a single chip instead of manufacturing a new one results in an average saving of 6.4 kg CO2e per chip. These savings stem from avoiding the energy-intensive processes involved in mining raw materials, wafer fabrication and chip manufacturing (Boundless, 2022). Scaling such recovery practices across the semiconductor industry could result in substantial environmental benefits.

There are, however, several barriers: semiconductor chips are often highly integrated with other components on circuit boards, making it difficult to separate them without damaging the chips. In most cases, microchips can only be reused in lower-end, general purpose applications or in non-critical roles, but not high-performance devices as harvested chips often do not meet the specifications required for new electronics. Refurbished chips may not meet the high-performance requirements of AI applications, which often rely on cutting-edge chips with advanced processing speeds, power efficiency, and optimized architectures.

When it comes to recycling of smaller semiconductor materials, this process is financially problematic, given that only small amounts of materials can be reclaimed from individual products such as smartphones. According to the IEEE, recycling of semiconductor materials is also not without its own environmental costs as the process results in significant waste and the emission of numerous toxic pollutants (IEEE, 2020). Recycling gold from semiconductors in electronic waste is not straightforward because the gold is embedded in a metal or plastic housing and may only be two percent by weight. New methods of recycling gallium arsenide from scrapped integrated circuits are being developed. For example, in a study by Zhan et al. (2020) gallium and arsenic recovery rates were 99.9 and 95.5%, respectively through the application of a hydrothermal-buffering method. Furthermore, 91.2% of the packaging materials were decomposed without releasing any toxic gases to the environment.

Ethical considerations are also a concern, as many used semiconductor products end up in developing world e-waste recycling facilities known for hazardous working conditions and exploiting child labour. Semiconductors as parts of electronics fall within the scope of e-waste laws when they are incorporated into a final product by an original equipment manufacturer. As such, circular solutions will require a collective approach for semiconductor industry working with technology companies, retailers, customers, and other stakeholders to identify shared solutions for used electronics (Stoddard et al., 2024). Some semiconductor companies have taken steps to address these issues. For example, the company Intel has set up a free of charge mail-back programme for various devices and products containing Intel semiconductors to recycle these products, with different state-level services. District of Columbia residents can return other manufacturer brand products on a one-to-one basis with the purchase of the same type of equipment for recycling free of charge. In Pennsylvania, Intel is registered with State Department of Environmental Protection and the state's electronic recycling programme (Intel, 2024).

In conclusion, our analysis addressing research question 1 ("How can circular economy practices transform the semiconductor value chain to reduce environmental impact and improve resource security?") indicates that integrating circular economy practices across every stage of the semiconductor value chain can improve the industry – minimizing environmental impacts while bolstering resource security. In the design stage, fabless companies and electronics designers lay the groundwork for circular solutions by prioritizing modularity and recyclability, which supports sustainable practices across subsequent stages. During the production phase, equipment manufacturers integrate closed-loop processes and design for durability, while front-end manufacturing focuses on optimizing silicon wafer fabrication to reduce waste and energy use. Back-end manufacturing further contributes by developing testing, assembly, and packaging methods that enable easier disassembly and material recovery, culminating in innovative end-of-life strategies that recover valuable components from electronic waste. Together, these practices, if adopted at scale, can diminish dependence on critical raw materials, reduce toxic waste and encourage the adoption of biobased solutions, ultimately fostering a more resilient semiconductor industry.

4 SEMICONDUCTOR VALUE CHAINS AS A COMPLEX SYSTEM – ENVIRONMENTAL FEEDBACKS, GEOPOLITICAL TENSIONS AND CIRCULAR SOLUTIONS

The following section offers a systems mapping perspective that illustrates the intricate interconnections between environmental and geopolitical issues across the semiconductor value chain. It underscores the interconnected nature of semiconductor manufacturing, illustrating both the challenges (resource constraints, climate impacts, pollution, geopolitical factors) and the potential solutions (material substitution, recycling, circular business models, renewable energy) that shape the industry's environmental and societal impacts. It identifies key chokepoints (Jie, 2023) where these challenges converge, such as water scarcity, tensions of CRM supply, trade restrictions and pollution from toxic waste. By adopting circular solutions, including material recovery, chip refurbishment, and resource-efficient manufacturing processes, we argue that some of these chokepoints can be mitigated. These interconnections and feedback loops are visually depicted in Figure 2.

Linear semiconductor manufacturing can contribute to a detrimental cycle with widespread negative environmental impacts and feedback loops. The already occurring impacts can trigger a series of reactions that either amplify (positive feedback) or dampen (negative feedback) the original change, leading to further environmental consequences. The high energy consumption inherent in semiconductor production, often reliant on fossil fuels, exacerbates climate change, thereby jeopardizing the availability of water resources crucial for manufacturing hubs in locations like Taiwan and Arizona (Sloan, 2024). As semiconductors reach the end of their lifecycle, their disposal in electronic waste streams results in pollution and adverse human health effects, perpetuating the linear model's environmental toll. Moreover, the loss of valuable materials during the disposal process further intensifies resource depletion. This cycle underscores the urgency of transitioning to circular economy practices in semiconductor manufacturing to break free from these interconnected negative consequences.

As highlighted in the introduction, there are geopolitical dimensions, such as the increasing demand and extraction of CRMs can fuel geopolitical tension and trade disputes, amplifying the strategic importance of securing access to these resources. Simultaneously, the need for cutting-edge semiconductor manufacturing technologies which are mostly manufactured in Taiwan adds another layer of geopolitical complexity. The ongoing tensions between Mainland China and Taiwan, U.S.-China relations, pose potential risks that could severely disrupt semiconductor chip supply chains through export restrictions, sanctions and other barriers (Zambonin, 2024).

Circular economy solutions can potentially play a pivotal role in mitigating the negative impacts associated with semiconductor manufacturing, fostering a virtuous cycle of sustainability. Semiconductors, crucial for renewable energy technologies such as solar PV panels and electric vehicles, contribute to decarbonizing the energy supply required for their own production. Water recycling and reuse practices within semiconductor fabrication facilities alleviate freshwater demands, enhancing the overall environmental efficiency of manufacturing processes. The maintenance, remanufacturing and refurbishment of lithography equipment offer a sustainable approach to ensure lifetime extensions of the equipment, reducing the need for new resources and minimizing waste. Furthermore, semiconductors are needed for circular business models and IoT-enabled circular manufacturing (Asif et al., 2018), and advanced data management and intelligent tracking technology (Delpla et al., 2022). Semiconductors are also required for dematerialization strategies that lead to reductions in the amount of materials or energy required to provide goods and services in the economy. In the circular economy for electronics, dematerialization can be achieved through reducing product sizes, closing loops between secondary material supply and primary material demand for electronics, and through digitally enabled shifts from products to services. Semiconductors are often regarded to be a prime example of dematerialization since value and utility is high while the size and weight of the product is negligible. However, dematerialization of electronics faces not only barriers in terms of product design, collection rates and efficient recycling infrastructure (Kasulaitis et al., 2019) – but the upstream material use in the semiconductor manufacturing phases suggests that dematerialization across the full electronics value chain is difficult to achieve (Williams et al., 2002).

As described above, flexible electronics are becoming a promising approach to target applications whose computational needs are not met by traditional silicon-based semiconductors. It is becoming possible to embed them into many products, bringing connectivity and traceability to everyday objects. Example applications include radio frequency identification (RFID) and near field communications (NFC), where microchips give everyday objects unique digital identities as well as interact with their environment. This brings benefits to the entire product lifecycle and enables circular solutions. For example, Pragmatic Semiconductors cooperates with drinkware specialists and digital returns platform providers to develop smart reusable coffee cup solutions which use NFC-based tags powered by Pragmatic's flexible integrated circuits, lowering cost and requiring much lower amount of materials in the manufacturing phase (Pragmatic Semiconductors, 2023).

Developing robust secondary markets for recovered and refurbished semiconductor chips could become essential to promote circularity and reduce reliance on primary resources. This requires the establishment of standardization and quality assurance schemes to ensure the reliability, compatibility, and performance of refurbished chips, helping to build industry trust and encourage wider adoption. Moreover, recycling CRMs from semiconductor components in electronic waste not only promotes responsible disposal practices but also contributes to the creation of more resilient supply chains through secondary materials. Embracing these circular economy principles in the semiconductor industry not only addresses environmental concerns but also establishes a positive feedback loop where sustainability practices benefit both the industry and the broader ecosystem (see Figure 2).

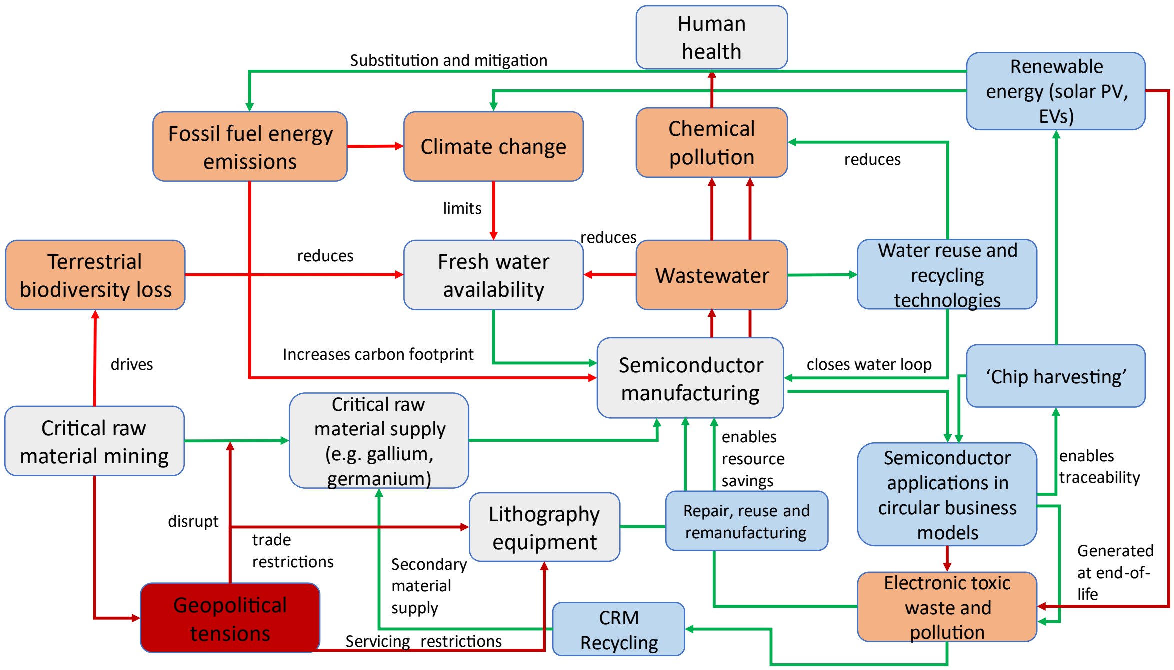

Figure 2. Semiconductor Manufacturing System Map Including Interactions Between Environmental Factors (Light Red), Geopolitical Factors (Dark Red), Technical and Economic Factors (Grey). Circular economy solutions (light blue) such as water reuse, materials recycling and equipment reuse and remanufacturing, use or renewable energy are included to show how they can create virtuous dynamics into the system. Red arrows indicate negative impacts such as worsening environmental conditions, health hazards or trade disruptions, while green arrows indicate positive impacts such as reduction in pollution to the environment, improved resource efficiency and supply security (Source: Authors' original diagram)

Our analysis addressing research question 2 ("How can these circular practices strengthen the value chain against geopolitical risks and supply chain disruptions?") shows that the potential to reduce geopolitical tensions through circularity measures such as alternative materials, resource diversification, recycling, and circular business models is conceptually sound. The approaches can potentially lessen dependency on single-source suppliers and mitigate raw material constraints. The systems map provides a useful high-level framework for understanding and visualising these dynamics. Future analysis could include deeper exploration of how market forces, regulatory policies and global trade relationships influence the feasibility and pace of change towards circularity in the semiconductor value chain.

5 DISCUSSION: REMAINING CHALLENGES AND KEY ISSUES FOR FUTURE RESEARCH

Implementing circular solutions in semiconductor manufacturing presents technical, political, and environmental challenges. One of the next steps in innovation for semiconductor chips will not only need to address impacts occurring during the manufacturing process, but also application of generic models of circular manufacturing systems (Roci et al., 2022) and related business models, which could also become more relevant for semiconductor manufacturing in the future. However, the complexity of the multiple stages in the manufacturing processes makes it difficult to identify and implement circular solutions across the full lifecycle and value chain.

The development of more circular semiconductor products that can be easily recovered and either reused or recycled at the end-of-life stages will be crucial. Extending lifecycles of products containing semiconductors – before recycling of materials becomes necessary - will be a key solution to address environmental impacts and reduce resource demands. Reducing the need for frequent replacements of devices and thereby minimizing waste generation and resource use is equally important. At the same time, supporting further R&D for materials specific processes, such as domestic recycling of gallium, to increase secondary supply of materials, has been recommended by institutions such as The Hague Centre for Security Studies as a option for Europe (Patrahau et al., 2020). This could mitigate geopolitical tensions which might lead to materials for semiconductors becoming a potential choke point for the clean energy transition in Europe and around the world. In the evolving geopolitical contexts, companies are already finding themselves entangled in the crossfire – an example is the Dutch company ASML which faces not only the restriction of equipment sales to China, but also restrictions on the maintenance and repair services for the ultraviolet lithography machines in China (Koc & Leonard, 2024).

While governments continue to impose trade restrictions not only on materials but also circular services, there are unintended consequences on companies. In the ongoing pursuit of technological dominance, companies may be forced to align with specific sides. The impact is not confined to semiconductor manufacturing alone; the ramifications of potential export restrictions of CRMs extend across various electronics sectors and geographies, potentially affecting companies and financial institutions on a global scale. Therefore, the design of semiconductors with alternative materials such as biodegradable materials that reduce the reliance on CRMs could become a key long-term strategy for the circular economy transition.

5.3 Future Research Questions

The research primarily relied on a comprehensive review of existing literature, foregoing the collection of primary data from industry sources. While this approach provides broad, horizontal insights across a range of topics relevant to the semiconductor chip value chain, it also limits the depth of analysis in specific areas, particularly those requiring detailed industry context. Future research could overcome these limitations by incorporating primary data collection methods such as interviews, surveys, or case studies from industry practitioners. By adopting a mixed-methods approach, subsequent studies would be able to triangulate literature findings with real-world industry data.

Future research needs to delve further into circular business models for semiconductor chips, focusing on specific aspects such as the technical and economic feasibility and implementation of these circular models within the global industry. This research would contribute to the evolving concept and the existing literature on circular business models (e.g. Nußholz, 2017). Empirical in-depth case studies with companies to investigate the specific drivers and barriers to circularity on company level as well as along the semiconductor value chain would be highly relevant to policymakers, industry leaders and researchers, providing insights into the systemic challenges and opportunities for promoting circular practices. Systematic mapping of key actors and circularity initiatives along the value chain, along with needs assessments for infrastructure, would offer a holistic understanding of the ecosystem and inform strategies for fostering a circular economy in the semiconductor industry. For example, the SEMI Climate Consortium was established in 2023 to bring together stakeholders to collaborate on climate and sustainability challenges (SEMI, 2024). Further quantitative studies are needed to better understand the potential of refurbished microchip markets. Such research could provide critical insights into the economic viability, technical feasibility, and market demand for refurbished microchips, helping to inform evidence-based policy development. What is needed in the long-term is a sustainability vision for both the fast-evolving field of AI and the semiconductor industry that addresses resilience of supply chains, resource security and environmental concerns. Key elements will be designing semiconductors and electronics for re-use to enable 'chip harvesting', operating zero-waste fabrication plants, building a well-connected infrastructure for electronics repair centres on global scale, preventing unnecessary waste by remanufacturing used parts and components, and realizing new business models for a resource-saving society and industry (Schröder, 2022).

Finally, key players in the semiconductor industry must collaborate in order to facilitate the implementation of circular economy practices across the global value chains and foster innovation in sustainable chip production (Stoddard et al., 2024). Industry collaborations and platforms such as Semiconductor Climate Consortium – an industry group to address greenhouse gas emissions and other climate change issues across the value chain – are urgently needed. However, geopolitical tensions might complicate this essential cooperation. From a theoretical perspective, this exploratory research contributes to the emerging literature on AI sustainability as well as the literature on drivers and barriers of the circular economy by furthering our understanding on determinants for circular solutions. By describing the potentials and barriers for circularity in the semiconductor chips value chain, we have identified some general patterns and trends, but further research into this complex global value chain is needed. On the policy level, more research is required to understand how policy can support alignment of semiconductor strategies more closely with evolving circular economy policy frameworks. For example, semiconductors are mentioned in the EU's Critical Raw Materials Act that was adopted in March 2024. While pillar 1 of the EU Chips Act (European Commission, 2023) provides incentives for R&D activities, including on the topics related to sustainable and greener manufacturing, on the EU level there currently is no explicit connection between the EU Chips Act and the EU Circular Economy Action Plan or the Green Deal. Furthermore, there has been criticism that the claim that the EU Chips Act aligns with climate policy rests almost entirely on wrong assumptions and only considers end-use technologies such as EVs, but does not consider manufacturing related energy consumption and emissions (Bertuzzi, 2022). The consideration of and alignment with wider environmental policies and standards will be needed to ensure the Chips Act supports Europe's broader sustainability transition.

Table 2. Future Questions for Circular Semiconductor Value Chain Research

Research area	**Future research questions**
Circular business models	What are the technical and economic feasibilities of implementing circular business models in the semiconductor industry? What are the opportunities for start-up companies?
Empirical company case studies	What are the specific drivers and barriers to circularity at the company level and across the semiconductor value chain?
Mapping key actors and initiatives	What are the roles and needs of key actors and networks (e.g. the SEMI Climate Consortium) to foster circularity in the semiconductor industry?
Refurbished microchip markets	What is the economic viability, technical feasibility and market demand for refurbished microchips?
Sustainability vision for AI and semiconductors	What strategies can address supply chain resilience, resource security, and environmental concerns in the context of AI and semiconductor growth?
Collaborative industry platforms	How can collaboration between semiconductor industry players facilitate the adoption of circular economy practices despite geopolitical tensions?
Policy alignment and support	How can policy frameworks, such as the EU Chips Act, better align with circular economy goals and address manufacturing-related emissions and resource use?

6 CONCLUSION

In conclusion, circularity offers tangible solutions for the semiconductor value chain by improving resource efficiency, reducing reliance on primary material supply chains, and enhancing supply chain security. While establishing recycling infrastructures and processes for semiconductor components and end-of-life chip materials is a long-term challenge, the groundwork for the essential information infrastructure can commence immediately. Emerging solutions, such as the adoption of biobased materials and the growth of markets for semiconductor chip refurbishment and reuse, hold significant promise for enhancing sustainability in the industry. At the same time, semiconductor companies stand to benefit from exploring circular business models in other sectors, especially the need for traceability systems such digital product passports, recognizing the valuable opportunities they present for fostering innovation and diversifying revenue streams in this evolving landscape.

However, while these circular approaches can address some sustainability concerns relating to AI hardware infrastructure, they do not confront the broader systemic questions. As digital infrastructures expand rapidly, this growth not only amplifies resource consumption but also drives an ever-increasing energy demand, posing significant environmental, societal and political challenges. A wider political and societal debate will be necessary to critically examine the uses of digital technologies and AI, evaluate their true necessity, distinguish between critical needs and more trivial demands, and potentially consider the need for slowing down development and placing overall limits. Only by addressing these fundamental issues can we ensure that the expansion of the semiconductor chip industry, digital infrastructures and AI aligns with long-term sustainability goals.

AUTHOR CONTRIBUTIONS

Patrick Schröder: Conceptualized the study, conducted the literature review and led the writing.
Martin Charter: Contributed to conceptualization, co-wrote sections of the manuscript and reviewed the final draft.
Jack Barrie: Contributed to conceptualization, co-wrote sections and participated in the review process.

DECLARATIONS

Competing interests The authors declare no competing interests.

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